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Utilisation of Sustainable Materials in Geopolymer Composites– A Review

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Abstract. Geopolymer composites made from sustainable ingredients which are used to make ecofriendly concrete in the infrastructure sector. The dramatic increase in infrastructure growth around the world demonstrates the daily demand for cement production. This study provides an overall view of research on the use of materials and the performance of geopolymer matrix based on strength and durability. Unlike cement, the reutilization of industrial by-products reduces greenhouse gas emissions during manufacture. Hence geopolymers can contribute to a better alternative to Portland cement. Natural raw materials, agricultural waste, and industrial waste by products from diverse industries are used as composite filler / binder materials in geopolymer matrix to improve workability , durability and reducing geopolymer concrete manufacturing costs. With the help of various curing procedures, the compressive strength of geopolymer concrete can be increased in a short amount of time. It has also been discovered that adding fibres to geopolymer concrete improves tensile strength, lowering the cost of structural maintenance.

Introduction

Concrete which is a commonly used global building material made with Portland cement. This increases cement production due to the enormous escalation in infrastructure and mechanization development. Geopolymer concrete is one made use of environmentally friendly materials to reduce CO_2 emission by extreme use of OPC. Initially geopolymer concrete research was constrained with the usage of natural source materials like calcined clays, kaolin, metakaolin and silica fumes. However, in order to solve the problem of industrial waste disposal, items includes fly ash, GGBS and palm oil ash etc., are commonly used to make the environment more sustainable while emitting less CO_2 than cement. The cement replacement materials should possess enough pozzolanic property [1]. He also stated that geopolymer concrete has an earlier strength, is more durable, and does not have the harmful alkali–aggregate interaction that portland cement has. Geopolymer concrete with low calcium fly ash and treated with various alkaline solutions has demonstrated great resistance to harsh environments.

Geopolymerisation process

Natural/alternative source materials and alkaline solutions are the two most significant components of geopolymer. Geopolymers are a polymer network made up of silicon and aluminium atoms connected jointly through oxygen atoms. As a source material for geopolymer binder, fly ash, ground granulated blast furnace slag (GGBS), metakoalin, Silica fume, and other amorphous minerals rich in Si and Al can be used. Geopolymer, like Portland cement, does not use a calcium-silicate-hydrate (CSHs) gel to improve structural stability; instead, it uses a poly condensation process with silica and alumina precursors. In the geopolymerization process, aluminosilicate oxides react chemically with alkali polysilicates to generate polymeric Si – O – Al links [2]. In the geopolymerization process, the amount of alkali solution, type of binder, Si/Al ratio, temperature, and curing conditions are all important variables. The key concept behind the fly ash-based geopolymer matrix is the alkali breakdown of aluminoslicate followed by the polycondensation process. Condensation between flyash and alkali solution produces Si4+ and Al3+ species, which are then nucleated, oligomerized, and polymerized to produce aluminoslicate matrix. The energetic Al3+ and Si4+ species react to form nuclei and aluminosilicate oligomers, as shown in Fig. 1. The aluminosilicate matrix network is balanced by alkali cations. The final structure of geopolymer materials is determined by the appropriate Si/Al ratio. Different aluminosilicate networks form as aluminosilicate oligomers, which eventually form geopolymer concrete/mortar, depending on the Si/Al molar ratio.

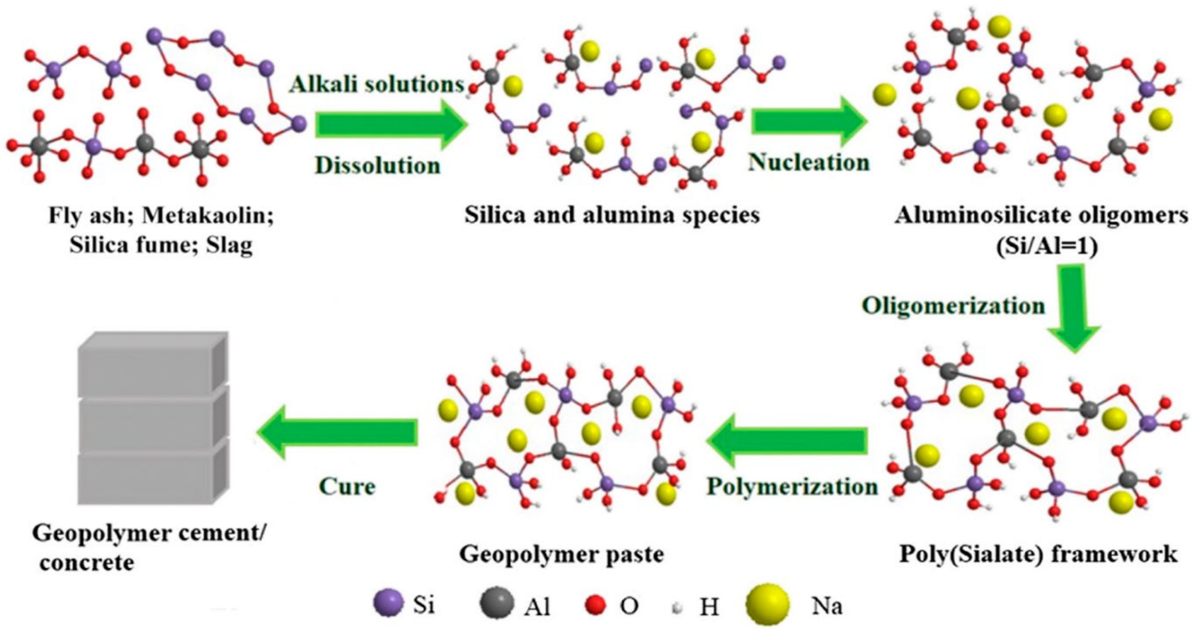

Fig. 1. Geo polymerisation Process [2,3]

