Mechanical Properties of Geopolymer Concrete

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Keywords: geopolymer concrete ; mechanical properties ; data analysis

1. Introduction

Initial research on geopolymers carried out by Davidovits [1] was on the linear organic polymer, which is a branch of organic chemistry. Later, this topic was extended beyond this scope and research conducted in the early 1970s was focused on developing nonflammable inorganic polymer materials suitable for fire resistance. This attempt was because of the fact that the used organic polymers at that time were of low heat resistance. The work was ended to develop an amorphous to semi-crystalline three-dimensional silico-aluminate composite called geopolymer. This invention was followed by the manufacturing of fire-resistant chipboard panels, different geopolymeric ceramics, and later, geopolymeric binders including high strength cement and fireproof geopolymer fiber reinforced composites [1].

Geopolymer is essentially different from the conventional concrete which consists of hydraulic cement as a binder. Instead, there is an alkali-activated mineral admixture as a binding medium holding an inert aggregate to form a compact mass. This new type of concrete can offer many benefits including high early strength [2], high temperature resistance [3], and good chemical resistance for aggressive environments [4], as compared with normal concrete. In particular, durability of ordinary Portland cement concrete is under examination, as many concrete structures, especially those built in corrosive environments, start to deteriorate after 20 to 30 years [5]. Other reasons for using geopolymer concrete (GPC) include the vital need to save the natural environment and to use cleaner construction material since there is a global warning against the use of Portland cement-based composite. It is clear that the production of Portland cement accompanies the use of natural resources including gravel, water, and raw materials required for manufacturing of cement, leading to destroying the surrounding environment. Reports showed that about 2.7 billion tonnes of the raw materials needed every year for cement manufacturing [6]. Other reports [7] indicate that in order to manufacture one ton of Portland cement there is a need for about 2.8 tons of raw materials, including fuel. Another problem to be considered is the environmental pollution encountered with production of Portland cement. During the manufacturing of Portland cement, large amounts of greenhouse gas (CO_2) will be released into the atmosphere, and the related reports indicate that the cement industry contributes around 8% of the worldwide yearly CO_2 emission [8].

Based on the above-mentioned facts, the problem-related use of concrete must be well addressed, and there is a vital need to reduce Portland cement concrete consuming or searching for the alternatives for construction purposes. In a recent paper [9], the performance of composite concrete-timber section for roof construction was investigated, and the authors concluded that there is a chance to reduce concrete thickness by one half if populous nigari joist is used to make a composite section. Geopolymers seem to be a good solution to produce a clean concrete, since the Portland cement can be totally replaced, and instead there is a special concrete depending on an alkali-activated pozzolanic material, such as fly ash and blast furnace slag, to provide a binding medium. Physical and mechanical properties of fly ash (FA)-based geopolymer concrete (GPC), compared to those of Portland cement concrete (PCC), were investigated by Nikoloutsopoulos et al. [10] through testing three GPCs with different FA content and three appropriate PCC. It was shown that in some cases, minor adjustments of the regulations are needed, while in other cases complete revision is required. GPC indicated competitive compressive strength compared to PCC, while modulus of elasticity was about 50% less than that of PCC. GPC shows a higher mid-span deflection during flexural test up to 35% compared with that of PCC. Furthermore, ultrasonic pulse velocity of GPC was found quite different from that of PCC, even for the same strength level. They concluded that the quality of GPC cannot be assessed using the classification table used for PCC. The ratio of binder (FA) to aggregates seems to have a significant effect on the properties of GPC, in which GPC with 750 kg/m^3 FA seems to be the best choice with regard engineering and environmental criteria.

It was reported that the frost resistance of alkali-activated materials (AAM) is very good [11]. This was confirmed by investigating mechanical properties of GPC and frost resistance of different compositions of alkali activators made of sodium water glass with a silicate modulus modified with potassium hydroxide. Bilek et al. [11] found that the strengths of AAMs are significantly affected by the curing method, while the frost resistance depends on the method of curing and on the composition of the activator. As a conclusion, good frost resistance can be achieved if: (a) the optimal ratio between the alkalis and silica in the activator, in which activation with hydroxide or with the water glass with a high silicate modulus (low (Na_2O + K_2O)/SiO_2 (R/S) mass ratios, was found not suitable. The optimal R/S was recommended to be between 50/50 to 70/30; (b) the optimal amount of activator—dry mass of the activator higher than 15% seems to be deleterious from the point of view of frost resistance, knowing that the strengths of these materials are very high.

