Geopolymer Concrete, Mortar, and Paste: A Review

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Abstract: The problems of global warming and environmental pollution with gaseous and solid wastes, made researchers think of finding effective alternatives to reduce the proportion of carbon dioxide in the atmosphere and make use of solid waste for iron manufacturing stations and power production stations. Thus, geopolymers are considered one of the most promising solutions in the field of structural engineering. Therefore, this paper presents a review of previous studies on geopolymer mixtures, which were investigated in three main parameters, included: slag addition, solution ratios, adding fibers, and Nano silica. The results of the previous investigation showed that the compressive strength increased with the increase in the slag ratio. At certain proportions, the compressive strength increases with increasing the sodium silicate to sodium hydroxide and increasing the sodium hydroxide concentration (M). While it was reduced fresh properties such as flow-ability and setting time. It was also found that the addition of fibers or Nano silica improved the microstructures of geopolymers, and thus a significant improvement in tensile strength and compressive strength. Finally, the addition of external water was found to improve flow-ability but reduce compressive strength, while the addition of the superplasticizer in certain proportions improves fresh properties.

Keywords: Geopolymer, slag, alkaline solution, fibers, and Nano silica.

1. Introduction

To reduce the proportion of greenhouse gases in the atmosphere, the researchers resorted to using alternative materials of Portland cement, and at the same time the recycling of solid waste or by-product materials produced from iron manufacturing plants or power plants, such as the geopolymer materials that have entered the field of engineering research's and was highlighted. Pozzolanic materials that rich in silicates and aluminates are considered sustainable and good alternatives to produce materials with properties similar to or better than the properties of ordinary Portland cement (OPC) such as fly ash, slag, rice husk ash, and metakaolin. Geopolymer is natural, inorganic materials, inert materials until they are activated by alkaline solutions through a process called polymerization, which results in substances material with good mechanical properties that depend mainly on the chemical composition (silicate and aluminate ratio) [1-5]. It is worth noting that, the researcher Davidovits (1978) was the first to release the designation of "Geopolymer" that published in (2008) a book entitled "Geopolymer Chemistry and Applications". In which, he discussed the chemical composition of the geopolymer, and mentioned that the geopolymer material is like cement in chemical composition, and it depends on the reaction of aluminosilicate within the alkaline activator. He named the chain of the material with different Si/Al ratios. Where, Si/Al is an effective factor in the properties of the geopolymer matrix, especially the
amount and concentration of alkaline materials that will react with aluminosilicate to produce a gel. In the case of using geopolymer, high temperature in the early curing stage is essential to provide enough strength increases to access high mechanical properties. However, there are several practical issues with the application of heat curing in structures; so we go towards several ways to accelerate the polymerization process for cured at ambient condition. Ground granulated blast furnace slag or Nano silica is one of the common pozzolanic materials for gaining wider attention due to its significant effect on the microstructural and mechanical properties of geopolymer based binders. There are several studies in the past touched on the geopolymer compounds as (paste, mortar, and concrete), it was addressed to study the effect of several factors, so this paper provides a review of a study on the geopolymer mixes were studied to investigate the following parameters: slag ratio, solutions ratio, fibers addition, and Nano silica.

2. The effect of slag addition on the mechanical properties of geopolymer

In (2014) Deb, et al. [6], studied the effect of slag-replacement ratios with fly ash in geopolymer concrete by (0%, 10%, and 20%), cured at ambient conditions (20±2°C), on workability, compressive strength, and tensile strength. The results indicated that the workability of the geopolymer concrete was decreased with increasing the proportion of slag-replacement. As for the compressive strength, it increased with an increased ratio of slag. Also, the compressive strength development was higher rates in early ages and less than at later ages above 28 days for all the geopolymer concrete mixtures.

In (2017) Saha, et al. [7], studied the effect of fly ash (FA) replacement ratio by slag in geopolymer paste that cured under ambient conditions. On promote the mechanical properties as the setting time and compressive strength. The replacement ratio of slag was (10%, 20%, 30%, 40%, and 50%). Where three standard molds were cast in 50 mm cubes dimensions for each parameter studied then examined at ages 7, 28, and 56 days. The test results were shown that the initial and final setting time exhibited a significant decrease with the increasing slag replacement ratio in mixtures. The tensile strength is affected by the addition of slag because the addition of slag leads to an improvement in the microstructure of the geopolymer mixtures and making them denser through the formation of C-S-H gel in addition to the formation of N-A-S-H gel in the early stages of the mixtures, which causes an improvement in mechanical properties such as compressive, tensile and flexural strength. Also, the compressive strength was increasing via increasing the ground granulated blast furnace slag ratio in geopolymer paste. So, the mixture of geopolymer paste that content 50% slag exhibited higher compressive strength compared with the other mixtures, as shown in Figure 1.

