The Need for a User Friendly Geopolymer Concrete - Ongoing research

Sherin Khadeeja Rahman [1] and Dr. Riyadh Al-Ameri [2]
[1]Ph.D candidate, School of Engineering, Deakin University, Victoria, Australia
[2]Senior Lecturer, School of Engineering, Deakin University, Victoria, Australia

Abstract: The quest for sustainable construction materials is always of great interest amongst the civil engineering professionals and the researchers. One of the major research outcomes in the field of sustainable construction materials is the development of geopolymer concrete. Initially, developed as a fire-resistant ceramic material, the now commonly known geopolymer concrete has found its way into construction industry as a potential substitute for the conventional Portland cement (OPC) concrete. Despite, high durability, high strength, and high resistance to chemical attacks the geopolymer concrete is not widely used majorly due to the requirement of high amount of chemical activators and need of heat curing systems unlike the ordinary cement concrete. This study conducts a comprehensive review of the research developments in production of a user-friendly geopolymer concrete. A user-friendly geopolymer concrete is a sustainable concrete which can be produced in the construction site in a safe manner by using less amount of chemicals and can be cured under ambient conditions without any requirement of additional sources of energy or resources. The adoption of a production method like that of OPC is ought to bring more acceptance for the geopolymer concrete since it primarily makes use of sustainable and recycled waste products as material constituents. This comprehensive review will contribute to compiling the various design mixes available for production of sustainable geopolymer concrete in a user- friendly and less material and energy intensive manner.

Keywords: Geopolymer Concrete, alkali activator, ambient curing, durability.

1. Introduction

Over the last decade, there has been an increased interest in research on sustainable construction materials with major focus on finding alternatives for conventional cementitious materials(Hasnaoui, Ghorbel and Wardeh, 2021). The negative impact of production and usage of conventional Portland cement and concrete in terms of increased carbon emissions and increased consumption of non-renewable raw materials is of greater concern to people in the construction industry(Liew, Sojobi and Zhang, 2017).A wise way to overcome these threats posed to the environment is to find sustainable cementitious materials which shall reduce the consumption of non-renewable resources having lower carbon footprint(Van Deventer, Provis and Duxson, 2012). The geopolymer concrete is one such sustainable cementitious material that is developed and being continually researched in the recent years(Davidovits, 2013; Mohajerani , 2019).The development of geopolymer materials is attributed to material scientist Davidovits(Davidovits, 2013; Kashani, Ngo and Mendis, 2019; Concrete *et al.*, 2020; Rahman and Al-Ameri, 2021) when his research on fire resistant materials resulted in the development of aluminosilicate inorganic polymer generated by the condensation polymerization of minerals like metakaolin in the presence of highly alkaline chemicals in the early 1990s. The research on geopolymer materials has since then progressed, with geopolymer materials finding applications in the field of fire-resistant ceramics, cements and concretes, fiberglass composites, aeronautic tooling and so on(Davidovits, 1991, 2013). In recent years, the civil engineering researchers have identified the potential of geopolymer cement and concrete to address the issues of Portland cement and a vast amount of research is being carried out in developing an industry ready geopolymer cement and concrete. Some of the industries like Wagner's, Zeobond, ROCLA, have developed geopolymer concrete mixes which completely replaces the use of ordinary Portland cement for construction purposes(Van Deventer, Provis and Duxson, 2012).

2. Geopolymer Concrete

The geopolymer concrete is a type of sustainable concrete made by reacting raw materials containing aluminosilicate compounds with high alkali containing chemicals in the presence of water to form a cementitious binder material that act similar to the conventional Ordinary Portland Cement concrete (Mohajerani et al., 2019). The initial research on geopolymer concrete was carried out using natural pozzolanic binders and metakaolin(Davidovits, 1991, 2013) in an attempt to develop a fire resistant material. It was found that unlike the conventional concrete, the geopolymer concrete when cured under heat conditions formed a fire-resistant concrete-like material leading to the development of third-generation concrete known as the geopolymer concrete(Davidovits, 1991; Zhuang *et al.*, 2016; Azad and Samarakoon, 2021). The ability to use any alumina silicate rich material as raw material has created increased amongst concrete researchers leading to the adoption of industry waste products as binder materials. Thus, adopting geopolymer concrete is found to sustainable owing to the use of recycled waste materials, resulting in lowered carbon emissions, embodied energy and greenhouse gas potential(Part, Ramli and Cheah, 2015; Liew, Sojobi and Zhang, 2017; Shehata, Sayed and Abdelkareem, 2021).

