NTU Journal of Engineering and Technology (2023) 2 (4) : 1-11
DOI: https://doi.org/10.56286/ntujet.v2i4.682

P-ISSN: 2788-9971 E-ISSN: 2788-998X
NTU Journal of Engineering and Technology
Available online at: https://journals.ntu.edu.iq/index.php/NTU-JET/index

# THE EFFECT OF DIFFERENT DESIGN RATIOS ON THE COMPRESSIVE STRENGTH OF GEOPOLYMER CONCRETE: A PARAMETRIC STUDY USING THE TAGUCHI METHOD

Ahmed Radhi Taha[1], Alyaa Abbas Al-Attar[1], Hasan Mohammed Ahmed[1]
Ahmed.Radhi@ntu.edu.iq [1] , dr.alyaa@ntu.edu.iq [1] , albegmprli@ntu.edu.iq [1]
[1]Department of Building and Construction Technology Engineering, Engineering Technical College,
Northern Technical University, Mosul, Iraq.

## Article Informations

**Received:** 09-09- 2023,
**Revised**: 22-10-2023,
**Accepted:** 05-11-2023,
**Published online**: 05-12-2023

**Corresponding author:**
Name: Ahmed Radhi Taha
Affiliation : Northern Technical University
Email: Ahmed.Radhi@ntu.edu.iq

**Key Words:**
geopolymer concrete
tagouchi method
fly ash
alkaline solution
Scanning electron microscopy

## ABSTRACT

This paper presents the influence of numerous limits on compressive strength of fly ash-based geopolymer concrete mixtures optimized by Taguchi method using Minitab program. The major goal is to find the optimal ratios that may give the greatest compressive strength of geopolymer concrete. A total of twenty five mixtures of geopolymer concrete with five mixtures of normal concrete were assessed considering the effect of inclusion of Alkali-Activator to binder ratio (AA/B), NaOH concentration (M), Influence of $Na_2SiO_3$ to NaOH ratio (SS/SH) and effect of binder content (B). Different molarities was used in this study: 8, 10, 12, 14, and 16. Flay ash by way of waste material is used in ratios of (15, 17.5, 20, 22.5, and 25) % and substituted via 90 % of ordinary Portland cement to output the geopolymer concrete. Also, sodium silicate to sodium hydroxide are utilized in ratios of 1, 1.5, 2, 2.5, and 3. The alkali activator was made using sodium silicate, sodium hydroxide, and water in ratios of (0.3, 0.35, 0.4, 0.45, and 0.5). One type of locally crushed coarse aggregate was used instead of normal coarse aggregate that has sizes of 19 mm, as well as, fine aggregate. The examined mechanical property is characterized by compressive strength. The outcomes specify that the geopolymer concrete exhibits The highest compressive strength has been reached when the alkali-activator to binder ratio equal to 0.45, NaOH concentrations equal to 16, $Na_2SiO_3$ to NaOH ratio equal to 1 and binder content reached to 25 %. Also, the result showed that the compressive increases as the curing age increases. Moreover, scanning electron microscopy was evaluated to show the geopolymer concrete microstructure.

THIS IS AN OPEN ACCESS ARTICLE UNDER THE CC BY LICENSE:
**https://creativecommons.org/licenses/by/4.0/**

## Introduction

THE UNIVERSAL CONSUMPTION OF CEMENT has increased every once in a while, and the practice of basis materials in cement manufacture has a detrimental influence on the environment. Furthermore, an enormous quantity of energy is spent in the manufacture of cement, and as a outcome, cement manufacture has become one of the utmost sources of carbon dioxide ($CO_2$) [1][2]. Also, the worldwide cement industry emits around (1.35) billion tons of greenhouse gases for each year, accounting for approximately 7 % of total man-made conservatory gas releases to the earth's air [3][4]. Furthermore, it has been noted that many concrete structures, particularly those erected in corrosive conditions, begin to disintegrate after 20 to 30 years, despite being planned for a service life of more than 50 years[5].

Additionally, the construction industry is keen to embrace a sustainable alternative to OPC that doesn't sacrifice strength and durability, as well as to reduce greenhouse gas emissions[6]. It is imperative to replace OPC partially or entirely with alternative green building materials that eventually provide the same or superior qualities of conventional concrete in order to decrease environmental pollution and greenhouse gas emissions.

It has been concluding from the above that the production of regular concrete must be reduced in order to reduce the environmental pollution resulting from the cement industry in addition to other concrete materials. Therefore, research in recent years has focused on producing environmentally friendly concrete.

So numerous studies aimed at reducing cement ingesting by the use of waste products or usual resources, such as Pozzolanic materials, had a good effect[7][8]. THE NAME OF THIS NON-CEMENTITIOUS MATERIALS IS GEOPOLYMER[9]. Davidovits originally created the geopolymer technique in 1978. His study amply demonstrates how the geopolymer technology application might lower the emissions of $CO_2$ brought on by the cement industry. Davidovits suggested that an alkaline liquid may be used to make a binder by reacting with aluminosilicate in a physical basis material or in by-product materials like fly ash[10].

Additionally, he completely substituted fly ash with Portland cement in the production of concrete, which is today known as geopolymer concrete. Geopolymer concrete is made by combining an alumino-silicate-based foundation ingredient with an alkaline solution. Fly ash, which is rich in alumina and silica, has the potential to be used as a raw material for geopolymer binder [11]. The polymerization reaction that takes place between aluminum, silica, and an alkaline solution in fly ash to create a structural binder paste is where the term "geopolymer" originated. The sodium hydroxide (NaOH) and sodium silicate ($Na_2SiO_3$)-based alkaline solution will act as the activator solution [12][13].