The setting behaviour, microstructure, and property development of fly ash-based geopolymers are fundamentally different from metakaolin-based geopolymers. The Gluhhovsky model divides the process into three stages: destruction–coagulation, coagulation–condensation, and condensation–crystallization. The essential process in geopolymerization is depicted in Fig. 2 as a very simplified reaction mechanism. A supersaturated alumina silicate solution is generated when aluminosilicate sources are dissolved in water. When concentrated liquids are present, a gel forms, which subsequently condenses to form huge networks, allowing the water to escape. The reaction media contains water, but it is trapped inside the pores of the gel [4, 5].

Effect of Filler materials on Geopolymerisation

To hydrate partial replacements of highly mixed cement with flyash, several alkali solutions are utilised. In terms of performance, this is preferable to normal Portland cement. The formation of gel, which consists of C-S-H and N-A-S-H, causes the setting and hardening of alkaline-hydrated (fly ash-rich) super-blended cement [6]. The fineness and surface qualities of the raw materials are primarily responsible for geopolymerization. The geopolymerization phase, which consists of a mixture of two or three source minerals, such as kaolinite, albite, and fly ash, activates and speeds up the reaction of the necessary gel phase, resulting in a high compressive strength [7].

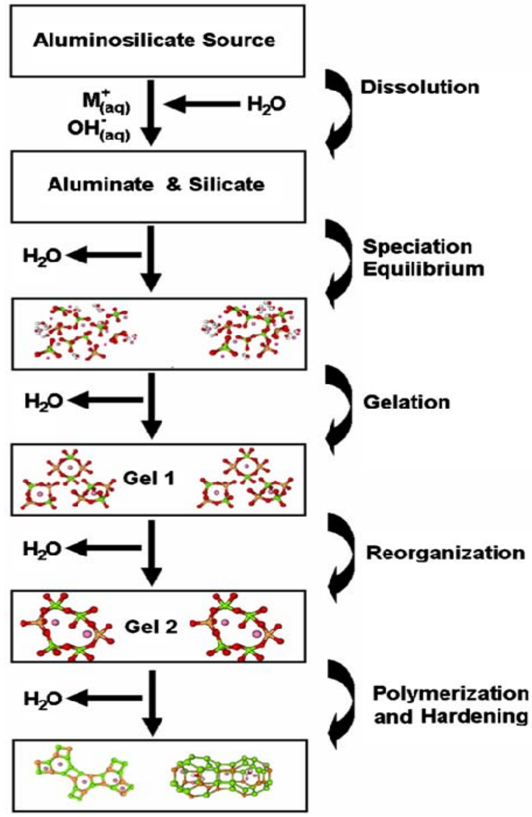

Fig. 2. Conceptual model of Geopolymerisation [3]

Based on curing temperature and methodology, the influence of alkali activator concentration enhances the process of geopolymerisation reaction and, moreover, leads to strength improvement [8]. Increased alkali activator solution proportions speed up the setting time, which reduces strength, thermal stresses, reaction rate, and geopolymerization peak time [9]. The amount of dissolving in NaOH solutions was greater than in KOH solutions when the most reactive components were utilised. In both alkaline and acidic conditions, Si and Al behave in a coordinated manner [10].

Effect of combination of binder materials with their performance

Reference	Waste Materials utilized	alkaline medium	Remarks
(Bhardwaj and Kumar 2019) [11]	GGBS+ flyash + waste foundary sand	NaoH, Na_2SiO_3 (14M)	Drop in workability and rise in strength with 60% foundary sand
(Ali, Naje, and Nasr 2020) [12]	Flyash +Chopped tyre rubber	Na_2SiO_3/ NaOH by w.t of FA (45%)	Compressive strength increases by 10%

(Republic and Republic 2006) [13]	Flyash + Ground Slag	SiO_2 /Na_2O (6-10%)	Microstructure phases are studied with co-existence of C–S–H phase. Maximal geopolymer strength was reached.
(Hawa, Tonnayopas, and Prachasaree 2013) [14]	Metakaolin + palm oil ash	SiO_2 /Al2O3 , Cao/Sio2	Highest compressive strength obtained from (SiO2 :Al2O3 =2.88 : 1)
(Chen and Id n.d.) [15]	Metakaolin + Ca	CaO:Na2O:Al2O3:SiO2:H2O (0.4:1:1:4:12.1)	Faster gel formation by calcium enhanced by faster metakolin dissolution
(Shi et al. 2020) [16]	Flyash + Metakaolin (Foamed Geopolymer)	calcium stearate, H2O2, NaOH, sodium silicate and expanded polysterene (EPS)	H2O2 causes expansion of foamed geopolymer, Metakaolin reduce pore diameter
(Oyebisi et al. 2020) [17]	Harnessed corncob ash (CCA) + (GGBFS)+ Portland lime cement	Sodium Silicate / Sodium Hydroxide – 2.5, Al / B - 0.54 (12M,14M,16M)	14 M of SH solution achieved highest compressive, flexural, and splitting tensile strengths for both M 30 and M 40.
(Panizza et al. 2020) [18]	Metakaolin + GGBS + flyash + furnace slag	Si/Al, K/Al	Geopolymer mortar produces better shrinkage and long term behaviour