2.1 Raw Materials for Geopolymer Concrete

The comprehensive review of literature points out that the geopolymer concrete production can incorporate a wide range of raw materials as binder materials given, they provide rich source of alumina silicate (Hardjito *et al.*, 2003).The major raw materials that find application in geopolymer concrete owing to the superior properties are fly ash, slag, rice husk ash, metakaolin, ferro slag , natural clay compounds(Van Deventer, Provis and Duxson, 2012; Singh *et al.*, 2015) . These are either naturally occurring resources or combustion products from various industries(Xu and Shi, 2018; Shehata, Sayed and Abdelkareem, 2021). These precursory materials are used as single binder material or as a combination of various sources of alumina silicate sources to prepare different mixes of geopolymer concrete creating different possible mixes of the geopolymer concrete(Hardjito *et al.*, 2003; Van Deventer, Provis and Duxson, 2012). The different sources of waste products that find application as binder materials in geopolymer concrete is shown in the figure 1 below:

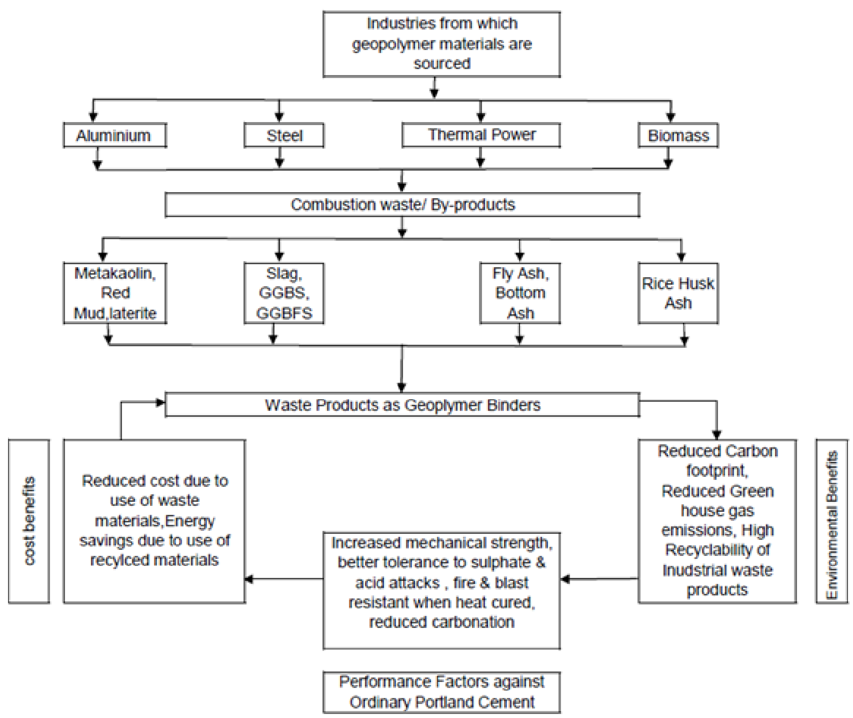
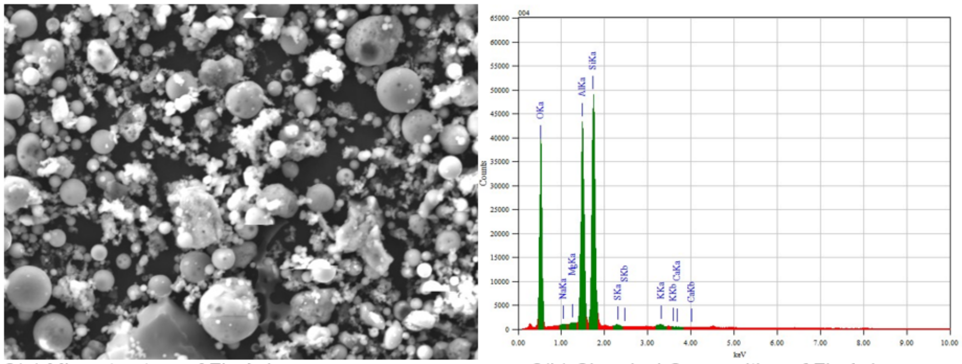