Regarding the method of design, the mixes were designed by one of the ODE methods (Taguchi design method). Taguchi methods are standardized approach, developed by Dr Genichi Taguchi in 1980 to determining the best combination of inputs to produce a product or service. Taguchi design focuses on four perspectives: robust design, parameter design, concept design, and tolerance design.

Olivia et al. (2011) were studied Taguchi method optimization of fly ash geopolymer combinations, as well as a research on the mechanical characteristics and durability of concrete generated from the ideal mixtures. The aggregate content influences, ratio of alkaline solution to fly ash, ratio of sodium silicate to sodium hydroxide, and process of curing were all considered in nine different combinations. The control mix consisted of regular Portland Cement (OPC) concrete with a strength of 55 MPa. T4, T7, and T10 were the three selected ideal mixes. According to the findings, 55 MPa of geopolymer concrete may be manufactured in 28 days. They produced reduced expansion and drying shrinkage, exhibited elastic modulus that were (14-28) % lower than those of the control mix of OPC, and had superior tensile and flexural strength [14].

Also, Mehta et al. (2017) were studied the effects of several variables on the compressive strength and water absorption characteristics of fly ash-based geopolymer concrete mixes optimized using Taguchi technique. The effects of substituting regular Portland cement for fly ash, using various molarities of sodium hydroxide solution, and using various curing temperatures were all taken into consideration while evaluating a total of sixteen mixes. According to the findings, fly ash-based geopolymer concrete produced maximum compressive strength over 7 days of 64.39 MPa and minimal water absorption of 3.04% [15].

## 1. Ingredients and Approaches

Ordinary Portland cement OPC and class F low-calcium fly ash FA are two of the binders employed in this investigation to represent two dissimilar types of binders. As displayed in Table 1, the binder's chemical composition is stated in proportions by way of the mass of the constituent oxides. All mixes employment sieve number 4.75 mm, through which normal-weight fine aggregate flows. The aggregates physical characteristics are shown in Table 2 for one form of coarse aggregate, which is signified in this study by crushed normal aggregate. Combining sodium silicates ($Na_2SiO_3$)

with sodium hydroxide solution (NaOH) creates the alkali activator that is employed. $Na_2O$ is 13.4%, $SiO_2$ is 32.5%, and water is 54% of the chemical composition of sodium silicates.

## 1. 1. Fly Ash (FA)

To improved use this industrial waste by-product material, fly ash has been chosen as the basis substantial for the geopolymer concrete mixture. Where, low-calcium class F fly ash from power plants in the United Arab Emirates was employed in the current study as a raw material for the mixture of GPC. Table 1 displays the fly ash chemical composition as specified by way of X-Ray fluorescence analysis (XRF).

## 1. 2. Conventional Cement (OPC)

The cement used was common Portland cement (type I), which was supplied by the Badoosh cement facility in Mosul, Iraq. In table 1, the chemical composition is shown.

**Table 1**. Chemical composition by X-Ray for (FA & OPC)*

| Constituents | FA | OPC |
|---|---|---|
| $SiO_2$ | 47.67 | 21.33 |
| $Al_2O_3$ | 27.73 | 5.43 |
| $Fe_2O_3$ | 18.42 | 2.326 |
| CaO | 5.11 | 60.3 |
| $SO_3$ | 0.34 | 1.83 |
| $C_3A$ | 42.38 | 0.26 |
| MgO | 2.65 | 3.88 |
| Free Cao | …. | ... |
| Cl- | … | .... |
| LOI | 3.71 | 2.18 |

*Chemical composition tests are carried out in Baghdad central Laboratory

## 1. 3. Crushed Coarse Aggregates

For entirely test samples, nearby obtainable crushed coarse aggregate with a maximum size of 19 mm has been employed. The coarse aggregate was employed in state of sturated surface dry. crushed aggregates: Table 2 presents their physical attributes.

## 1. 4. Fine Aggregates

For entirely test samples, nearby obtainable normal fine aggregate that from sieve no. 4 was passed, utilized in the making of all test samples. The normal fine aggregate has been utilized in state of saturated surface dry. Fine aggregates: Table 2 presents their Physical properties.

**Table 2.** aggregates physical characteristics, both (fine and crushed coarse)*

| Estate | Crushed coarse aggregate | Fine aggregate |
|---|---|---|
| Dry specific gravity | 2.61 | 2.59 |
| S.S.D. specific Gravity | 2.64 | 2.65 |
| Absorption capacity (%) | 1.2 | 2.91 |

*The test was evaluated in the laboratory of construction materials – college of technical engineering – Mosul

## 1. 5. Sodium Hydroxide (NaOH)

Sodium hydroxide is accessible in local marketplaces in pellet or flakes unite. Sodium Hydroxide Flakes with 97 % Purity, commercial available was utilized as a based solution to make alkaline activator by making a blend of (solution of sodium silicates and sodium hydroxide), the molarity of sodium hydroxide which is located in this work was 8, 10, 12, 14 and 16. Table 3 shows the concentration of NaOH obtained by combining flakes with water in the proportions specified. Because sodium hydroxide flakes were less expensive than potassium hydroxide, they were used.

**Table 3.** The Molarity of NaOH [16]

| Molarity (M) | NaOH (Solid) % | Water % |
|---|---|---|
| 8 | 26.23 | 73.77 |
| 10 | 31.37 | 68.63 |
| 12 | 36.09 | 63.91 |
| 14 | 40.43 | 59.57 |
| 16 | 44.44 | 55.56 |

When preparing a NaOH solution, sodium hydroxide flakes are added to cold water and agitated until they dissolve and the solution reaches the desired homogeneity and concentration. The mixing of NaOH and water is an important process and it's known as an exothermic process; therefore, it stays to cool the solution.