2. State-of-the-Art Review of Mechanical Properties of Geopolymer Concrete

Understanding mechanical properties of GPC is an important step toward producing large quantities of GPC with reasonably consistent and predictive engineering properties. These properties were the subject of numerous investigations in the past 20 years. The authors have been reviewed more than 250 research works on this topic and found that there are many ways to produce the geopolymers of different properties. Below, reviewing of important mechanical properties have been done and those parameters governing each property and relation among them are briefly investigated. Important parameters governing the performance of geopolymer binder are (a) activator solution-to-source material (fly ash, slag, etc.) ratio, (b) concentration of NaOH solution (molarity), (c) sodium silicate solution-to-sodium hydroxide solution ratio (Na_2SiO_3/NaOH), and this parameter depends on the composition of the sodium silicate solution, (d) curing temperature, (e) curing period, and (f) water content [10]. Indeed, if the basic pozzolanic material is partially replaced with other materials, there is a chance to adjust the binding characteristics

Different properties of geopolymer paste [12][13], mortar [13], and concrete [14] were experimentally investigated. If the density of concrete is considered, there are two types of geopolymer concrete, normal weight and lightweight, and the latter may be foamed concrete [15], or others based on lightweight aggregate [16][17]. Properties of self-compacting geopolymer concrete were experimentally investigated by Memon et al. [18], Ushaa et al. [19] and Saini and Vattifalli [20]. Behavior of GPC with nanomaterials was investigated by Phoo-ngernkham et al. [13]. Pozzolanic materials used for GPC mixes were mostly class F fly ash; however, class C fly ash [21], Phoo-ngernkham et al. [22], natural Pozzolan [23], ground granulated blast furnace slag (GGBS) [24][25], metakaolin [26][27], rice husk ash [28], a mixture of two or more Pozzolanic materials [29][30][31], and ceramic dust waste [32] were also examined. Some special ashes or compounds were used by some investigators such as palm oil fuel ash (POFA) [33], waste bottle glass (WBG) [34], and sugarcane bagasse ash (SCBA) [35][36]. With regard to the curing of GPC, several methods of curing were attempted by the researchers, including oven heating, membrane curing, steam curing, hot gunny curing, hydrothermal curing, room temperature, and water curing. Among them, oven curing proved to be the most efficient [37]. Heat curing regime of GPC depending on both temperature and duration, and initial temperature for curing varied between 30 °C [37] and 120 °C [38] or normally cured at the ambient temperature [22][24], while curing time up to 110 h was attempted [39]. Below, important mechanical properties of GPC are mentioned and discussed.

2.1. Compressive Strength

This property was extensively investigated in the laboratory and majority of research works on geopolymer concrete contained data on this property. Those parameters governing compressive strength of GPC are briefly discussed herein. Shehab et al. [40] observed that the values of compressive strength, bond strength, splitting tensile strength and flexural strength are the highest at 50% ordinary Portland cement (OPC) replacement with fly ash, while Vijai et al. [41] found that replacement of 10% of fly ash by OPC in GPC mix resulted in an enhanced compressive strength, split tensile strength and flexural strength. Tests by Lloyd and Rangan [42] showed that the inclusion of a 24 h period before curing increased the compressive strength of GPC. Curing at ambient condition will produce low early strength concrete, while there is a significant strength improvement on using high temperature. It should be noted that extended curing time able to enhance the geopolymerization mechanism and consequently the strength; however, longer duration of curing at an elevated temperature results in failure of the concrete [43]. In general, higher initial curing temperature and duration resulted in higher compressive strength [14][44][45][46]. Experimental tests by Adam and Horianto [38] showed that both temperature and duration of initial heat curing plays a major role for the strength development of fly ash-based geopolymer mortar. The optimum heat curing regime was found to be at 120° for 20 h. Tests by Joseph and Mathew [47] indicate 100 °C as the best temperature, while the optimum time of curing at 60 °C observed by Chindaprasirt et al. [48] was 3 h. These researchers found that the optimum curing temperature is 75 °C. The reaction was completed at 7 days to obtain the maximum strength and no further strength was observed. The importance of initial heat curing was also observed by Vijai et al. [41], Abdullah et al. [49] and Almuhsin et al. [50]. The latter researchers found an increase of 56% in the compressive strength for concrete subjected to one hour of oven curing at 90 °C. Increasing heat curing time to 90 h [51][52], and 110 h [39][53] resulted in an increase in compressive strength. Duration of heat curing was also investigated by Görhan and Kürklü [54], in which they found that there is an increase in compressive strength when heat curing (65 °C and 85 °C) increased from 5 to 24 h. Curing time more than 24 h was found has no appreciable effect on the strength [47].

Tests by Sathish Kumar et al. [55] indicate that the ratio of 7 days to 28 days compressive strength of ternary blend GPC is between 88% and 90%. Other tests by Nguyen et al. [2] showed that more than 93% of the 28-day compressive strength can be achieved at 7 days, regardless of fly ash type, heat curing method, or fly ash (FA) replacement with GGBS. In contrast, tests by Chi [56] indicate that the ratio is 88% for mortar cured at 65 °C which is larger than 66% when normally cured. For the metakaolin-based GPC mix subjected to normal air curing, the ratio of 7 days to 28 days compressive strength was found to be 73% and 88% [27]. Tests on self-compacting GPC based on fly ash and metakaolin show that the 7 days compressive strength value is close to the 28 days strength [57].