Figure 1. Various sources of binder materials used in Geopolymer Concrete

The benefits of using the two most common geopolymer binders namely fly ash and slag are discussed in the following sections:

2.1.1 Fly Ash

Fly ash is the industrial combustion by-product of coal powered plants and are pozzolanic materials containing high amount of calcium and silica(Lloyd and Rangan, 2009). The calcium composition of fly ash is a governing factor of the geopolymer concrete since a higher calcium content would reduce its compressive strength(Diaz, Allouche and Eklund, 2010).Thus, based on the calcium content ASTM C618 classifies fly ash based into low calcium containing Class F –Fly Ash and high calcium containing Class C Fly ash(Chopra, Siddique and Kunal, 2015; Xu and Shi, 2018). Class F fly ash hence, finds more applications in the geopolymer concrete production offering improved strength , microstructure and other mechanical properties (Singh *et al.*, 2015; Concrete *et al.*, 2020).However, the use of class F fly ash is found to require heat curing conditions and has increased the setting time creating a need to include calcium rich alternative which will not affect the strength properties. Thus the researchers focused on using calcium rich slag for improving the setting based properties of geopolymer concrete (Liew, Sojobi and Zhang, 2017; Xu and Shi, 2018; Concrete *et al.*, 2020). The figure 2 below shows the composition and microstructure of Class F fly ash being used in the Deakin University by the authors.

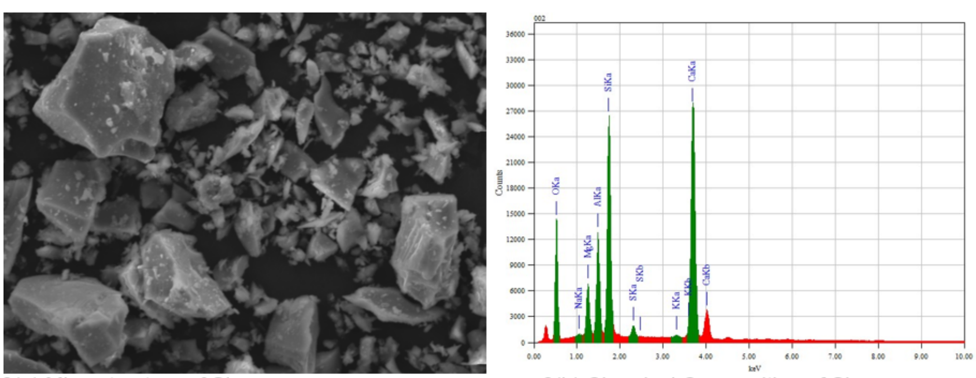


2(a) Microstructure of Fly Ash 2(b) Chemical Composition of Fly Ash

Figure 2. Microstructure & chemical composition of Fly Ash

2.1.2 Slag

The requirement of high temperature for curing of fly ash-based concrete has led to search of other sources of binder materials. Slag is the waste produced during smelting of ores and is high in calcium content. The use of slag in has reduced the setting time and increase the mechanical properties(Patel and Shah, 2018; Nagajothi and Elavenil, 2020). The slag grind down to smaller particles called as ground granulated blast furnace slag along with fly ash is found to increase the compressive, split tensile and flexural strength of by the researchers(Sandanayake *et al.*, 2018; Azad and Samarakoon, 2021; Zakka, Abdul Shukor Lim and Chau Khun, 2021). Thus, slag is nowadays being considered as a binder material used along with fly ash to produce high strength geopolymer concrete(Kashani, Ngo and Mendis, 2019; Concrete *et al.*, 2020; Rahman and Al-Ameri, 2021). The figure 3 below shows the composition and microstructure of Slag used in the Deakin University by the authors for developing a new geopolymer concrete mix.