### 1. 6. Sodium Silicates ($Na_2SiO_3$)

Sodium Silicates ($Na_2SiO_3$) are generated via fusibility of sand ($SiO_2$) by sodium-potassium or sodium carbonate ($K_2CO_3$ or $Na_2CO_3$) at a severe high temperature of 1100°C, and then melting at high-pressure fumes to form water glass (liquid glass)[17]. the sodium silicates chemical composition was display in table 4 and known as (glass water). the ratios of $Na_2SiO_3$ / NaOH has been used are (1, 1.5, 2, 2.5, and 3) for all molarity.

**Table 4.** Illustrates chemical composition of (SS)

| | |
|---|---|
| **$Na_2O$ %** | 13.7 |
| **$SiO_2$ %** | 33 |
| **Water %** | 53.3 |
| **Density-20 Baum** | 50.5-51.5 |
| **Specific Gravity** | 1.534-1.551 |
| **Viscosity** | 600-1200 |

### 1. 7. Water.

Distilled water is used to prepare a NaOH solution depending on the required molarity and to mix it.

### 1. 8. Superplasticizer (SP)

High performance concrete superplasticizer (formerly known as Flocrete PC200) from (DCP company) was used as a high range water reduction additive (HRWRA) type G which conforms to ASTM C494 [18] To improve the fresh concrete's workability and vital flowability. The dosage used was 2 % by weight of binder for all geopolymer and normal concrete. Table 5 details the technical features of Superplasticizer.

**Table 5.** Superplasticizer technical features*

| | |
|---|---|
| Colour | Light yellow liquid |
| point of Freezing | - 3°C |
| Special gravity | 1.05 |
| Entrainment of air | less than 2 % additional air at normal dosages |
| potion | (0.5 - 2.5) litre / 100 kg of cementitious ingredients in the mixture. |

* The Properties from datasheet

## 2. Design of Mix, Forming, Samples Curing.

The investigational program is focused on the manufacturing of treated fly ash for geopolymer concrete by means of one kind of typical aggregate and an alkaline activator of variable molarity. In the course of this investigation, twenty five geopolymer concrete mixes with five mixes of normal concrete were created. All generated proportions of other materials for both geopolymer and conventional concrete are utilized in Table 6. Also, Table 7 provides the parameter information for GPC mixes that were designed by the Taguchi method in the Minitab software program. The design of normal concrete mixes is taken depending on the Taguchi design method that has been applied on geopolymer concrete mixes as shown in table 6. 90% (FA) and 10% (OPC) cement serve as the mixture's binder. To allow the removal of the mold within 24 hours, OPC was utilized to induce early hardening. Eight, ten, twelve, fourteen, and sixteen molar sodium hydroxide were noticed in this study.

Depending on the molarity and concentration required, NaOH bits were thawed in distilled water 24 hours before usage. Prior to use, crushed aggregates that had a tendency to absorb the alkaline solution more than other types of aggregates were arranged in state of a saturated surface dry, as well as, fine aggregate. The mixing method has a significant influence on the geopolymer concrete final composition. After the dry components had been well combined in the mixing pan for about three minutes, the prepared alkaline activator was added. To attain more homogeneity, the mixture was wet-mixed for five more minutes.

To assess the geopolymer and normal concrete compressive strength, cubic specimens 100 × 100× 100 mm were cast. The molds were sealed once the concrete had been poured into them to keep the specimens from evaporating and deforming after 24 hours. Prior to testing, the geopolymer concrete underwent a 24-hour heat cure at 65 degrees Celsius in an oven, during which time it was kept at room temperature. Founded on the results of previous studies, the duration of the curing and testing was chosen[19][20].