Effect of curing temperature on alkali activator

The effect of curing procedures, as well as the inclusion of binder/filler ingredients in various alkaline activator dosages, on geopolymer concrete's strength qualities, may be beneficial. Curing temperature has a significant impact on geopolymeric processes and material characteristics [19]. The effect of the Si/Al ratio in the range of 1.7 to 2.9 on weight losses, residual strength, volumetric shrinkage, and water sorptivity vary dramatically with temperature, as illustrated in Fig. 3 and 4. The colour of the specimens changes from grey to bright crimson as the temperature rises, accompanied by the formation of microscopic cracks. At higher temperatures, the lower Si/Al ratio causes more weight loss and volumetric strain. The higher Si/Al ratio exhibits best results in terms of residual compressive strength after exposure to elevated temperatures as shown in Fig. 5 & 6.

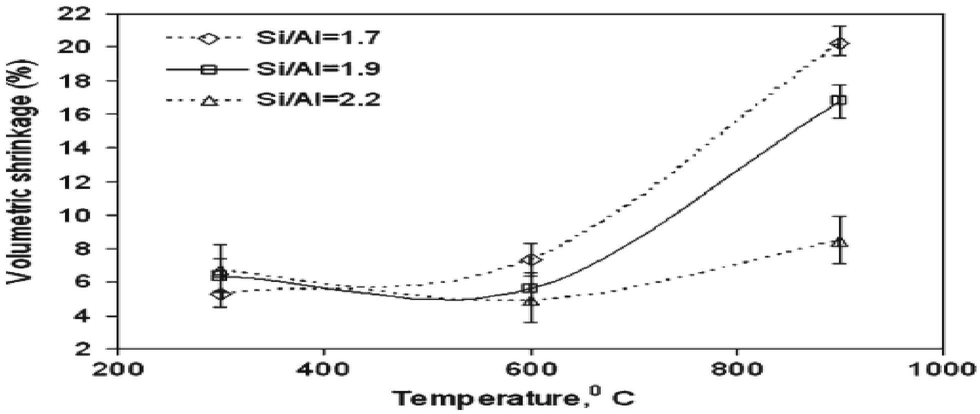

Fig. 3. Variation of volumetric shrinkage

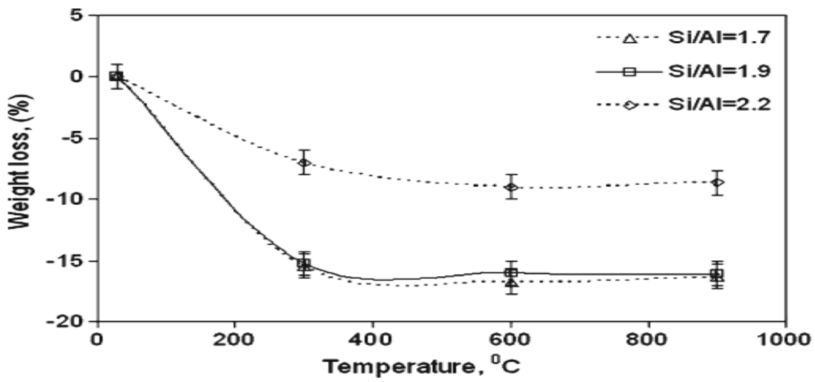

Fig. 4. weight loss of geopolymer with respect to temperature [20]

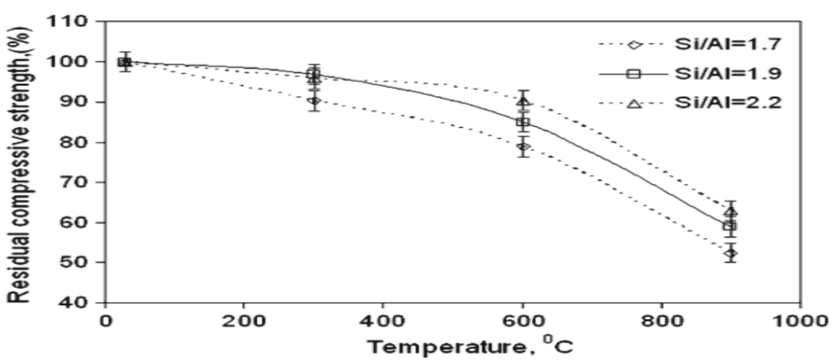

Fig.5. Variation of compressive strength

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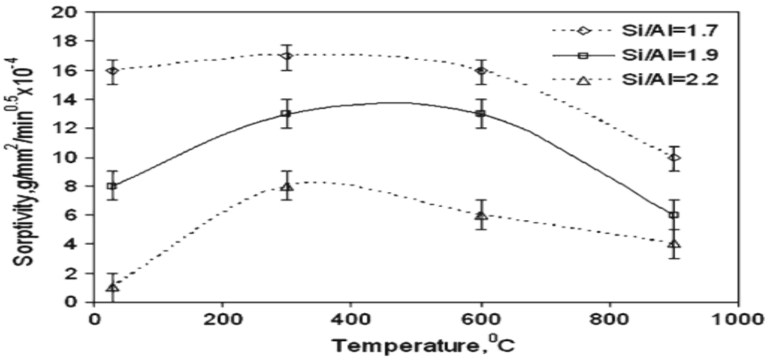
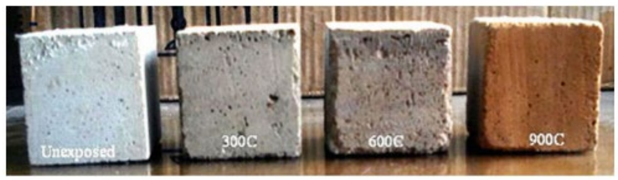