3(a) Microstructure of Slag 3(b) Chemical Composition of Slag

Figure 3. Microstructure & chemical composition of Slag

2.2 Alkali Activator

The above-mentioned binder materials are unreactive powders in the original state similar to the conventional Portland cement and requires strong alkali reagents to perform geopolymerisation (Davidovits, 1991; Razak, Zainal and Shamsudin, 2020; Dhasindrakrishna *et al.*, 2021). These chemicals referred to as alkali activators are found in solid or liquid forms are used as a combination of hydroxides of sodium and/or potassium or silicates of sodium and/or potassium(Nematollahi, Sanjayan and Shaikh, 2015; Phoo-Ngernkham *et al.*, 2015; Tennakoon *et al.*, 2016). However, an addition of superplasticers to the alkali-activators aids in better workability of the geopolymer concrete mixes(Chopra, Siddique and Kunal, 2015; Tennakoon *et al.*, 2016; Razak, Zainal and Shamsudin, 2020). When a geopolymer is made using liquid form of activator it is referred to as two-part geopolymer concrete and for geopolymer containing solid forms of activator are the one-part geopolymers. A depiction of the two types of geopolymer mixes available and their pros and cons is depicted in the figure 4 below:

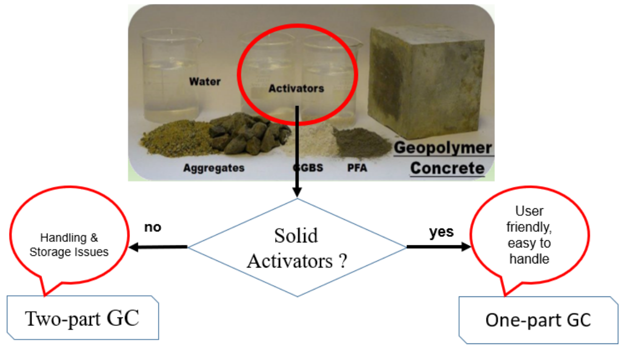


Figure 4. Two-Part & One-Part Geopolymer Concrete

2.2.1 Two-part and One-part Geopolymer concrete

The alkali activators when added in solid and liquid forms are found to have significant effects on the properties of the geopolymer concrete with respect to the mixing and curing regimes(Nematollahi, Sanjayan and Shaikh, 2015; Askarian *et al.*, 2019).Like depicted in the figure , the use of two-part geopolymer concrete involves alkali activator solution that needs to be prepared prior to the geopolymer concrete mixing. This causes handling and storge issue because of its strong alkaline properties limiting worksite practicality (Adesanya *et al.*, 2018; Luukkonen *et al.*, 2018).Also, the requirement of additional water is found to change the molar concentrations of the activator leading to faiure of the mix(Nematollahi, Sanjayan and Shaikh, 2015; Askarian *et al.*, 2019; Kashani, Ngo and Mendis, 2019). Thus two-part mixes is considered to pose danger and hazard at workplace and construction sites(Luukkonen *et al.*, 2018; Askarian *et al.*, 2019).
However, considering the sustainabe aspects of geopolymer concrete it is essential to find a alternate solution for using alkali activators in a safe manner(Luukkonen *et al.*, 2018). Thus, one-part geopolymer concrete was developed which makes use of dry form of activators like anhydrous sodium silicate, anhy.sodium metasilicate, potassium silicate, sodium silicate(Kashani, Ngo and Mendis, 2019; Rahman and Al-Ameri, 2021). This type of geopolymer concrete can be produced very similar to the OPC concrete where the dry ingredients are mixed along with the additon of required water based on water/bindr ratio. of purposes(Askarian *et al.*, 2019; Rahman and Al-Ameri, 2021). Thus, one part geopolymers are considered as a user-friendly option replacing the need to store and handle highly corrosive alkali solutions(Kashani, Ngo and Mendis, 2019; Concrete *et al.*, 2020). M.Askarian et.al. 2019 reports that when solid activators like sodium silicate /calcium hydroxide /lithium hydroxide were combined with fly ash and slag the geopolymer concrete achieved a compressive strength of 38MPa under ambient conditions(Askarian *et al.*, 2019). This was confirmed by the authors in their study were one-part geopolymer concrete made using single solid activator cured under ambient conditions reported a compressive strength of 40MPa(Rahman and Al-Ameri, 2021).