According to Nguyen et al. [2], increasing water/solid ratio from 0.2 to 0.3, can decrease the compressive strength of the FA-based GPC for alkaline-to-binder ratios of 0.3 and 0.4, while tests by Ahmad [58] for GPC subjected to initial curing at 70 °C (Oven) for 24 h showed that the optimum water/binder ratio is 0.25 to obtain maximum compressive strength. There was a strength increase with increasing alkali/fly ash ratio up to 0.45, lower than 0.5 measured by Al Bakri et al. [59] and Abdullah et al. [49]. With regard the liquid alkali/fly ash ratio the optimum value was observed to be 0.4 [60][61], while tests by Phoo-ngernkham and Phiangphimai [22] indicate a compressive strength reduction with increasing alkali activator solution/fly ash ratio from 0.4 to 0.9 for both M10 and M15 NaOH solutions. For GPC based on GGBS, optimal composition of solid/liquid ratio was noted to be 3.0 indicating the ratio of 0.33 for the alkali/GGBS ratio.

Al Bakri et al. [59] tested GPC of initial curing at 70 °C (Oven) for 24 h, the maximum compressive strength was for the mix of Na_2SiO_3/NaOH equal to 2.5. The same observation was made by Abdullah et al. [49], Aliabdo et al. [61], Aziz et al. [25], Joseph and Mathew [47], and Hadi et al. [62]. However, Vora and Dave [51] reported that the ratio of 2 resulted into a higher compressive strength. A value of 1.17 was found the best for GPC under ambient curing [50]. Other tests by Niş [63] showed that the critical silicate modulus depends on the molarity, in which for 14 M there was a ratio of 1, while for lower molarities the recommended value is 2. This finding supports that obtained previously by Rattanasak and Chindaprasirt [64]. Furthermore, a value of 1.5 was found to be the optimum for 10 M according to tests by Sathonsaowaphak et al. [60]. The use of a mix of NaOH and sodium silicate with a ratio of 1:1(SiO_2/Na_2O = 8) was able to activate the geopolymerization of fly ash [65].

NaOH solution molarity value for the alkali solution was found to be 12 for the highest compressive strength [49][58][59], while other tests [19][51][55][62][66] showed that the best molarity is 14. These experiments are not compatible with that performed by Raijiwala and Patil [67], Aliabdo et al. [61], Rachmansyah et al. [68] and Mathew and Issac [69] in which the molarity of 16 gives the highest compressive strength. In contrast, tests by Samantasinghar and Singh [70] indicate molarity of 8 for the maximum compressive strength.

Experiments by Puertas et al. [71] and Rajini et al. [72] showed that maximum compressive strength is related to 100% GGBS regardless the curing condition and any replacement of slag with fly ash resulted in the strength loss. Similarly, Guru Jawahar and Mounika [73] and Hadi et al. [62] found that the maximum compressive strength is related to the use of GGBS and if this material is partially replaced with fly ash or silica fume or metakaolin there is a strength loss, or there is a strength enhancement when the basic Pozzolana is replaced with GGBS [74]. The latter authors concluded that the replacement of fly ash with GGBS is a suitable alternative to oven curing. Nearly the same results were obtained by Bhargav and Kumar [75], Sarvanan and Elavanil [76] and Chidhambar and Manjunath [36]. The superiority of slag on fly ash for GPC subjected to different curing regimes was also observed by Kurtoğlu et al. [77]. Other tests showed that replacement of fly ash by GGBS up to 30% leads to an increase in compressive strength regardless of the curing temperature [2]. On the other hand, Yunsheng et al. [26] and Abhilash et al. [78] reported that the maximum compressive strength is related to replacing 50% metakaolin with GGBS. The same observation was also made by Raut et al. [79], Mathew and Issac [69] and Navyashree and Mogaveera [80] on geopolymer concrete made of fly ash replaced by GGBS. According to Okoya et al. [81], replacement of fly ash with silica fume up to 40% was found to be helpful to enhance compressive strength.

Using superplasticizers had very little effect on the compressive strength up to about 2% of this admixture to the amount of fly ash by mass [14]. This finding was supported by the observations of Malkawi et al. [82]. A reduction of compressive strength of GPC was observed when the superplasticizer dosage increased from 2% to 4% [51], while no significant change of compressive strength was observed by Aliabdo et al. [61] with increasing superplasticizer content.