Fig. 6. Variation of sorptivity against temperature of geopolymer concrete [20]



Specimen	Colour Name	HEX Code	Shades
Unexposed	Alice Blue	#F0F8FF	
300°C	Light Grey	#D3D3D3	
600°C	Rosy Brown	#BC8F8F	
900°C	Chocolate	#D2691E	

Fig. 7. Specimens at different temperature exposure and standard colour indices [20]

When subjected to high temperatures, higher Si/Al ratios, on the other hand, have proved to have significant strength as shown in Fig. 7. As a result, increasing the Si concentration in geopolymer composites increases their performance when exposed to higher temperatures, demonstrating that they are temperature resistant materials [20]. The compressive strength of concrete was improved by raising the SiO3/OH ratio from 0.5 to 1.5 after the geopolymerization procedure was successful. As the temperature rises, the strength of geopolymer concrete gradually increases [21].

Environmental sustainability

The severe environmental impact of carbon dioxide emissions, as well as the predicted ongoing expansion of industrial development, needs retooling the construction industry with sustainable and environmentally acceptable materials in order to develop alternate binder systems. The impacts of estimating the carbon footprint of geopolymer and OPC concrete, including energy consumption from all activities required to source raw ingredients, create concrete, and complete the construction process. The CO2 footprint of geopolymer concrete was roughly 9% lower than that of OPC concrete binder, as shown in fig. 8. Greater OPC emission was linked to cement and sodium silicate in geopolymer concrete [22].

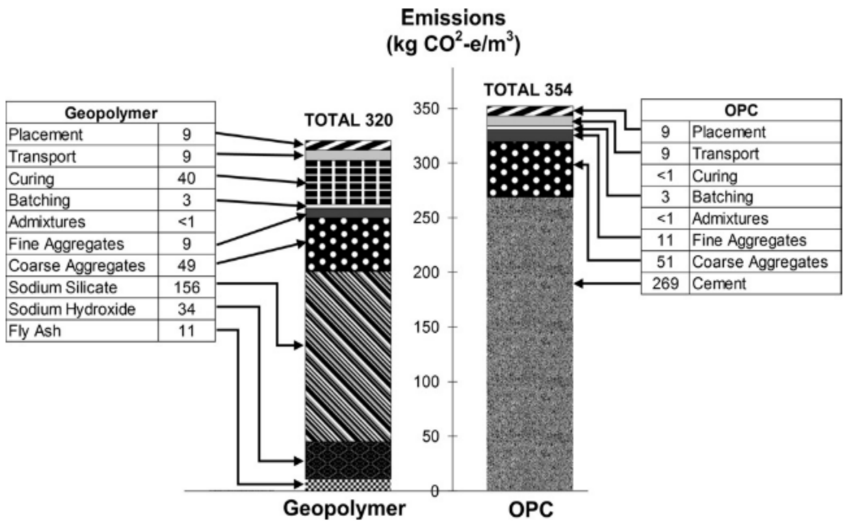


Fig. 8. Summary of CO_2 emission for OPC and geopolymer binders [22]

The energy consumed in the production of ordinary Portland cement (OPC) and supplemental cementitious materials (SCM'S) is depicted in Fig. 9. Cement clinker calcination absorbs a significant quantity of fossil fuel energy and releases additional CO2 via a decarbonation reaction. The extensive use of basic materials such as FA and GGBS as geopolymer binder in power plants and steel manufacturing has no detrimental impact on CO2 emissions. Geopolymer binders [23] provide a game-changing answer to the OPC industry's environmental issues. Green concrete's growth is aided by the use of SCMs in its manufacture, such as high-volume fly ash concrete, ultra-high performance concrete, geopolymer concrete, lightweight concrete, and so on. Increased strength, durability, workability, low permeability, controlled bleeding, reduced shrinkage, and greater resilience to severe environments are just a few of the long-term and cost-effective benefits of green concrete. Green concrete also promotes the creative and long-term use of waste and alternative materials in the construction industry [24].

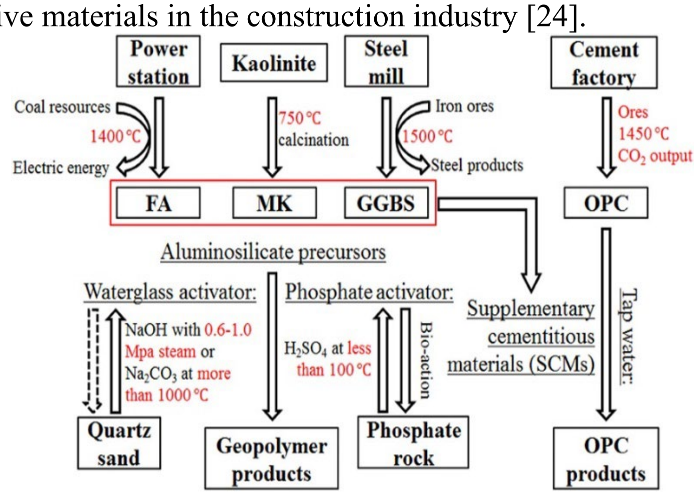


Fig. 9. Energy Expenditure diagrams of Geopolymer and OPC products [23]