**Table 6.** Proportions of generated mixes

| Mix no. | FA | OPC | sand | Crushed gravel | W/C | SS | SH | M | Extra water | Compressive strength (Mpa) | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | $kg/m^3$ | | | | | | | | % | 7 day | 28 days |
| NC 1 | … | 330 | 708.4 | 1062.6 | 0.4 | … | … | - | … | 27.623 | 34.487 |
| NC 2 | … | 385 | 672.1 | 1008.15 | 0.4 | … | … | - | … | 28.928 | 38.633 |
| NC 3 | … | 440 | 633.6 | 950.4 | 0.4 | … | … | - | … | 39.673 | 46.301 |
| NC 4 | … | 495 | 592.9 | 889.35 | 0.4 | … | … | - | … | 46.201 | 53.428 |
| NC 5 | … | 550 | 550 | 825 | 0.4 | … | … | - | … | 49.385 | 59.691 |
| GPC1 | 297 | 33 | 708.4 | 1062.6 | … | 49.5 | 49.5 | 8 | 7 | 21.652 | 29.257 |
| GPC2 | 346.5 | 38.5 | 672.1 | 1008.15 | … | 80.85 | 53.9 | 8 | 7 | 24.997 | 31.845 |
| GPC3 | 396 | 44 | 633.6 | 950.4 | … | 117.33 | 58.66 | 8 | 7 | 29.603 | 36.925 |
| GPC4 | 445.5 | 49.5 | 592.9 | 889.35 | … | 159.10 | 63.64 | 8 | 7 | 30.929 | 37.289 |
| GPC5 | 495 | 55 | 550 | 825 | … | 206.25 | 68.75 | 8 | 7 | 32.044 | 38.855 |
| GPC6 | 297 | 33 | 695.2 | 1042.8 | | 79.2 | 52.8 | 10 | 7 | 21.729 | 27.656 |
| GPC7 | 346.5 | 38.5 | 656.7 | 985.05 | … | 115.5 | 57.75 | 10 | 7 | 26.061 | 37.787 |
| GPC8 | 396 | 44 | 616 | 924 | … | 157.1429 | 62.85714 | 10 | 7 | 24.319 | 36.405 |
| GPC9 | 445.5 | 49.5 | 622.6 | 933.9 | | 111.375 | 37.125 | 10 | 7 | 30.238 | 29.487 |
| GPC10 | 495 | 55 | 583 | 874.5 | … | 96.25 | 96.25 | 10 | 7 | 33.611 | 45.2 |
| GPC11 | 297 | 33 | 682 | 1023 | … | 110 | 55 | 12 | 7 | 27.338 | 30.687 |
| GPC12 | 346.5 | 38.5 | 679.8 | 1019.7 | … | 82.5 | 33 | 12 | 7 | 28.245 | 35.623 |
| GPC13 | 396 | 44 | 642.4 | 963.6 | … | 115.5 | 38.5 | 12 | 7 | 29.605 | 37.144 |
| GPC14 | 445.5 | 49.5 | 602.8 | 904.2 | … | 99 | 99 | 12 | 7 | 30.794 | 38.067 |
| GPC15 | 495 | 55 | 561 | 841.5 | … | 148.5 | 99 | 12 | 7 | 33.503 | 39.667 |
| GPC16 | 297 | 33 | 701.8 | 1052.7 | … | 82.5 | 33 | 14 | 7 | 28.007 | 34.441 |
| GPC17 | 346.5 | 38.5 | 664.4 | 996.6 | … | 115.5 | 38.5 | 14 | 7 | 38.916 | 46.269 |
| GPC18 | 396 | 44 | 624.8 | 937.2 | … | 99 | 99 | 14 | 7 | 33.451 | 41.37 |
| GPC19 | 445.5 | 49.5 | 583 | 874.5 | … | 148.5 | 99 | 14 | 7 | 35.014 | 42.481 |
| GPC20 | 495 | 55 | 594 | 891 | … | 110 | 55 | 14 | 7 | 37.547 | 37.697 |
| GPC21 | 297 | 33 | 688.6 | 1032.9 | … | 111.375 | 37.125 | 16 | 7 | 37.921 | 44.334 |
| GPC22 | 346.5 | 38.5 | 649 | 973.5 | … | 96.25 | 96.25 | 16 | 7 | 35.721 | 42.637 |
| GPC23 | 396 | 44 | 651.2 | 976.8 | | 79.2 | 52.8 | 16 | 7 | 32.541 | 34.095 |
| GPC24 | 445.5 | 49.5 | 612.7 | 919.05 | | 115.5 | 57.75 | 16 | 7 | 33.316 | 40.303 |
| GPC25 | 495 | 55 | 572 | 858 | | 157.1429 | 62.85714 | 16 | 7 | 35.244 | 41.53 |

**Table 7.** Illustrates the parameters of mixes that were designed by the Taguchi method.

| M | B (%) | SS/SH | AA/B |
|---|---|---|---|
| 8 | 0.15 | 1 | 0.3 |
| 8 | 0.175 | 1.5 | 0.35 |
| 8 | 0.2 | 2 | 0.4 |
| 8 | 0.225 | 2.5 | 0.45 |
| 8 | 0.25 | 3 | 0.5 |
| 10 | 0.15 | 1.5 | 0.4 |
| 10 | 0.175 | 2 | 0.45 |
| 10 | 0.2 | 2.5 | 0.5 |
| 10 | 0.225 | 3 | 0.3 |
| 10 | 0.25 | 1 | 0.35 |
| 12 | 0.15 | 2 | 0.5 |
| 12 | 0.175 | 2.5 | 0.3 |
| 12 | 0.2 | 3 | 0.35 |
| 12 | 0.225 | 1 | 0.4 |
| 12 | 0.25 | 1.5 | 0.45 |
| 14 | 0.15 | 2.5 | 0.35 |
| 14 | 0.175 | 3 | 0.4 |
| 14 | 0.2 | 1 | 0.45 |
| 14 | 0.225 | 1.5 | 0.5 |
| 14 | 0.25 | 2 | 0.3 |
| 16 | 0.15 | 3 | 0.45 |
| 16 | 0.175 | 1 | 0.5 |
| 16 | 0.2 | 1.5 | 0.3 |
| 16 | 0.225 | 2 | 0.35 |
| 16 | 0.25 | 2.5 | 0.4 |

Fly ash-based geopolymers' microstructure and strength growth are meaningfully affected by the curing situations. Geopolymers based on low-calcium fly ash take meaningfully lengthier to set and acquire less strength in the early ages than geopolymers cured by heat at high temperatures[21][22].

Finally, the specimens were tested at ages 7 and 28 days for each mixture's compressive strength.

Note: All results in figures 3, 4, 5 and 6 were obtained from interaction diagrams of the MINITAB software program.

## 3. Outcomes and Descussion

The four parameters of AA/B ratio, NaOH concentration, $Na_2SiO_3$ to NaOH, and binder content will be discussed. In addition, the slump value will be descussed, as well as, workability of fresh concrete.

### 3. 1. Fresh Concrete Workability

Workability experiments were performed on geopolymer and normal concrete mixtures. Depending on the sodium hydroxide to sodium silicate ratio, the geopolymer concrete had varying degrees of workability. The geopolymer concrete became more malleable as the sodium silicate and sodium hydroxide proportions were reduced. In fact, geopolymer concrete was discovered to have greater workability than conventional concrete when viewed from a particular angle. The round shape of FA particles and the influence of sodium hydroxide and sodium silicate ratio are likely to blame. Also, the development of strength in geopolymer concrete is influenced via the fly ash's fineness. The flow test revealed that a higher fineness increased workability [23]. These characteristics boosted the fresh geopolymers viscosity and stickiness, leading to better flowability than normal concrete. Slump values for various geopolymer and normal concrete combinations are depicted graphically in Fig. 1.