It is of interest to mention the effect of other parameters influencing the strength of GPC. Tests by Joseph and Mathew [47] showed that the best total aggregate is 70% and the ratio of fine/coarse aggregate is 35% for mix of alkali/fly ash of 0.55. Saini and Vattifalli [20] found that addition of 2% nano silica resulted in improved workability, mechanical and durability performance of self-compacting GPC. Tests by Savitha et al. [35] showed that 5% replacement of GGBS by sugarcane bagasse ash (SCBA) gives highest compressive strength. On the other hand, compressive strength, splitting tensile strength, and elastic modulus of fly ash GPC improved with the increase of calcium aluminate cement [83].

2.2. Splitting Tensile Strength and Flexural Strength

Indirect tensile strength and flexural strength following similar trend of compressive strength of GPC [30][67], and in general, increasing compressive strength is accompanying with both splitting tensile (f_{sp}) and flexural strengths (f_r) enhancement. Consequently, those parameters governing compressive strength discussed in Section 2.1 govern these two properties. Test results by Hardijito [14] showed that the splitting tensile strength of geopolymer concrete is only a fraction of the compressive strength. However, there are some deviations from this general response described by some investigators.

Ryu et al. [65] reported that the rate of tensile strength increase slows with an increase of the compressive strength. Replacing fly ash with GGBS was found to have lower effect on splitting tensile and flexural strengths as compared with that on compressive strength [78]. Tests by Oderji et al. [84] showed a reduction in flexural strength as the fly ash replacement with slag increased from 15% to 20%, knowing that there is a compressive strength enhancement with this modification. Test data by Hassan et al. [45] showed that in contrast to elastic modulus of GPC the compressive and flexural strengths are enhanced well as a result of preheating of concrete at 75 °C for 26 h. Other tests by Sarvanan and Elavenil [76] showed that in contrast to the compressive strength, if 50% of fly ash is replaced with GGBS, there is a significant splitting tensile strength enhancement. The same observation was made for the elastic modulus property. Comparing data given by Partha et al. [29] with the others showed that using a special heat curing has an effect to enhance the flexure/compression ratio and to a lesser degree the tensile/compression ratio, as compared with the case of ambient temperature curing.

2.3. Modulus of Elasticity and Poisson's Ratio

Modulus of elasticity (E_c) follows similar trend of compressive strength of GPC, and according to tests by Hardijito [14], modulus of elasticity of GPC is increased with increasing compressive strength. Nath and Sarker [85] found that curing regime has no appreciable effect on the elastic modulus of GPC. Tests by Sarvanan and Elavenil [76] showed that in contrast to the compressive strength, if 50% of fly ash is replaced with GGBS, there is a significant elastic modulus enhancement.

With regard the Poisson’s ratio, this property has not been investigated as well compared with the other properties and consequently there is limited test data. The values of Poisson’s ratio fall between 0.23 and 0.26, which is slightly higher than the values assigned for normal strength OPC-based concrete [37]. Lower values of Poisson’s ratio were observed by other researchers for different GPCs [15][16][86][87]. In contrast to the other mentioned properties, there is no regular change with the compressive strength of GPC. This property tends to reduce with compressive strength reduction [15], while Sofi et al. [37] found an increase of Poisson’s ratio with increasing compressive strength. Other tests show that in contrast to other properties of GPC, increasing fly ash replacement with GGBS will lead to reducing the Poisson’s ratio [88]. In total, this behavior may complicate the work on developing equations for predicting Poisson’s ratio; however, this problem has been solved in the current investigation.

References

1. Davidovits, J. 30 Years of Successes and Failures in Geopolymer Applications. Market Trends and Potential Breakthroughs. In Proceedings of the Geopolymer 2002 Conference, Melbourne, Australia, 28–29 October 2002; pp. 1–16.
2. Nguyen, T.T.; Goodier, C.I.; Austin, S.A. Factors affecting the slump and strength development of geopolymer concrete. Constr. Build. Mater. 2020, 261, 119945.
3. Lyon, R.E.; Balaguru, P.N.; Foden, A.; Sorathia, U.; Davidovits, J.; Davidovics, M. Fire-resistant aluminosilicate composites. Fire Mater. 1997, 21, 67–73.
4. Palomo, A.; Blanco-Varela, M.T.; Granizo, M.L.; Puertas, F.; Vazquez, T.; Grutzeck, M.W. Chemical stability of cementitious materials based on metakaolin. Cem. Concr. Res. 1999, 29, 997–1004.
5. Mehta, P.K.; Burrows, R.W. Building Durable Structures in the 21st Century. Concr. Int. 2001, 23, 57–63.