Utilization of Nanomaterials in Geopolymer concrete

Geopolymers have been successfully made from fly ash, silica fume, rice husk ash, red mud, and crushed granulated blast furnace slag. The use of nanoparticles improves the structural properties of geopolymer concrete and mortars. Nanomaterials such as nanosilica (NS), nanotitania (NT), nanoalumina (NA), nano clay (NC), geothermal nanosilica waste (GSW), and carbon nanotubes considerably improve the mechanical and durability properties of geopolymers, according to various publications. Silicon dioxide (SiO2) nanoparticles form a dense concrete mix that increases the strength and endurance of the materials [25, 26]. The workability of nanoparticles in geopolymer concrete is limited due to their larger surface area. The beginning and final setting durations of geopolymer matrix are lowered due to the acceleration effect of nanoparticles, making the optimum content of nanoparticles with varying percentages appropriate for geopolymer applications. A larger concentration of nanoparticles diminishes mechanical strength and increases water absorption and porosity by forming more voids in the matrix due to particle agglomeration and pore dispersion. In geopolymer concrete, nano-silica with a particle size of 10 nm was used up to 8%, resulting in increased compressive strength, decreased permeability, and a dense geopolymer concrete matrix. In GPC-N cubes containing 8% nano silica, chloride and sulphate incursions were found to be low. Geopolymer concrete containing nano silica, according to preliminary study, is a feasible alternative to OPC. The GPC-N also performed well in a number of situations [27]. Adding 2% weight of nano-Al2O3 particles to a fly ash-based geopolymer matrix improves mechanical properties, as seen in figures. 10 and 11 [28]. As a result, nanoalumina, like nanosilica, speeds up the geopolymerisation procedure, resulting in a denser geopolymeric gel.

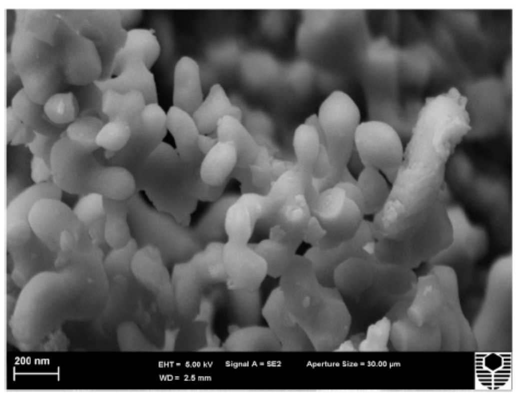


Fig. 10. SEM image of nano- Al_2O_3 powder [28]

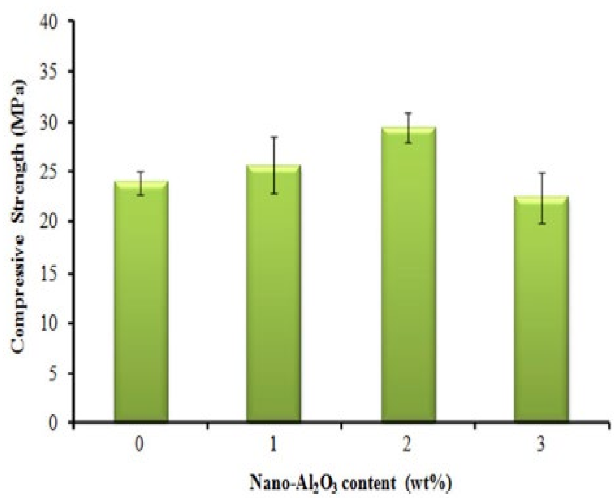


Fig. 11. Compressive strength of geopolymer nanocomposites as a function of nano-Al_2O_3 content [28]

As shown in fig. 12, adding nanotitania (TiO2) to flyash-based geopolymer concrete with varied percentages improves mechanical properties in later ages. Increased geopolymerisation processes triggered the strength [29].

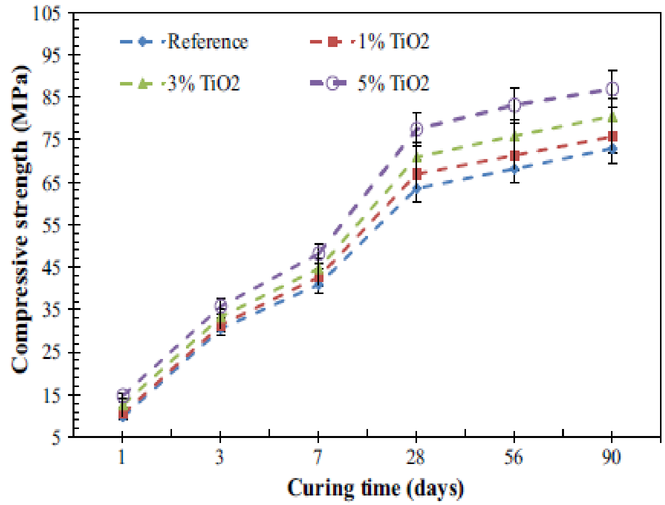


Fig. 12. Effects of nano-TiO2 on the compressive strength of geopolymer at 1, 3, 7, 28, 56 and 90 days [29]