![Figure 1: The compressive strength of geopolymer paste with different ratios of slag [7]](image-url)
In (2018) El-Hassan, and Ismail, [8] studied the effect of geopolymer mortar that consist of different ratio of fly ash and slag (F.A: GGBFS), (i.e. 50:50, 75:25, and 100:0) on fresh and hard mechanical properties such as flow-ability, setting time, and compressive strength, respectively. Three cubes of the same configuration with dimensions of (50×50×50mm cubic) were prepared and tested at (1, 7, and 28) days. The test results provided that the flow-ability and setting time decreased with an increase in the amount of slag (GGBFS more than 50%) in the mixes, so the mechanical performance decreased. Although further replacement of GGBS to 100% led to a drier mixture, such geopolymer could be more suitable for in situ construction applications if its rheological and mechanical properties could be enhanced. The results also demonstrated an increase in compressive strength was the highest for geopolymer with 100% GGBS because the addition of slag leads to an improvement in the microstructure of the geopolymer mixtures and making them denser through the formation of C-S-H gel in addition to the formation of N-A-S-H gel in the early stages of the mixtures. Figure 2 illustrates the compressive strength, flow-ability, and setting time.

![Figure 2: Mechanical and fresh properties of geopolymer mortar, (a) flow-ability and setting time, (b) compressive strength. [8]](image)

In (2019) Hadi, et al. [9] studied the optimum ratio of geopolymer paste and geopolymer concrete by examined its mechanical properties such as compressive strength, setting time, and workability. The main variables included the slag content (0% to 40% by increment 10%). Whereas, total mixtures for the geopolymer paste was 28 and 3 mixtures for the ordinary Portland cement OPC. The dimensions of the cylinder mold to obtain the compressive strength were (50 mm diameter × 100 mm height) that examined at 7 and 28 days. After determining the optimal ratio, it was applied to the geopolymer concrete to ensure the specifications that apply to the geopolymer pastes have the same effect on the geopolymer concrete then compared it with the conventional concrete. The results show that the compressive strength of geopolymer paste was increase with the increased slag content in the mixture. The workability and setting time of geopolymer paste were shown significant decreasing with the increasing slag content, shown in Figure 3. So, the optimum mix design of geopolymer paste was the mix with slag ratio, SS/SH, Al/Bi, and Aw/Bi, represent (40%, 2, 0.5, and 0.15) respectively. Also, the geopolymer concrete was a similar specification of geopolymer paste when applying the optimal mix designed, as well as, the geopolymer
paste and concrete were exhibited higher mechanical properties compared with the conventional concrete.

![Graph of GGBFS content vs. compressive strength](image1)

![Graph of GGBFS content vs. setting time](image2)

**Figure 3:** Effect of GGBFS on the compressive strength and setting time [9]

In (2020) Sachet, et al. [10] studied the effect of replacing fly ash with slag in geopolymer paste on the development of compressive strength. The rates of replacing fly ash with slag include from (0% to 100% with a gradual increase of 10%). The samples with dimensions of 50 mm-cubes were cured at ambient conditions and examined at 7 and 28 days. Based on the test results, it was found that the addition of ground granulated blast furnace slag (GGBFS) to geopolymer paste based fly ash caused an increase significantly in compressive strength when cured at ambient condition, and the optimum mix was found to have GGBFS content of 100%, can be improved the compressive strength as high as (74% and 62%) at 7 and 28 days respectively. Figure 4 shows the compressive strength of geopolymer paste with different slag ratio.

![Graph of compressive strength vs. GGBFS content](image3)

**Figure 4:** Compressive strength of geopolymer paste with different slag ratio [10]

3. The effect of solution ratios on the mechanical properties of geopolymers

In (2009) Rattanasak and Chindaprasirt, [11] organized a study about the effect of sodium hydroxide (NaOH) concentration on the formation of aluminosilicate for geopolymer paste and mortar. Three different concentrations of NaOH were used in this study (5, 10, and 15 M). The mixes were cured at 65°
C for 48 h. The results showed that the optimum concentration of NaOH (with Na$_2$SiO$_3$/NaOH = 1.0) was 10M, which gave compressive strength (70 MPa).