6. Mehta, K. Greening of concrete industry for sustainable development. Concr. Int. 2002, 24, 23–28.
7. Guo, X.; Shi, H.; Dick, W.A. Compressive strength and microstructural characteristics of class C fly ash geopolymer. Ce m. Concr. Compos. 2010, 32, 142–147.
8. Olivier, J.G.J.; Janssens-Maenhout, G.; Muntean, M.; Peters, J.A.H.W. Trends in Global CO2 Emissions: 2015 Report; Environmental Assessment Agency: Hague, The Netherlands, 2015; pp. 1–80.
9. Mohammed, A.A.; Mohammed, O.K. Composite concrete—Unregularized timber section for flat roof construction. Struc tures 2020, 27, 1324–1334.
10. Nikoloutsopoulos, N.; Sotiropoulou, A.; Kakali, G.; Tsivilis, S. Physical and Mechanical Properties of Fly Ash Based Geo polymer Concrete Compared to Conventional Concrete. Buildings 2021, 11, 178.
11. Bilek, V.; Sucharda, O.; Bujdos, D. Frost Resistance of Alkali-Activated Concrete—An Important Pillar of Their Sustaina bility. Sustainability 2021, 13, 473.
12. Phoo-Ngernkham, T.; Chindaprasirt, P.; Sata, V.; Pangdaeng, S.; Sinsiri, T. Properties of high calcium fly ash geopolym er pastes with Portland cement as an additive. Int. J. Miner. Met. Mater. 2013, 20, 214–220.
13. Adak, D.; Sarkar, M.; Mandal, S. Effect of nano-silica on strength and durability of fly ash based geopolymer mortar. Co nstr. Build. Mater. 2014, 70, 453–459.
14. Hardjito, D. Studies on Fly Ash-Based Geopolymer Concrete. Ph.D. Thesis, Curtin University of Technology, Bentley, A ustralia, 2005.
15. Abdullah, M.M.A.B.; Hussin, K.; Bnhussain, M.; Ismail, K.N.; Yahya, Z.; Razak, R.A. Fly Ash-based Geopolymer Lightw eight Concrete Using Foaming Agent. Int. J. Mol. Sci. 2012, 13, 7186–7198.
16. Jamal, A.S. Preparation and Properties of Structural Lightweight Aggregate Geopolymer Concrete. Master's Thesis, Un iversity of Salahaddin-Erbil, Erbil, Iraq, 2019. Unpublished.
17. Posi, P.; Teerachanwit, C.; Tanutong, C.; Limkamoltip, S.; Lertnimoolchai, S.; Sata, V.; Chindaprasirt, P. Lightweight geo polymer concrete containing aggregate from recycle lightweight block. Mater. Des. 2013, 52, 580–586.
18. Memon, F.A.; Nuruddin, M.F.; Shafiq, N. Effect of silica fume on the fresh and hardened properties of fly ash-based self -compacting geopolymer concrete. Int. J. Miner. Metall. Mater. 2013, 20, 205–213.
19. Ushaa, T.G.; Anuradha, R.; Venkatasubramani, G.S. Performance of self-compacting geopolymer concrete containing d ifferent mineral admixtures. Indian J. Eng. Mater. Sci. 2015, 22, 473–481.
20. Saini, G.; Vattifalli, U. Assessing properties of alkali activated GGBS based self-compacting geopolymer concrete using nano-silica. Case Stud. Constr. Mater. 2020, 12, e00352.
21. Topark-Ngarm, P.; Chindaprasirt, P.; Sata, V. Setting Time, Strength, and Bond of High-Calcium Fly Ash Geopolymer C oncrete. ASCE J. Mater. Civ. Eng. 2014, 27, 04014198.
22. Phoo-Ngernkham, T.; Phiangphimai, C.; Damrongwiriyanupap, N.; Hanjitsuwan, S.; Thumrongvut, J.; Chindaprasirt, P. A Mix Design Procedure for Alkali-Activated High-Calcium Fly Ash Concrete Cured at Ambient Temperature. Adv. Mate r. Sci. Eng. 2018, 2018, 2460403.
23. Bondar, D.; Lynsdale, C.J. Engineering Properties of Alkali-Activated Natural Pozzolan Concrete. ACI Mater. J. 2011, 1 08, 64–72.
24. Yang, K.-H.; Cho, A.-R.; Song, J.-K. Effect of water–binder ratio on the mechanical properties of calcium hydroxide-bas ed alkali-activated slag concrete. Constr. Build. Mater. 2012, 29, 504–511.
25. Aziz, I.H.; Al Bakri Abdullah, M.M.; Salleh, M.M.; Azimi, E.A.; Chaiprapa, J.; Sandu, A.V. Strength development of solely ground granulated blast furnace slag geopolymers. Constr. Build. Mater. 2020, 250, 118720.
26. Zhang, Y.; Sun, W.; Chen, Q.; Chen, L. Synthesis and heavy metal immobilization behaviors of slag based geopolymer. J. Hazard. Mater. 2007, 143, 206–213.
27. Abbas, R.; Khereby, M.A.; Ghorab, H.Y.; Elkhoshkhany, N. Preparation of geopolymer concrete using Egyptian kaolin cl ay and the study of its environmental effects and economic cost. Clean Technol. Environ. Policy 2020, 22, 669–687.
28. Hardjasaputra, H.; Fernando, I.; Indrajaya, J.; Cornelia, M. The Effect of Using Palm Kernel Shell Ash and Rice Husk A sh on Geopolymer Concrete. MATEC Web Conf. 2018, 251, 01044.
29. Partha, S.D.; Pradib, N.; Prabir, K.S. Strength and Permeation Properties of Slag Blended Fly Ash Based Geopolymer Concrete. Adv. Mater. Res. 2013, 651, 168–173.
30. Rashad, A.M. Properties of alkali activated fly ash concrete blended with slag. Iran. J. Mater. Sci. Eng. 2013, 10, 57–6 4.