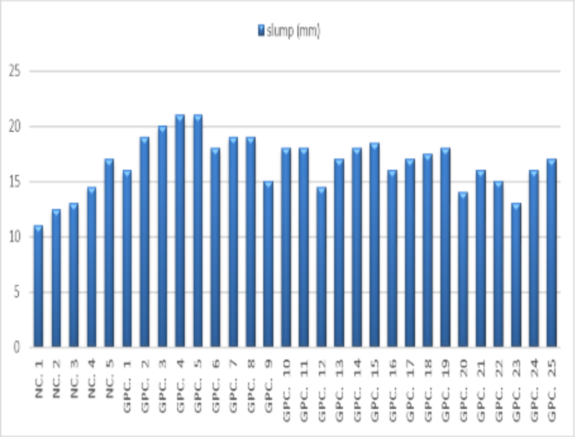


**Figure 1.** different mixes Slump value

### 3. 2. Effect of Alkali-Activator to Binder Ratio (AA/B)

The alkali/binder ratio effect has been examined in this research for the ratios 0.3, 0.35, 0.4, 0.45, and 0.5.

geopolymer concrete An exothermic reaction and hydrolysis occur as a result of the geopolymerization process, comparable to the cement hydration reaction [24]. The compressive strength of geopolymer concrete can be enhanced by increasing the percentage of alkali activator in the mixture. Where there is a minor improvement in compressive strength at the same age of curing when using a different alkali to binder ratio. The compressive strength improves further at a different age for the same AA/B ratio.

As shown in figure 2, the effect of heat curing on compressive strength is great at the early age of 7 days, while the development of compressive strength in heat curing is slow at the late age of 28 days, whereas the strength under heat curing was close to the ages of 7 and 28 days due to the heat curing that accelerated the reactions of concrete and made the strength improve early.

As demonstrated in figure 2, the compressive strength of GPC at an age of 7 days was in the range of (21-37) Mpa, whereas the compressive strength at an age of 28 days was in the range of (27-46) Mpa. The highest compressive strength has been reached when the AA/B ratio reaches 0.45, where the outcomes display that the compressive strength of the AA/B ratio of 0.45 is about 40 MPa, as presented in Fig. 3.

Despite the irregularity of the strengths, their development has been with an increasing AA/B ratio, dependent on the quality of the chemical reaction to the geopolymerization process. The quantity of reactive silica is the most important component in this process.

The increase in AA/B works to increase the available amount of $SiO_2$ obtained from dissolved silica in the binder and alkali solution, which leads to an increase in the $SiO_2/Al_2O$ ratio, which gives additional Si-O-Si links that are stronger than Si-O-Al links, and their attendance clarifies why the strength of geopolymer development increases with increasing AA/B.

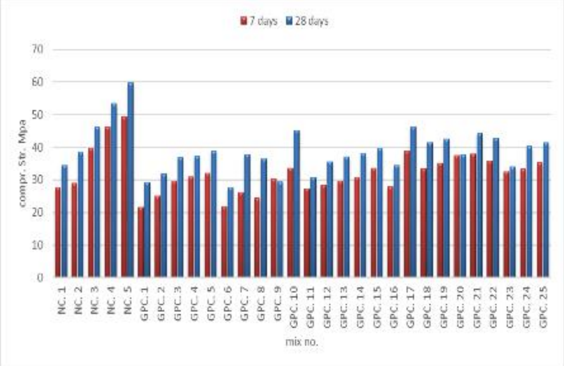


**Figure 2**. Strength development with age

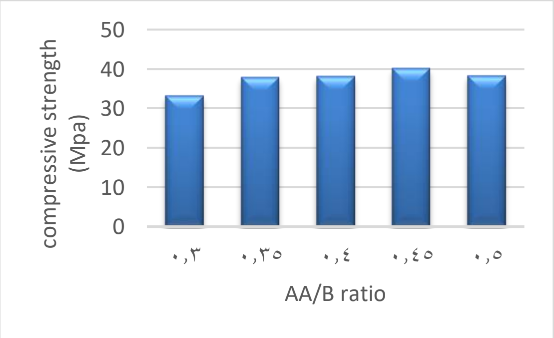


**Figure 3.** Explain the ratio of the AA/B effect on compressive strength

## 3. 3. Effect of NaOH Concentration (M)

The main factor affecting the results is the NaOH concentration. The geopolymer concrete's compressive strength is improved by raising the NaOH concentrations. As displayed in figure 4, the compressive strength improved as the concentration of NaOH increased in each combination comprising different weights of NaOH. Also The test outcome indicated that the compressive strength improved as the binder weight increased. As displayed in Table 5, the compressive strength of mixtures of 8 molarity increased from 31.845 Mpa to 38.855 Mpa at an age of 28 days, and for mixtures of 10 molarity, the compressive strength increased from 27.656 Mpa to 45.2 Mpa at an age of 28 days.

Strong alkalis are necessary for activating and rupturing the bonds of the principal oxides during the geopolymerization process, and increased NaOH concentration activates the Si and Al in Fa. The increase in NaOH concentration improves the development of the gel of alumino-silicate at an early stage and increases the breaking of the bond between molecules Si and Al in fly ash. Additionally, a crucial aspect of the geopolymerization process is the rise in Na ions in the matrix. This is because ions of Na were employed to equilibrium the matrix's charges and make a network of an alumino-silicate as the mixture's binder [25].