In (2014) Deb, et al. [6] studied the effect of the ratios of the alkaline solution to binder (F/b) ratio was (0.40 and 0.35), and the ratio of sodium silicate to sodium hydroxide (SS/SH) ratio was (2.5 and 1.5), on the mechanical properties of geopolymer concrete based on a blend of slag and fly ash as a binder, cured at ambient condition. Three identical specimens were tested for each age (7, 28, 56, 90, and 180) days. The results indicated that workability of the geopolymer concrete was decreased with increasing the ratio of sodium silicate to sodium hydroxide (SS/SH) from (2.5 to 1.5), also, increased it at the ratio of alkaline solution 0.35 compared to alkaline solution ratio 0.40 due to the addition of extra water. As for the compressive strength, it increased with an increased ratio of sodium silicate to sodium hydroxide (SS/SH) and alkaline solution ratios (F/b) from (2.5 to 1.5) and (0.40 to 0.35), respectively. As shown in Figure 5.

![Figure 5](image)

Figure 5: Compressive strength of geopolymer concrete based on a different blend of slag and fly ash, a-SS/SH ratio =1.5.  b- SS/SH ratio =2.5, [6]

In (2017) Saha, et al. [7] studied the effect of concentration of sodium silicate (M) in geopolymer paste based on slag and fly ash as a binder, which cured under ambient conditions. To promote the compressive strength. Which, that the activator solution to the binder, and sodium silicate to sodium hydroxide (SS/SH) have been studied with a constant ratio, respectively. The ratio of the concentration of sodium silicate (M) was (8, 10, 12, 14, and 16). Where three standard molds were cast in 50 mm cubes dimensions for each parameter studied then examined at ages 7, 28, and 56 days. The test results were shown that, the mixture of geopolymer paste that content 50:50 of slag: fly ash with 16 sodium hydroxide concentrations (M) exhibited higher compressive strength estimated by 2.3 times compared with the fly ash mixtures.

In (2018) Değirmenci, [12] studied the effect of mix design on the engineering properties for geopolymer mortar. The Natural Zeolite (NZ), Fly Ash (FA), and Ground Granulated Blast Furnace Slag (GGBS) were a binder and sodium silicate with sodium hydroxide was an activator solution. Three different molarity of sodium hydroxide (8, 10, and 12) M were used, and the ratio of sodium silicate/sodium hydroxide was different also (1, 2, and 3). The specimens were cured at ambient temperature (30° C). The compressive strength was determined at (2, 7, 14, 21, and 28) days by testing three specimens from each mixture. The results showed that compressive strength was increased with the increase in GGBS content and the concentration of alkaline solution until (12 M) that produced the maximum compressive strength, and the compressive strength increases with an increase in the ratio of sodium silicate-to-sodium hydroxide, where the maximum compressive strength was obtained at a ratio equal to 3.
In (2018) El-Hassan, and Ismail, [8] studied the effect of geopolymer mortar that consist of different ratio of fly ash and slag (F.A: GGBFS), on flow-ability, setting time, and compressive strength. The variables included: superplasticizer (Sp. %) content in the geopolymer mortar mixture (1, 1.5, 2, and 2.5) % by binder mass, sodium silicate/sodium hydroxide (SS/SH) ratio (1.5, 1.75, 2, 2.25, and 2.5), activator solution to binder ratio (0.40, 0.45, and 0.50). Totally forty specimens were examined, three cubes of the same configuration with dimensions of (50×50×50) mm cubic were prepared and tested at (1, 7, and 28) days. The test results provided that the mixes consisting of a combination of fly ash and slag exhibited an increase in compressive strength decrease in flow-ability and setting time, with increased the ratio of sodium silicate to sodium hydroxide. As well as, "An increase in the alkali-activator solution content produced a more workable concrete that required longer durations to set. The compressive strength was the highest for geopolymer with 0.50 of activator solution content", by binder mass. On the other hand, the mechanical performance of the full slag (100% GGBFS) mixes improved by adding a superplasticizer and the optimum ratio of the addition was 2%. Figure 6, shows the mechanical and fresh properties of geopolymer mortar with different F/b ratio and SS/SH ratio.

![Image](image_url)

Figure 6: Mechanical and fresh properties of geopolymer mortar with different F/b and SS/SH ratio.