31. Albitar, M.; Ali, M.S.M.; Visintin, P.; Drechsler, M. Effect of granulated lead smelter slag on strength of fly ash-based geo polymer concrete. Constr. Build. Mater. 2015, 83, 128–135.

32. Amin, S.; El-Sherbiny, S.; El-Magd, A.A.; Belal, A.; Abadir, M. Fabrication of geopolymer bricks using ceramic dust wast e. Constr. Build. Mater. 2017, 157, 610–620.

33. Liu, M.Y.J.; Alengaram, U.J.; Jumaat, M.Z.; Mo, K.H. Evaluation of thermal conductivity, mechanical and transport prop erties of lightweight aggregate foamed geopolymer concrete. Energy Build. 2014, 72, 238–245.

34. Huseien, G.F.; Ismail, M.; Khalid, N.H.A.; Hussin, M.W.; Mirza, J. Compressive strength and microstructure of assorted wastes incorporated geopolymer mortars: Effect of solution molarity. Alex. Eng. J. 2018, 57, 3375–3386.

35. Savitha, T.M.; Manjunath, Y.M.; Srinivas, D. Micro-behavioral Study of Bagasse Ash based Geopolymer Concrete. Int. J. Innov. Technol. Explor. Eng. 2019, 8, 3494–3501.

36. Chidhambar, E.; Manjunath, Y.M. Experimental investigation on geopolymer concrete subjected to elevated temperatur e. Int. J. Adv. Res. Ideas Innov. Technol. 2019, 5, 290–296.

37. Sofi, M.; van Deventer, J.S.J.; Mendis, P.A.; Lukey, G.C. Engineering properties of inorganic polymer concretes (IPCs). Cem. Concr. Res. 2007, 37, 251–257.

38. Adam, A.A.; Horianto, X. The effect of temperature and duration of curing on the strength of fly ash based geopolymer mortar. Procedia Eng. 2014, 95, 410–414.

39. Hardjito, D.; Rangan, B.V. Development and Properties of Low-Calcium FlyAsh-based Geopolymer Concrete; Researc h Report GC1; Faculty of Engineering, Curtin University of Technology: Perth, Australia, 2005.

40. Shehab, H.K.; Eisa, A.S.; Wahba, A.M. Mechanical properties of fly ash based geopolymer concrete with full and partial cement replacement. Constr. Build. Mater. 2016, 126, 560–565.

41. Vijai, K.; Kumutha, R.; Vishnuram, B.G. Experimental investigations on mechanical properties of geopolymer concrete composites. Asian J. Civ. Eng. 2012, 13, 89–96.

42. Lloyd, N.; Rangan, V. Geopolymer Concrete—Sustainable Cementless Concrete. In Proceedings of the Tenth ACI Inter national Conference on Recent Advances in Concrete Technology and Sustainability Issues, Seville, Spain, 12 October 2009; Gupta, P.R., Holland, T.C., Malhorta, V.M., Eds.; American Concrete Institute: Farmington Hills, MI, USA, 2009; p p. 33–53.

43. Nurruddin, M.F.; Sani, H.; Mohammed, B.S.; Shaaban, I. Methods of curing geopolymer concrete: A review. Int. J. Adv. Appl. Sci. 2018, 5, 31–36.

44. Hardjito, D.; Wallah, S.E.; Sumajouw, D.M.J.; Rangan, B.V. Fly Ash-Based Geopolymer Concrete. Aust. J. Struct. Eng. 2005, 6, 77–86.

45. Hassan, A.; Arif, M.; Shariq, M. Effect of curing condition on the mechanical properties of fly ash-based geopolymer con crete. SN Appl. Sci. 2019, 1, 1694.

46. Jindal, B.B.; Parveen Singhal, D.; Goyal, A. Predicting Relationship between Mechanical Properties of Low Calcium Fly Ash-Based Geopolymer Concrete. Trans. Indian Ceram. Soc. 2017, 76, 258–265.

47. Joseph, B.; Mathew, G. Influence of aggregate content on the behavior of fly ash based geopolymer concrete. Sci. Iran. Trans. A Civ. Eng. 2012, 19, 1188–1194.