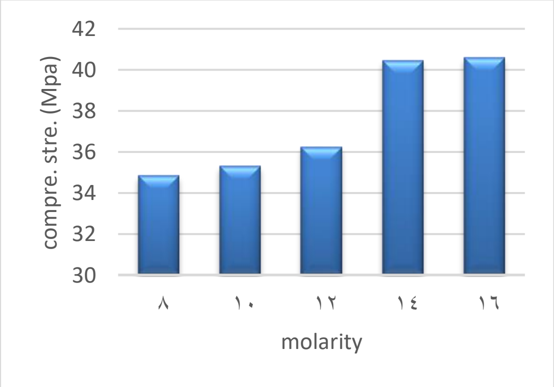


**Figure 4.** Illustrates the molarity influence on compressive strength

## 3. 4. Effect of $Na_2SiO_3$ to NaOH ratio (SS/SH)

When the SS/SH ratio was changed unevenly, the compressive strength of geopolymer concrete increased.

The $Na_2SiO_3$ to NaOH ratio effect on the geopolymer concrete mechanical properties was spotted when the $Na_2SiO_3$ to NaOH ratio was 1, and after that, the mechanical properties improved as the $Na_2SiO_3$ to NaOH ratio increased, as shown in Fig.

5. Hardjito et al. discovered that compressive strength grows with the content of FA and rises with alkali solution concentration. This is due to the increase in sodium oxide content, which is mostly required for the reaction of geopolymerization [26]. Due to the low level of $OH^-$ in the mixtures, which prevents $OH^-$ from reacting with carbon dioxide in the atmosphere and developing calcium carbonate, which causes cracks to form and weakens the matrix of geopolymer concrete, the mechanical characteristics of the geopolymer concrete were better for a $Na_2SiO_3$ to NaOH ratio of 1.

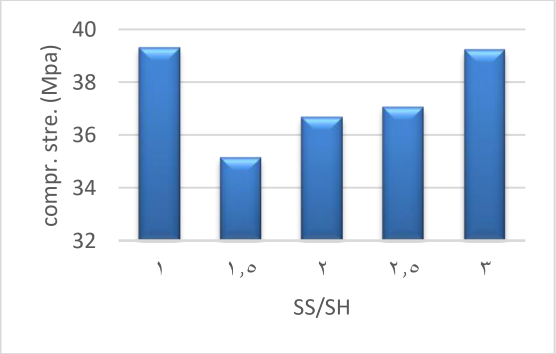


**Figure 5.** The ratio of silicate sodium to sodium hydroxide Influence on compressive strength

## 3. 5. Effect of Binder Content (B)

The mechanical characteristics of geopolymer concrete are influenced by the content of fly ash in the matrix of geopolymer; where the binder content increases, it will reduce the porosity of geopolymer concrete, which leads to an increase in the volume of geopolymer paste, resulting in the formation of the geopolymerization process. Additionally, adding more fly ash to the mix will result in additional Si and Al, which accelerate the reactions with alkaline activators and progress the geopolymer concrete's mechanical characteristics.

As seen in Fig. 6, the best compressive strength of geopolymer concrete was found at a 25% binder level. Furthermore, the procedure of polymerization includes a comparatively fast chemical reaction on Si and Al minerals under alkaline circumstances, resulting in a three-dimensional polymeric series and circle structure molded of Si-O-Al-O links [27].

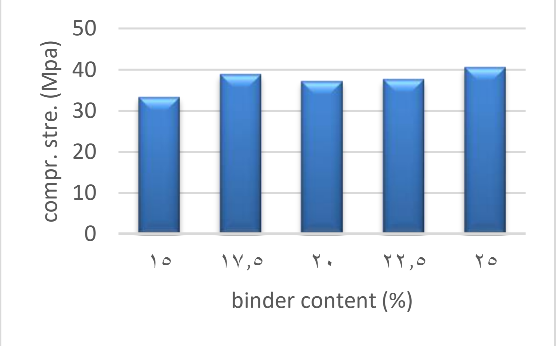
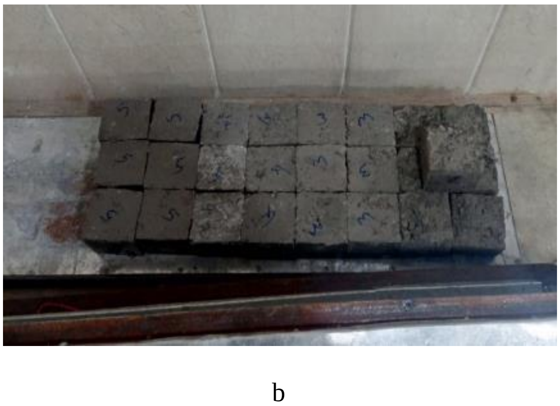


**Figure 6.** Binder content influence on compressive strength

Figure 7 displays a group of normal and geopolymer concrete that had been cast in the field.

a



b

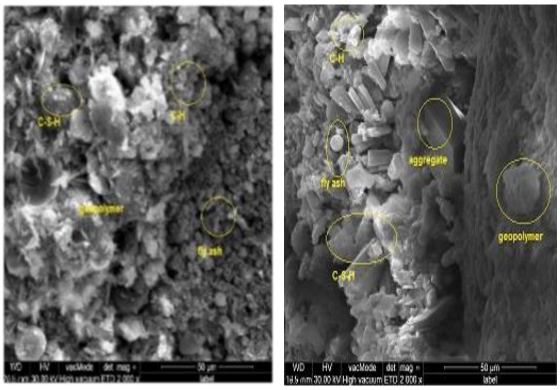
**Figure 7.** Illustrates a) normal and b) geopolymer specimens