[8] Where: F/b; fluid to binder ratio, SS/SH; sodium silicate to sodium hydroxide

In (2019) Hadi, et al. [13] studied the optimum mixture design of geopolymer paste by examined its mechanical properties such as compressive strength, setting time, and workability. The main parameters included the fluid to binder (F/b) ratio (0.4, 0.5, 0.6, and 0.7), sodium silicate to sodium hydroxide (SS/SH) ratio (1, 1.5, 2, and 2.5), and the extra water to binder (Aw/b) ratio (0.09, 0.12, and 0.15). Whereas, total mixtures for the geopolymer paste were 28 with dimensions of 50mm diameter × 100mm height, which were examined at 7 and 28 days. On the other hand, to obtain the workability of
geopolymer paste was utilizing a mini size-slump test. The results show that the compressive strength of geopolymer paste was decreasing with increasing the fluid to binder ratio or extra water ratio. Also, the higher compressive strength was an exhibit with an SS/SH ratio of 2. The workability and setting time of geopolymer paste were shown significantly decreasing with the increasing SS/SH ratio, and increasing them with the increased fluid to binder ratio or extra water ratio. So, the optimum mix design of geopolymer paste was the mix with SS/SH, F/b, and Aw/b, represent to (2, 0.5, and 0.15) respectively. Figure 7 shows the effect of F/b and SS/SH ratio on the compressive strength of geopolymer paste.

![Figure 7: Effect of F/b and SS/SH ratio on compressive strength of geopolymer paste [13]](image)

4. The effect of adding fibers and Nano silica to geopolymer compounds

In (2014) Phoo-ngernkham, et al. [14] presents a study about the effect of Nano-material on the properties of geopolymer paste. They were used fly ash class C with add (0, 1, 2, and 3) % dosages of nano-SiO₂ in one series and nano-\(\text{Al}_2\text{O}_3\) in another series. The concentration of sodium hydroxide was 10 molar, sodium silicate to sodium hydroxide ratio was equal to 2.0, and the alkaline solution to binder ratio was 0.6. The specimens were cured at room temperature (23°C). After finishing the curing time, many tests were conducted and documented the properties of mixtures, such as X-Ray Diffraction (XRD), Scanning Electron Microscopy (SEM), setting time, compressive strength, flexural strength, and shear bond strength. The results of the SEM and XRD showed that the proportions (2%) of nano-SiO₂ and (1%) nano-\(\text{Al}_2\text{O}_3\) gave denser matrix of geopolymer pastes, but in the proportion (3%) there were un-reactant nano-particles in geopolymer matrix. Also, the adding of Nano-particles to the geopolymer paste made to decrease in setting time due to the formation of CSH which accelerated the setting and hardening. The compressive strength, elastic modulus, and flexural strength increase with add (2%) of nano-SiO₂ or (1%) of nano-\(\text{Al}_2\text{O}_3\). As the shear bond strength between the concrete substrate and geopolymer was improve with (2% nano-SiO₂ and nano-\(\text{Al}_2\text{O}_3\)). These improvements in all properties go back to the formation of additional CSH or CASH and NASH gels in the geopolymer matrix.

In (2014) Eswaramoorthi, and Arunkumar, [15] studied the effect of adding polypropylene fibers 1% by weight, on mechanical properties such as compressive strength, tensile strength, and load-deflection of the geopolymer concrete based on low-calcium fly ash cured at water tanks. Where, was compared with class F-fly ash based geopolymer concrete without fibers and the conventional concrete. The dimensions of the specimens included 150 mm cubes to test the compressive strength, while the dimensions of the cylinder include (150 mm diameter × 300 mm length) to test the tensile strength. As well as, the dimensions of the beam (150 mm × 230 mm × 1000 mm) to test the load deflections. Three specimens for each variable were cast and tested at the age of 28 days. The results indicated that the geopolymer concrete gave higher mechanical properties than conventional concrete. Also, the addition of polypropylene fibers resulted in a significant increase in the mechanical properties of the geopolymer concrete compared with the conventional concrete. Figure 8, was shown the compressive and tensile strength of geopolymer concrete with fibers.
In (2016) Al-Majidi, et al. [16] studied the effect of addition steel fiber to geopolymer mortar composite on mechanical properties (compressive and tensile strength). Also, the microstructural of geopolymer composite was analyzed by utilizing the scanning electron microscopy (SEM). Six mixtures of geopolymer mortar were prepared with (50% fly ash, 40% slag, and 10% silica fume) as a binder, and different steel fiber ratio, also, four cubes with dimension (100×100×100 mm) were casting, cured at ambient condition, and tested at 28 days. The main parameters included; aspect ratio (L/D) and volume fraction of steel fiber addition (i.e. 37.5 or 81.25), and (0%, 2%, or 3%) respectively. The results were obtained that, the compressive and tensile strength was increased with the increased aspect ratio (L/D) and volume fraction of steel fiber. On the other hand, the (SEM) test was illustrating good bonds between steel fiber surface and geopolymer mortar matrix which causes an evolution of the mechanical properties. Figure 9, shows the compressive strength and microstructure of geopolymer composite.