48. Chindaprasirt, P.; Chareerat, T.; Sirivivatnanon, V. Workability and strength of coarse high calcium fly ash geopolymer. Cem. Concr. Compos. 2007, 29, 224–229.

49. Abdullah, M.M.A.; Kamarudin, H.; Bnhussain, M.; Nizar, I.K.; Rafiza, A.R.; Zarina, Y. The relationship of NaOH molarity, Na2SiO3/NaOH ratio, fly ash/alkaline activator ratio, and curing temperature to the strength of fly ash-based geopolym er. Adv. Mater. Res. 2011, 328–330, 1475–1482.

50. Almuhsin, B.; al-Attar, T.; Hasan, Q. Effect of discontinuous curing and ambient temperature on the compressive streng th development of fly ash based Geopolymer concrete. MATEC Web Conf. 2018, 162, 02026.

51. Vora, P.R.; Dave, U.V. Parametric Studies on Compressive Strength of Geopolymer Concrete. Procedia Eng. 2013, 51, 210–219.

52. Hardjito, D.; Wallah, S.E.; Sumajouw, D.M.; Rangan, B.V. On the Development of Fly Ash-Based Geopolymer Concret e. ACI Mater. J. 2004, 101, 467–472.

53. Patankar, S.V.; Ghugal, Y.M.; Jamkar, S.S. Effect of Concentration of Sodium Hydroxide and Degree of Heat Curing on Fly Ash-Based Geopolymer Mortar. Indian J. Mater. Sci. 2014, 2014, 938789.

54. Gorhan, G.; Kurklu, G. The influence of the NaOH solution on the properties of the fly ash-based geopolymer mortar cu red at different temperatures. Compos. Part B Eng. 2014, 58, 371–377.

55. Kumar, V.S.; Ganesan, N.; Indira, P.V. Effect of Molarity of Sodium Hydroxide and Curing Method on the Compressive Strength of Ternary Blend Geopolymer Concrete. IOP Conf. Ser. Earth Environ. Sci. 2017, 80, 012011.

56. Chi, M. Effects of the alkaline solution/binder ratio and curing condition on the mechanical properties of alkali-activated fly ash mortars. Sci. Eng. Compos. Mater. 2017, 24, 773–782.

57. Arun, B.R.; Nagaraja, P.S.; Srishaila, G.M. An Effect of NaOH Molarity on Fly Ash—Metakaolin-Based Self-Compacting Geopolymer Concrete. Sustain. Constr. Build. Mater. Lect. Notes Civ. Eng. 2019, 25, 233–244.

58. Ahmad, H.Q. Flexural Response of Geopolymer Concrete Beams Reinforced with FRP Rebars. Ph.D. Thesis, Universit y of Salahaddin-Erbil, Erbil, Iraq, 2020. Unpublished.

59. Mustafa Al Bakri, A.M.; Kamarudin, H.; Bnhussain, M.; Rafiza, A.R.; Zarina, Y. Effect of Na2SiO3/NaOH Ratios and Na OH Molarities on Compressive Strength of Fly-Ash-Based Geopolymer. ACI Mater. J. 2012, 109, 503–508.

60. Sathonsaowaphak, A.; Chindaprasirt, P.; Pimraksa, K. Workability and strength of lignite bottom ash geopolymer morta r. J. Hazard. Mater. 2009, 168, 44–50.

61. Aliabdo, A.A.; Elmoaty, A.M.A.; Salem, H.A. Effect of water addition, plasticizer and alkaline solution constitution on fly ash based geopolymer concrete performance. Constr. Build. Mater. 2016, 121, 694–703.

62. Hadi, M.N.S.; Farhan, N.A.; Sheikh, M.N. Design of geopolymer concrete with GGBFS at ambient curing condition usin g Taguchi method. Constr. Build. Mater. 2017, 140, 424–431.

63. Niş, A. Compressive strength variation of alkali activated fly ash/slag concrete with different NaOH concentrations and sodium silicate to sodium hydroxide ratios. J. Sustain. Constr. Mater. Technol. 2019, 4, 351–360.

64. Rattanasak, U.; Chindaprasirt, P. Influence of NaOH solution on the synthesis of fly ash geopolymer. Miner. Eng. 2009, 22, 1073–1078.

65. Ryu, G.S.; Lee, Y.B.; Koh, K.T.; Chung, Y.S. The mechanical properties of fly ash-based geopolymer concrete with alkal ine activators. Constr. Build. Mater. 2013, 47, 409–418.

66. Somna, K.; Jaturapitakkul, C.; Kajitvichyanukul, P.; Chindaprasirt, P. NaOH-activated ground fly ash geopolymer cured at ambient temperature. Fuel 2011, 90, 2118–2124.