## 4. Scanning Electron Microscopy (SEM).

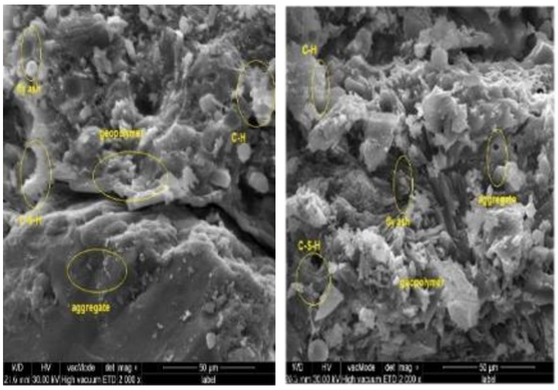
It is obvious from Figure 8. The quantity of the binder has a clear influence on the geopolymer concrete's performance, as the higher the amount of the binder, the higher the compressive strength, as the C-S-H crystals increased with the increase in the binder amount. Together, the molarities have the highest influence on the formations of geopolymer concrete gel paste, where the higher the NAOH concentration, the greater the geopolymer concrete compressive strength.

As can be seen from the observed outcomes of Sem images in Figure 8, it’s clear that the binder content plays a main role in the geopolymer concrete's compressive strength. Whereas, sample no. 25 has a higher content of binder than sample no. 11, which has the lowest binder content. The microstructural characteristics of fly ash atoms and calcium content have a major influence on the compressive strength and setting time of geopolymer concrete, and the resulting geopolymer generally has a glasslike structure [28].

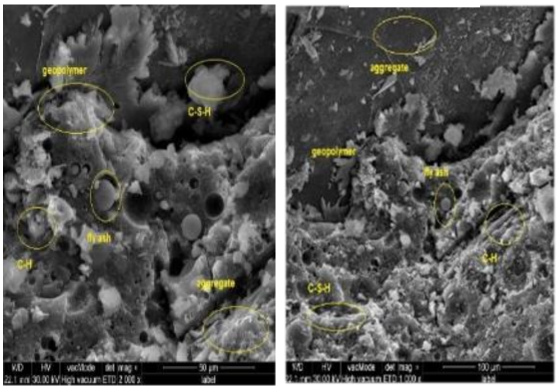
Moreover, the crystals of C-S-H are present in mixture no. 25 more than in other mixtures, and for this reason, mixture no. 25 has the highest compressive strength of all the mixtures. As illustrated in figure 8, the combination no. 25 seems to have a denser internal microstructure than the other samples due to the creation of the C-S-H gel phase, which prevents the production of gypsum crystals and calcium hydroxide. This job is shared by all samples.



GPC 3 GPC 8



GPC 11 GPC 19



GPC 25

**Figure 8.** Sem images display the microstructure of geopolymer concrete for different molarities

## Conclusion

Based on the gained information, the next conclusions can be summarized below.

1. The geopolymer concrete's compressive strength increases as the concentration of sodium hydroxide solution increases.
2. The workability of geopolymer concrete is more than of normal concrete due to the surface area of fly ash is more than of ordinary portland cement leading to consume more liquid.

3. The low-calcium fly ash geopolymer concrete compressive strength treated at 65 C increases as the curing age increases, up toward 28 days, this applies to the normal concrete.
4. The GPC outcomes obtain of compressive strength at an age of 7 days in the range of (21–37) Mpa, whereas the compressive strength at an age 28 days in the range of (27–46) Mpa, which indicates convergence to the compressive strength of normal concrete.
5. The NC results obtain compressive strength at an age of 7 days in the range of (27–49) Mpa, whereas the compressive strength at an age of 28 days is in the range of (34–59) Mpa.
6. The ratio of SS/SH is highly affected the geopolymer concrete compressive strength treated at 65 ◦C. The highest strength is reached using SS/SH = 1.0, as the compressive strength is 41.8 Mpa when studying the factor separately.
7. The optimal parameter ratio that gives the best compressive strength of GPC is AA/B =0.45, as the compressive strength is 40 MPa when studying the factor separately.
8. The optimal parameter ratio that gives the best compressive strength of the GPC of NaOH concentration (M) is 16, as the compressive strength is 41.9 Mpa when studying the factor separately.
9. The optimal parameter ratio that gives the best compressive strength of the GPC of binder content is 25%, as the compressive strength is 41.3 MPa when studying the factor separately.
10. The geopolymer concrete microstructure appears the increases of binder content has a big influence on geopolymer concrete mechanical properties and this role applies to the other molarities of geopolymer concrete.

## References

[1] M. J. Almufarji, F. Hejazi, and A. A. Al-Attar, “Compressive strength of class F fly ash blended geopolymer- hybrid mortar,” IOP Conf. Ser. Earth Environ. Sci., vol. 357, no. 1, 2019, doi: 10.1088/1755-1315/357/1/012019.

[2] E. A. Obonyo, E. Kamseu, P. N. Lemougna, A. B. Tchamba, U. C. Melo, and C. Leonelli, “A sustainable approach for the geopolymerization of natural iron-rich aluminosilicate materials,” Sustainability, vol. 6, no. 9, pp. 5535–5553, 2014.

[3] J. M. Abed and H. S. Abed, “Effect of Partial Replacement of Fly Ash and Expanded Polystyrene waste on Properties of Geopolymer Concrete Bricks,” J. Adv. Res. Appl. Sci. Eng. Technol., vol. 17, no. 1, pp. 85–102, 2019.