Effect of fibres in geopolymer concrete

Fibres, in combination with a geopolymer binder, are used in varying proportions to improve strength and durability, as well as to reduce building costs. Glass, polypropylene, and steel fibres have all been utilised in studies and have proven to have superior durability. Increased rupture modulus, bond strength, compressive strength, and flexural characteristics are all benefits of steel fibre. When fibres are added to concrete, its workability is reduced [30, 31, 32, and 33]. The application of cellulose fibre geopolymer matrix composite enhances specimen strength and fracture resilience via cellulose modification [34]. The brittleness of geopolymer concrete is reduced when glass and polypropylene fibres are mixed with hybrid fibres. The presence of hybrid fibres resulted in greater performance in the post-cracking stage, while the presence of polypropylene fibre resulted in a delay in the formation of the first crack with an increase in toughness index [35, 36, and 37].

Applications of geopolymer matrix and concrete

Source	Materials	Geopolymer	Remarks
		Concrete applications	
(Liew et al. 2017) [24]	Flyash based concrete	High volume fly ash concrete, ultra High performance concrete (containing admixtures), lightweight concrete	High strength, Increase durability, improved workability, Reduced permeability and Shrinkage.
(Laskar and Talukdar 2017) [38]	Blast furnace slag + flyash	As Concrete repairing agent	Improvement in strength and workability aspects.

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(Deb, Nath, and Sarker 2015) [39]	GGBS+ flyash	Heat cured methodology is employed for concrete strength enhancement	Improvement in strength and higher GGBS contents leads to lower workability aspects.
(Lee et al. 2019) [40]	GGBS+ flyash	Excellent chloride resistance concrete	Durability test – Nine months of curing period. Better compressive strength.
(Deb et al. 2015) [39]	Low calcium Flyash+ Blast furnace slag	Early strength development with 10-20% GGBS	Reduction in shrinkage aspects
Marine applications			
(Hassan, Arif, and Shariq 2020) [41]	Flyash based mix	Amorphous aluminosilicate geopolymeric gel formation are chemically stable in sea water	Low Permeability. Inhibit penetration of sea water
(Arbi et al. 2016) [42]	Alkali activated materials (Flyash + slag)	Durability enhancement by chemistry of pore solution	Better resistance to chemical attacks. Improvement in durability aspects.
(Mahmood 2019) [43]	Steel furnace slag aggregate +fly ash + blast furnace slag	Size reduction in break water structures	Repair works , Delayed hydration process
(Fan et al. 2018) [44]	Flyash based mix	High performance geopolymer mortar for repair works	Better for aggressive environments such as seawater and acidic environments

Conclusion

The review summarises the important findings of several investigations on the utilisation of materials and the strength of geopolymer concrete. The geopolymer binder's source material should have a strong pozzolanic activity, with a suitable alkali solution ratio activating the geopolymerisation reaction. A greater grasp of the source materials' chemical and physical properties can help you decide which binders to use and in what ratio. A combination of materials, curing temperature, curing procedure, and alkali activator ratio improve the strength of the Geopolymer. The longevity of geopolymer concrete is affected by the component and design mix ratios used in its preparation. Pavements, maintenance work, coastal area constructions, and bridges are where geopolymer concrete is most commonly used. The addition of fibres to geopolymer concrete improves its resiliency after it has cracked.

References

[1] Davidovits, Joseph., Geopolymer Chemistry and Applications, 5-Th Edition (2020).

[2] Zhuang, Xiao Yu, Liang Chen, Sridhar Komarneni, Chun Hui Zhou, Dong Shen Tong, Hui Min Yang, Wei Hua Yu, and Hao Wang, Fly Ash-Based Geopolymer: Clean Production, Properties and Applications, Journal of Cleaner Production 125:253-67 (2016). https://doi.org/10.1016/j.jclepro.2016.03.019

[3] Shamsaei, Ezzatollah, Owen Bolt, Felipe Basquiroto de Souza, Emad Benhelal, Kwesi Sagoe-Crentsil, and Jay Sanjayan., Pathways to Commercialisation for Brown Coal Fly Ash-Based Geopolymer Concrete in Australia, Sustainability (Switzerland) 13(8) (2021). https://doi.org/10.3390/su13084350

[4] Duxson, P., A. Fernández-Jiménez, J. L. Provis, G. C. Lukey, A. Palomo, and J. S. J. Van Deventer, Geopolymer Technology: The Current State of the Art, Journal of Materials Science 42(9):2917-33 (2007). https://doi.org/10.1007/s10853-006-0637-z

[5] Xu, Hua and J. S. J. Van Deventer, The Geopolymerisation of Alumino-Silicate Minerals, (2000). https://doi.org/10.1016/S0301-7516(99)00074-5

[6] Palomo, A., A. Fernández-Jiménez, G. Kovalchuk, L. M. Ordoñez, and M. C. Naranjo, Opc-Fly Ash Cementitious Systems: Study of Gel Binders Produced during Alkaline Hydration, Journal of Materials Science 42(9):2958-66 (2007). https://doi.org/10.1007/s10853-006-0585-7

[7] Xu, Hua and Jannie S. J. Van Deventer, Effect of Source Materials on Geopolymerization, Industrial and Engineering Chemistry Research 42(8):1698-1706 (2003). https://doi.org/10.1021/ie0206958

[8] Görür, E. B., O. Karahan, C. Bilim, S. Ilkentapar, and E. Luga. 2015, Very High Strength (120 MPa) Class F Fly Ash Geopolymer Mortar Activated at Different NaOH Amount , Heat Curing Temperature and Heat Curing Duration, 96:673-78 (2003). https://doi.org/10.1016/j.conbuildmat.2015.08.089

[9] Ling, Yifeng and Ashley Buss, Proportion and Performance Evaluation of Fly Ash- Based Geopolymer and Its Application in Engineered Composites, Iowa State University Captones, Theses and Dissertations 140 (2018).