In (2019) Salman, at el. [17] studied the effect of steel fiber on the mechanical and elastic properties of the fly ash based-geopolymer mortar, then used in the casting of Ferro-geopolymer slab panel. The main variables included the volumetric ratio of steel fiber (0% to 3%, by increment 0.25%). The results indicated a significant development in the behavior of the Ferro-geopolymer mortar slab panel, which led to superior mechanical properties, especially compressive and tensile strength. Where, was found that the addition of steel fibers at a rate of 2.25% gave the best development in mechanical properties, as shown in Figure 10.
Figure 10: Mechanical properties of Ferro-geopolymer mortar [17] a- Compressive strength b- Tensile strength

In (2019) Hadi, et al. [9] presented a study on the effect of the addition of micro steel fiber and Nano silica on the compressive strength of geopolymer based on fly ash, cured under room temperature. Variables included the replacement ratio of Nano silica with the binder of (0 to 1.4%, increment 0.2%), and the addition ratio of micro steel fibers (0% to 2%, increment 0.5%). Samples were prepared with standard dimensions of (50mm-cubes) and tested at ages (7 and 28) days. The results indicate that the best replacement rate of Nano silica, and addition rate of micro steel fiber that gave the highest development of compressive strength, which is estimated by 77%, was (0.8% and 1%) respectively.

In (2020) Hadi, et al. [18] studied the effect of adding different type’s fiber to the geopolymer paste based on fly-Ash class-F, on the mechanical properties, then used as a sustainable alternative to the epoxy adhesive with near-surface mounted technology. The main variables included the type and ratio of added fiber, (0.5%, 1%, 1.5%, or 2%) of micro steel fiber, and (0.2%, 0.4%, or 0.6%) of each carbon fiber and polypropylene fiber. The dimensions of the samples used were as follows (50 × 50 × 50) mm-cubes, cylinders (50mm diameter ×100mm length), and prisms with grooves (40 ×40 ×160mm). Totally eleven mixes were prepared and examined at the age of (7 and 28) days. The results indicated that the addition of fibers to the geopolymer paste resulted in a significant improvement in mechanical properties, especially compressive and bonding strength. Thus, exceeded the epoxy adhesive bonding by (4% and 11%) when used micro steel fiber and carbon fiber. While the polypropylene fiber formed about 93% of epoxy adhesive bonding usage in near-surface mounted technique.

5. Conclusion

From the previous brief review of some research, which covered the main three axes, included that the effect of slag addition, and the effect of solution ratios, also, the effect of adding fibers and Nano silica to geopolymer compounds on the mechanical properties of geopolymers, we can conclude with the following observations:

1. The addition of slag to geopolymer mixtures (paste, mortar, and concrete) significantly improved mechanical properties by 2 times such as compressive and tensile strength, while reducing fresh properties such as flow-ability and setting time by 85 to 92 %.

2. At certain proportions, found that increasing the concentration of sodium hydroxide solution and increasing the ratio of sodium silicate/sodium hydroxide, lead to the development of compressive strength of geopolymer mixtures. While increasing the ratio of fluid to the binder and adding external water, improves flow-ability, but reduces compressive strength. It is worth noting that the use of the superplasticizer improves fresh properties such as flow-ability and setting time.

3. The addition of different fibers such as steel fiber, carbon fiber, and polypropylene fiber, at certain proportions, was improved the microstructure of geopolymer mixtures. This leads to the
development of mechanical properties, especially tensile strength and thus compressive strength with a percentage estimated by 15-23%.

4. Finally, the addition of Nano silica at certain proportions accelerated the polymerization process by 78% and improved the mechanical properties of geopolymer mixtures by 2.2 times.

Reference

[1] Al-Majidi, M.H., Lampropoulos, A. and Cundy, A., 2016, January. Mechanical properties of steel fibre reinforced geopolymer composites cured under ambient temperature. In Fib symposium 2016 Performance-based approaches for concrete structures. (pp. 0-0).