[4] D. Hardjito, S. E. Wallah, D. M. J. Sumajouw, and B. V. Rangan, “Factors influencing the compressive strength of fly ash-based geopolymer concrete,” Civ. Eng. Dimens., vol. 6, no. 2, pp. 88–93, 2004.

[5] V. M. Malhotra, “Introduction: sustainable development and concrete technology,” Concr. Int., vol. 24, no. 7, 2002.

[6] M. T. Junaid, O. Kayali, A. Khennane, and J. Black, “A mix design procedure for low calcium alkali activated fly ash-based concretes,” Constr. Build. Mater., vol. 79, pp. 301–310, 2015.

[7] H. M. Albegmprli, Z. K. A. Al-Qazzaz, and S. K. Rejeb, “Strength performance of alkali activated structural lightweight geopolymer concrete exposed to acid,” Ceram. Int., vol. 48, no. 5, pp. 6867–6873, 2022, doi: 10.1016/j.ceramint.2021.11.240.

[8] C. Y. Heah et al., “Study on solids-to-liquid and alkaline activator ratios on kaolin-based geopolymers,” Constr. Build. Mater., vol. 35, pp. 912–922, 2012.

[9] N. F. Shahedan et al., “Thermal Insulation Properties of Insulated Concrete,” Rev. Chim, vol. 70, pp. 3027–3031, 2019.

[10] S. Wallah and B. V. Rangan, “Low-calcium fly ash-based geopolymer concrete: long-term properties,” 2006.

[11] U. Rattanasak and P. Chindaprasirt, “Influence of NaOH solution on the synthesis of fly ash geopolymer,” Miner. Eng., vol. 22, no. 12, pp. 1073–1078, 2009.

[12] J. Davidovits, “Geopolymer cement,” A Rev. Geopolymer Institute, Tech. Pap., vol. 21, pp. 1–11, 2013.

[13] J. Davidovits, “Properties of geopolymer cements,” in First international conference on alkaline cements and concretes, 1994, vol. 1, pp. 131–149.

[14] M. Olivia and H. Nikraz, “Properties of fly ash geopolymer concrete designed by Taguchi method,” Mater. Des., vol. 36, pp. 191–198, 2012, doi: 10.1016/j.matdes.2011.10.036.

[15] A. Mehta, R. Siddique, B. P. Singh, S. Aggoun, G. Łagód, and D. Barnat-Hunek, “Influence of various parameters on strength and absorption properties of fly ash based geopolymer concrete designed by Taguchi method,” Constr. Build. Mater., vol. 150, pp. 817–824, 2017, doi: 10.1016/j.conbuildmat.2017.06.066.

[16] D. Hardjito and B. V. Rangan, “Development and properties of low-calcium fly ash-based geopolymer concrete,” 2005.

[17] A. Fernández-Jiménez, A. Palomo, I. Sobrados, and J. Sanz, “The role played by the reactive alumina content in the alkaline activation of fly ashes,” Microporous Mesoporous Mater., vol. 91, no. 1–3, pp. 111–119, 2006.

[18] A. Designation, “C494 Standard Specification for Chemical Admixtures for Concrete,” Annu. B. ASTM Stand. Am. Soc. Test. Mater., 2008.

[19] T. Bakharev, J. G. Sanjayan, and Y.-B. Cheng, “Resistance of alkali-activated slag concrete to acid attack,” Cem. Concr. Res., vol. 33, no. 10, pp. 1607–1611, 2003.

[20] P. K. Sarker, R. Haque, and K. V Ramgolam, “Fracture behaviour of heat cured fly ash based geopolymer concrete,” Mater. Des., vol. 44, pp. 580–586, 2013.

[21]P. Nath and P. K. Sarker, “Effect of GGBFS on setting, workability and early strength properties of fly ash geopolymer concrete cured in ambient

condition," Constr. Build. Mater., vol. 66, pp. 163–171, 2014, doi: https://doi.org/10.1016/j.conbuildmat.2014.05.080.

[22] K. Vijai, R. K. Rathinam, and B. G. Vishnuram, "Effect of types of curing on strength of geopolymer concrete," Int. J. Phys. Sci., vol. 5, pp. 1419–1423, Sep. 2010.

[23] S. S. Jamkar, Y. M. Ghugal, and S. V. Patankar, "Effect of fly ash fineness on workability and compressive strength of geopolymer concrete," Indian Concr. J., vol. 87, no. 4, pp. 57–62, 2013.

[24] J. Wongpa, K. Kiattikomol, C. Jaturapitakkul, and P. Chindaprasirt, "Compressive strength, modulus of elasticity, and water permeability of inorganic polymer concrete," Mater. Des., vol. 31, no. 10, pp. 4748–4754, 2010.

[25] A. Sathonsaowaphak, P. Chindaprasirt, and K. Pimraksa, "Workability and strength of lignite bottom ash geopolymer mortar," J. Hazard. Mater., vol. 168, no. 1, pp. 44–50, 2009.

[26] D. Hardjito, S. E. Wallah, D. M. J. Sumajouw, and B. V. Rangan, "On the development of fly ash-based geopolymer concrete," ACI Mater. J., vol. 101, no. 6, pp. 467–472, 2004, doi: 10.14359/13485.

[27] J. Davidovits, "High-alkali cements for 21st century concretes," Spec. Publ., vol. 144, pp. 383–398, 1994.

[28] G. Nagalia, Y. Park, A. Abolmaali, and P. Aswath, "Compressive Strength and Microstructural Properties of Fly Ash–Based Geopolymer Concrete," J. Mater. Civ. Eng., vol. 28, no. 12, pp. 1–11, 2016, doi: 10.1061/(asce)mt.1943-5533.0001656.