[10] Panagiotopoulou, Ch, E. Kontori, Th Perraki, and G. Kakali, Dissolution of Aluminosilicate Minerals and By-Products in Alkaline Media, Journal of Materials Science 42(9):2967-73 (2007). https://doi.org/10.1007/s10853-006-0531-8

[11] Bhardwaj, Bavita and Pardeep Kumar, Comparative Study of Geopolymer and Alkali Activated Slag Concrete Comprising Waste Foundry Sand, Construction and Building Materials 209:555-65 (2019). https://doi.org/10.1016/j.conbuildmat.2019.03.107

[12] Ali, Isam Mohamad, Ahmed Samir Naje, and Mohammed Salah Nasr, Eco-Friendly Chopped Tire Rubber as Reinforcements in Fly Ash Based Geopolymer Concrete, Global Nest Journal 22(3):342-47 (2020).

[13] Republic, Czech and Czech Republic, Microstructure Of Geopolymer Materials Based On Fly Ash, 50(4):208-15 (2006).

[14] Hawa, Abideng, Danupon Tonnayopas, and Woraphot Prachasaree, Performance Evaluation and Microstructure Characterization of Metakaolin-Based Geopolymer Containing Oil Palm Ash, The Scientific World Journal (2013). https://doi.org/10.1155/2013/857586

[15] Chen Xu, Andre Sutrisno and Leslie J. Struble, Effects of Calcium on Setting Mechanism of Metakaolin -based Geopolymer, Orcid ID : 0000-0002-6813-2849, 0-2.

[16] Shi, Jinyan, Baoju Liu, Yuanchun Liu, Enliang Wang, Zhihai He, Huijie Xu, and Xiaodong Ren, Preparation and Characterization of Lightweight Aggregate Foamed Geopolymer Concretes Aerated Using Hydrogen Peroxide, Construction and Building Materials 256:119442 (2020). https://doi.org/10.1016/j.conbuildmat.2020.119442

[17] Oyebisi, Solomon, Anthony Ede, Festus Olutoge, and David Omole, Geopolymer Concrete Incorporating Agro-Industrial Wastes: Effects on Mechanical Properties, Microstructural Behaviour and Mineralogical Phases, Construction and Building Materials 256:119390 (2020). https://doi.org/10.1016/j.conbuildmat.2020.119390

[18] Panizza, Matteo, Marco Natali, Enrico Garbin, Vilma Ducman, and Sergio Tamburini, Optimization and Mechanical-Physical Characterization of Geopolymers with Construction and Demolition Waste (CDW) Aggregates for Construction Products, Construction and Building Materials 264:120158 (2020). https://doi.org/10.1016/j.conbuildmat.2020.120158

[19] Shin, S., G. Goh, and C. Lee., Predictions of Compressive Strength of GPC Blended with GGBFS Developed at Varying Temperatures, Construction and Building Materials 206:1-9 (2019). https://doi.org/10.1016/j.conbuildmat.2019.01.181

[20] Thokchom, Suresh, Kalyan Kr Mandal, and Somnath Ghosh., Effect of Si/Al Ratio on Performance of Fly Ash Geopolymers at Elevated Temperature, Arabian Journal for Science and Engineering 37(4):977-89 (2012). https://doi.org/10.1007/s13369-012-0230-5

[21] Rajarajeswari, A. and G. Dhinakaran., Compressive Strength of GGBFS Based GPC under Thermal Curing, Construction and Building Materials 126:552-59 (2016). https://doi.org/10.1016/j.conbuildmat.2016.09.076

[22] Turner, Louise K. and Frank G. Collins., Carbon Dioxide Equivalent (CO2 -e) Emissions : A Comparison between Geopolymer and OPC Cement Concrete, Construction and Building Materials 43:125-30 (2013). https://doi.org/10.1016/j.conbuildmat.2013.01.023

[23] Wang, Yan Shuai, Yazan Alrefaei, and Jian Guo Dai., Silico-Aluminophosphate and Alkali-Aluminosilicate Geopolymers: A Comparative Review, Frontiers in Materials 6(May 2019):1-17.