67. Raijiwala, D.B.; Patil, H.S. Geopolymer Concrete A Green Concrete. In Proceedings of the 2010 2nd International Conf erence on Chemical, Biological and Environmental Engineering (ICBEE 2010), Cairo, Egypt, 2–4 November 2010.

68. Hardjasaputra, H.; Cornelia, M. Experimental study of effect additional water on high performance geopolymer concret e. MATEC Web Conf. 2019, 270, 01004.

69. Mathew, G.; Issac, B.M. Effect of molarity of sodium hydroxide on the aluminosilicate content in laterite aggregate of lat erised geopolymer concrete. J. Build. Eng. 2020, 32, 101486.

70. Samantasinghar, S.; Singh, S.P. Fresh and Hardened Properties of Fly Ash–Slag Blended Geopolymer Paste and Mort ar. Int. J. Concr. Struct. Mater. 2019, 13, 47.

71. Puertas, F.; Martinez-Ramirez, S.; Alonso, S.; Vazquez, T. Alkali-activated fly ash/slag cement Strength behaviour and hydration products. Cem. Concr. Res. 2000, 30, 1625–1632.

72. Rajini, B.; Rao, A.V.N.; Sashidhar, C. Cost analysis of geopolymer concrete over conventional concrete. Int. J. Civ. Eng. Technol. 2020, 11, 23–30.

73. Jawahar, J.G.; Mounika, G. Strength properties of fly ash and GGBS based geopolymer concrete. Asian J. Civ. Eng. 20 16, 17, 27–35.

74. Venu, M.; Rao, T.D.G. An experimental investigation of the stress-strain behavior of geopolymer concrete. Slovak J. Ci v. Eng. 2018, 26, 30–34.

75. Bhargav, M.V.; Kumar, B.S.C. Strength and durability of geopolymer concrete incorporating metakaolin and GGBS with 10M alkali activator solution. Int. J. Civ. Eng. Technol. 2017, 8, 473–487.

76. Sarvanan, S.; Elavenil, S. Strength properties of geopolymer concrete using M-sand by assessing their mechanical cha racteristics. ARPN J. Eng. Appl. Sci. 2018, 13, 4028–4041.

77. Kurtoğlu, A.E.; Alzeebaree, R.; Aljumaili, O.; Nis, A.; Gulsan, M.E.; Humur, G.; Cevik, A. Mechanical and durability prop erties of fly ash and slag based geopolymer concrete. Adv. Concr. Constr. 2018, 6, 345–362.

78. Abhilash, P.; Sashidhar, C.; Reddy, I.R. Strength properties of Fly ash and GGBS based Geo-polymer Concrete. Int. J. ChemTech Res. 2016, 9, 350–356.

79. Raut, U.; Shalini, A.; Prabu, B. Strength of geopolymer concrete reinforced with basalt fiber. Int. Res. J. Eng. Technol. 2 019, 6, 3811–3817.

80. Navyashree, B.R.; Mogaveera, G. Study on Strength of Geopolymer Concrete. Int. J. Adv. Sci. Technol. 2020, 29, 11045–11050.

81. Okoye, F.N.; Durgaprasad, J.; Singh, N.B. Effect of silica fume on the mechanical properties of fly ash based-geopolymer concrete. Ceram. Int. 2016, 42, 3000–3006.

82. Malkawi, A.B.; Nuruddin, M.F.; Fauzi, A.; Al-Mattarneh, H.; Mohammed, B.S. Effect of Plasticizers and Water on Properties of HCFA Geopolymers. Key Eng. Mater. 2017, 733, 76–79.

83. Wang, Y.; Hu, S.; He, Z. Mechanical and Fracture Properties of Fly Ash Geopolymer Concrete Addictive with Calcium Aluminate Cement. Materials 2019, 12, 2982.

84. Oderji, S.Y.; Chen, B.; Ahmad, M.R.; Shah, S.F.A. Fresh and hardened properties of one-part fly ash-based geopolymer binders cured at room temperature: Effect of slag and alkali activators. J. Clean. Prod. 2019, 225, 1–10.

85. Nath, P.; Sarker, P.K. Flexural strength and elastic modulus of ambient-cured blended low-calcium fly ash geopolymer concrete. Constr. Build. Mater. 2017, 130, 21–31.

86. Olivia, M.; Nikaraz, H. Properties of fly ash geopolymer concrete designed by Taguchi method. Mater. Des. 2012, 36, 191–198.

87. Albitar, M.; Visintin, P.; Mohamed Ali, M.S.; Drechsler, M. Assessing Behaviour of Fresh and Hardened Geopolymer Concrete Mixed with Class-F Fly Ash. KSCE J. Civ. Eng. 2014, 19, 1445–1455.

88. Sivakumar, A.; Kishore, R. Evaluation of mechanical properties of fly ash and GGBS based geopolymer concrete. J. Emerg. Technol. Innov. Res. 2017, 4, 1028–1033.