[2] Davidovits, J., 2008. Geopolymer Chemistry and Applications. 2nd. Institute Geopolymere, France.

[3] Deb, P.S., Nath, P. and Sarker, P.K., 2014. The effects of ground granulated blast-furnace slag blending with fly ash and activator content on the workability and strength properties of geopolymer concrete cured at ambient temperature. Materials & Design (1980-2015), 62, pp.32-39.

[4] Değirmenci, F.N., 2018. Utilization of natural and waste pozzolans as an alternative resource of geopolymer mortar. International Journal of Civil Engineering, 16(2), pp.179-188.

[5] Eswardamoorthi, P. and Arunkumar, G.E., 2014. Fibers Study On Properties Of Geopolymerconcrete With Polypropylene. International Refereed Journal of Engineering and Science, 3(2), pp.60-75.

[6] Hadi, M.N., Zhang, H. and Parkinson, S., 2019. Optimum mix design of geopolymer pastes and concretes cured in ambient condition based on compressive strength, setting time and workability. Journal of Building Engineering, 23, pp.301-313.

[7] Hadi, N.S., Oleiwi, S.M., Salman, W.D., Ibrahim, A.M. and Mansor, A.A., 2020, July. Modified geopolymer paste adhesive bond material for near surface mounted strengthening technique. In IOP Conference Series: Materials Science and Engineering (Vol. 888, No. 1, p. 012053). IOP Publishing.

[8] Hadi, N.S., Salman, W.D. and Oleiwi, S.M., 2020, March. Production of geopolymer adhesive paste material for NSM technique. In AIP Conference Proceedings (Vol. 2213, No. 1, p. 020150). AIP Publishing LLC.

[9] Hadi, N.S., Salman, W.D. and Oleiwi, S.S.M., 2019, August. Effect of Nano-Silica and Micro Steel Fiber on Compressive Strength Development of Fly Ash Geopolymer Paste Cured Under Ambient Temperature. In IOP Conference Series: Materials Science and Engineering (Vol. 584, No. 1, p. 012010). IOP Publishing.

[10] Ibrahim, A.M., Oukaili, N.K.A. and Salman, W.D., 2013. Flexural behavior and sustainable analysis of polymer bubbled reinforced concrete slabs. In Fourth Asia Pacific Conference on FRP in Structures (APFIS 2013)(Melbourne, Australia, 11-13 December).

[11] Phoo-ngernkham, T., Sata, V., Hanjitsuwan, S., Ridhirud, C., Hatanaka, S. and Chindaprasirt, P., 2016. Compressive strength, bending and fracture characteristics of high calcium fly ash geopolymer mortar containing portland cement cured at ambient temperature. Arabian Journal for Science and Engineering, 41(4), pp.1263-1271.

[12] Rattanasak, U. and Chindaprasirt, P., 2009. Influence of NaOH solution on the synthesis of fly ash geopolymer. Minerals Engineering, 22(12), pp.1073-1078.

[13] Sachet, W.H., 2020. Experimental Investigation on Compressive Strength Enhancement of Geopolymer Paste Fly Ash/Slag Based Cured at Ambient Condition. DJES, 13(2), pp.87-92.

[14] Sachet, W.H. and Salman, W.D., 2020, November. Compressive Strength Development of Slag-Based Geopolymer Paste Reinforced with Fibers Cured at Ambient Condition. In IOP Conference Series: Materials Science and Engineering (Vol. 928, No. 2, p. 022117). IOP Publishing.
[16] Saha, S. and Rajasekaran, C., 2017. Enhancement of the properties of fly ash based geopolymer paste by incorporating ground granulated blast furnace slag. *Construction and Building Materials, 146*, pp.615-620.

[17] Salman, W.D. and Mahdi, O.S., 2019. Flexural Behavior and Mechanical Properties of Steel Fibers Ferro geopolymer One way Slabs Mortar. *Journal of engineering and applied sciences, 14*(15), pp.5267-1281.

[18] Salman, W.D. and Mansor, A.A., 2020. Confinement of concrete in double skin tubular members under axial compression loads. *Asian Journal of Civil Engineering*, pp.1-12.

[19] Salman, W.D., Mubarak, H.M. and Mahmood, M.S., 2018. Structural behavior and mechanical properties of ferrocement slab panels incorporating fibers. *International Journal of Civil Engineering and Technology (IJCIET), 9*, pp.2289-98.