[24] Liew, K. M., A. O. Sojobi, and L. W. Zhang.,Green Concrete: Prospects and Challenges, Construction and Building Materials 156:1063-95 (2017). https://doi.org/10.1016/j.conbuildmat.2017.09.008

[25] Jindal, Bharat Bhushan and Rahul Sharma., The Effect of Nanomaterials on Properties of Geopolymers Derived from Industrial By-Products: A State-of-the-Art Review, Construction and Building Materials 252:119028 (2020). https://doi.org/10.1016/j.conbuildmat.2020.119028

[26] Rashad, Alaa M., Effect of Nanoparticles on the Properties of Geopolymer Materials, Magazine of Concrete Research 71(24):1283-1301 (2019). https://doi.org/10.1680/jmacr.18.00289

[27] Vyas, Sameer, Sameer Mohammad, Shilpa Pal, and Neetu Singh., Strength and Durability Performance of Fly Ash Based Geopolymer Concrete Using Nano Silica, International Journal of

Engineering Science Technologies 4(2):1-12 (2020). https://doi.org/10.29121/ijoest.v4.i2.2020.73

[28] Alomayri, Thamer., Experimental Study of the Microstructural and Mechanical Properties of Geopolymer Paste with Nano Material (Al2O3), Journal of Building Engineering 25(February 2019):100788. https://doi.org/10.1016/j.jobe.2019.100788

[29] Duan, Ping, Chunjie Yan, Wenjun Luo, and Wei Zhou., Effects of Adding Nano-TiO2 on Compressive Strength, Drying Shrinkage, Carbonation and Microstructure of Fluidized Bed Fly Ash Based Geopolymer Paste, Construction and Building Materials 106:115-25 (2016). https://doi.org/10.1016/j.conbuildmat.2015.12.095

[30] Rekha, KP and R. Hazeena., Strength and Durability of Fibre Reinforced Geopolymer Concrete, International Journal of Scientific & Engineering Research 5(7):412-16 (2014).

[31] Saranya, P., Praveen Nagarajan, and Aikot Pallikkara Shashikala., Performance Studies on Steel Fiber-Reinforced GGBS-Dolomite Geopolymer Concrete, Journal of Materials in Civil Engineering 33(2):04020447 (2021). https://doi.org/10.1061/(ASCE)MT.1943-5533.0003530

[32] Meng, Qingfei, Chengqing Wu, Hong Hao, Jun Li, Pengtao Wu, Yekai Yang, and Zhongqi Wang, Steel Fibre Reinforced Alkali-Activated Geopolymer Concrete Slabs Subjected to Natural Gas Explosion in Buried Utility Tunnel, Construction and Building Materials 246:118447 (2020). https://doi.org/10.1016/j.conbuildmat.2020.118447

[33] Ganesan, N., Ruby Abraham, and S. Deepa Raj., Durability Characteristics of Steel Fibre Reinforced Geopolymer Concrete, Construction and Building Materials 93:471-76 (2015). https://doi.org/10.1016/j.conbuildmat.2015.06.014

[34] Taveri, Gianmarco, Enrico Bernardo, and Ivo Dlouhy., Mechanical Performance of Glass-Based Geopolymer Matrix Composites Reinforced with Cellulose Fibers, Materials 11(12) (2018).

[35] Chithambar Ganesh, A., M. Muthukannan, M. Dhivya, C. B. Sangeetha, and S. P. Daffodile., Structural Performance of Hybrid Fiber Geopolymer Concrete Beams, IOP Conference Series: Materials Science and Engineering 872(1) (2020). https://doi.org/10.1088/1757-899X/872/1/012155

[36] Selvi, D. Kalai Arul, M. Mariyappan, and P. Sowmiya Devi., Performance of Geopolymer Concrete Using Polypropylene Fiber, (May 2020):3572-79.

[37] Bahador, Amir, Alireza Esparham, and Mohammad Jamshidi., Physical & Mechanical Properties of Fiber Reinforced Metakaolin-Based Geopolymer Concrete, Construction and Building Materials 251:118965(2020). https://doi.org/10.1016/j.conbuildmat.2020.118965

[38] Laskar, Sulaem Musaddiq and Sudip Talukdar., Preparation and Tests for Workability, Compressive and Bond Strength of Ultra-Fine Slag Based Geopolymer as Concrete Repairing Agent, Construction and Building Materials 154(November 2017):176-90. https://doi.org/10.1016/j.conbuildmat.2017.07.187

[39] Deb, Partha Sarathi, Pradip Nath, and Prabir Kumar Sarker., Drying Shrinkage of Slag Blended Fly Ash Geopolymer Concrete Cured at Room Temperature, Procedia Engineering 125:594-600 (2015). https://doi.org/10.1016/j.proeng.2015.11.066

[40] Lee, Wei Hao, Jhi Hao Wang, Yung Chin Ding, and Ta Wui Cheng., A Study on the Characteristics and Microstructures of GGBS/FA Based Geopolymer Paste and Concrete, Construction and Building Materials 211:807-13 (2019). https://doi.org/10.1016/j.conbuildmat.2019.03.291

[41] Hassan, Amer, Mohammed Arif, and M. Shariq., A Review of Properties and Behaviour of Reinforced Geopolymer Concrete Structural Elements- A Clean Technology Option for Sustainable Development, Journal of Cleaner Production 245(October 2020):118762. https://doi.org/10.1016/j.jclepro.2019.118762

[42] Arbi, Kamel, Marija Nedeljković, Yibing Zuo, and Guang Ye., A Review on the Durability of Alkali-Activated Fly Ash/Slag Systems: Advances, Issues, and Perspectives, Industrial and Engineering Chemistry Research 55(19):5439-53 (2016). https://doi.org/10.1021/acs.iecr.6b00559

[43] Mahmood, Aziz Hasan., Development of a High-Density Geopolymer Concrete for Coastal Protection Applications, (September 2019).

[44] Fan, Fenghong, Zhen Liu, Guoji Xu, Hui Peng, and C. S. Cai., Mechanical and Thermal Properties of Fly Ash Based Geopolymers, Construction and Building Materials 160:66-81(2018). https://doi.org/10.1016/j.conbuildmat.2017.11.023