2.3 Curing Conditions

The geopolymer concrete is considered superior to the conventional concrete in terms of their inherent fire resistance(Nematollahi, Sanjayan and Shaikh, 2015; Tennakoon *et al.*, 2016). Thus, geopolymer concrete has an endothermic curing process unlike the conventional exothermal curing of OPC(Davidovits, 1991; Zhuang *et al.*, 2016). Also, studies report that under heat cured conditions geopolymer concrete attains strength equivalent to the 28day values in just 3 days of curing(Singh *et al.*, 2015; Al-Majidi *et al.*, 2016; Nagajothi and Elavenil, 2020). Thus, unlike the conventional concrete most of the studies on geopolymer concrete focused on heat curing methods(Chen *et al.*, 2021; Dhasindrakrishna *et al.*, 2021). However, this method is found to be energy intensive and limits the in-situ application of the product. Also, the heat curing process below 60^0C is found to decrease the compressive strength and create materials shrinkage cracks creating a requirement for additional equipment for heat curing regime which may affect the cost factor of the geopolymer concrete production(Singh *et al.*, 2015; Nagajothi and Elavenil, 2020).Some studies also reports negative effect on material and strength properties owing to rapid curing which called for a rest day of 24 hour ambient curing prior to heat curing for better results(Lloyd and Rangan, 2009;

Singh *et al.*, 2015).Furthermore, the heat curing process is limited to a prefabrication facilities and lab environments and there is a need to research efficient method of curing under ambient conditions which can be adopted by the industries(Mohajerani *et al.*, 2019; Tao and Pan, 2019; Shehata, Sayed and Abdelkareem, 2021).

The studies on ambient cured geopolymer can be attributed to the research by Hardjito et.al which report that the strength of geopolymer concrete does not vary much with age and curing conditions (Hardjito *et al.*, 2003, 2004).It is reported that ambient cured geopolymer concrete can attain comparable compressive strengths similar to that of the conventional OPC concrete however, report lower tensile and flexural strengths(Zannerni, Fattah and Al-Tamimi, 2020).But further studies, on changing the mix ratios of fly ash/slag and similar binders reports improvement in the properties reporting a new type of less energy intensive curing technique(Singh *et al.*, 2015; Patel and Shah, 2018; Zannerni, Fattah and Al-Tamimi, 2020).Despite, studies on the ambient cured geopolymer concrete, most of the geopolymer concrete applications are limited to the prefabrication industry. A reason for this can be due to the challenges in sourcing best performing activator and lack of knowledge and studies on the development of ambient cured mixes(Kashani, Ngo and Mendis, 2019; Mohajerani *et al.*, 2019; Zannerni, Fattah and Al-Tamimi, 2020). best

2.4 Geopolymer Concrete - Benefits & Challenges

The successful use of a newly developed product in any industry is highly dependent on its benefits and challenges of the application of the product. In the case of geopolymer concrete, as widely acclaimed it is a sustainable alternative in comparison to the conventionally used Portland cement. However, the need of alkali activators, heat or different curing conditions and a wide range of raw materials can pose a threat to them widespread use of the geopolymer concrete in the construction industry. The following sections reviews the benefits and challenges in using the geopolymer concrete.

2.4.1 Benefits of using Geopolymer Concrete

The use of geopolymer concrete is found to bring down the carbon emissions by 80% per tonne in comparison to that of Ordinary Portland Cement(Shehata, Sayed and Abdelkareem, 2021). Further, the use of industrial combustion products for binder materials has resulted in reduction of need for virgin raw materials leading to development of green concrete (Hardjito *et al.*, 2003; Part, Ramli and Cheah, 2015).This has also led to the reduction in the cost of procuring raw materials reducing overall cost for up to 30% by complete replacement of OPC(Chau *et al.*, 2017; Shehata, Sayed and Abdelkareem, 2021). The use of geopolymer concrete is found to meet the green building standards achieving sustainability goals and direct reduction of global warming potential(Lloyd and Rangan, 2009; Azad and Samarakoon, 2021).The geopolymer concrete indirectly adopts circular economy approach were the wastes are brought back into the ecosystem in the form of sustainable construction materials(Liew, Sojobi and Zhang, 2017; Shehata, Sayed and Abdelkareem, 2021). The summary of benefits of using the geopolymer concrete in comparison to the ordinary Portland cement (OPC) is depicted in figure 5 below:

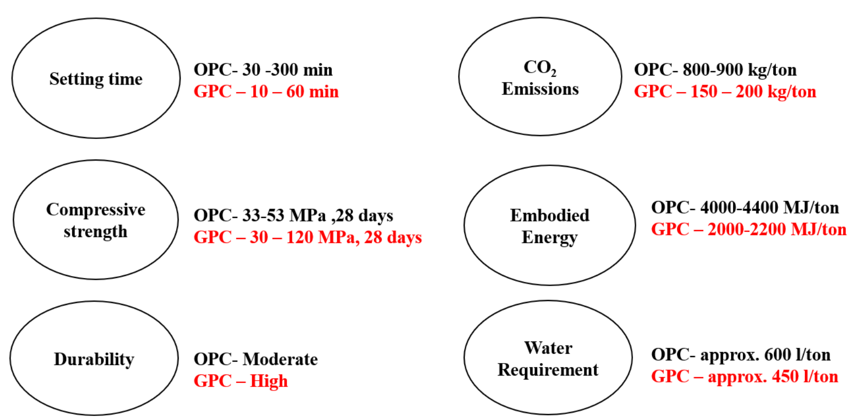


Figure 5. Benefits of Geopolymer concrete vs Ordinary Portland Cement

2.4.2 Challenges of using Geopolymer Concrete

Even though, geopolymer concrete is a sustainable alternative to the problems caused by the conventional concrete, the use of alkali activator chemicals is a major disadvantage(Part, Ramli and Cheah, 2015; Shehata, Sayed and Abdelkareem, 2021). Majority of the mixes developed till date uses one-or more activators increasing the hazard potential of the geopolymer concrete(Van Deventer, Provis and Duxson, 2012). The activator also proves to be the costly component in the production of geopolymer concrete(Xu and Shi, 2018). There is a need for more studies on the reduction of chemical usage leading to reduced costs and better environmental impact. Even though geopolymer concrete is in the industry for past two decades, there is very limited knowledge on the durability of geopolymer concrete over long term exposure conditions. It is also, reported that under harsh environments, the formation of slat leading to efflorescence is disadvantageous to some of the geopolymer concrete mixes(Xu and Shi, 2018; Shehata, Sayed and Abdelkareem, 2021). Again, for heat cured geopolymers the cost component is high and requires heating conditions limiting the widespread application(Singh *et al.*, 2015).

2.5 Construction friendly Geopolymer Concrete – an ongoing research

It is understood from the literature that a geopolymer concrete which can be produced under in-situ conditions is a need of the hour(Azad and Samarakoon, 2021; Shehata, Sayed and Abdelkareem, 2021). An ongoing study on developing construction friendly geopolymer concrete by the authors reports a new mix of ambient cured geopolymer concrete offering self-compacting properties without using superplasticers or Ordinary Portland cement. The new geopolymer concrete which can be cured under ambient conditions uses only 10% of the binder content as the alkali activator reducing the usage of additional chemicals(Rahman and Al-Ameri, 2021). This mix called as the self-compacting geopolymer concrete (SCGC) is a flowable concrete which does not require any vibrators for placing and casting activities. The mix containing Fly Ash, Slag and micro fly ash as binder materials offers 40 MPa compressive strength after 28 days of curing under room conditions. The mix also developed after conducting experimental trials on several combination of trial mixes offers the following properties(Rahman and Al-Ameri, 2021):

Table 1. Properties of Self Compacting Geopolymer Concrete

Properties of Self-Compacting Geopolymer Concrete	**Workability**			Initial Setting Time (minutes)	Final Setting Time (minutes)	**Strength (MPa)**	
	Slump Flow (mm)	T_{500} (Seconds)	J ring (mm)			Compressive Strength	Tensile Strength
	700	4.34	7	140	530	40	3

Even though, the new mix offered promising results, to ensure the full-scale application it is important to assess the long-term strength and durability properties of the mix. Identifying this need an ongoing experimental study on long term properties of SCGC cylinders and beams exposed to harsh marine environment by using aging tanks is planned to be conducted at Deakin University. The use of aging tanks containing salt water will simulate the marine exposure and the tidal conditions are achieved by alternating 6hr. wet and 6 hr. dry cycles for a period of 12 months. This study will help in understanding the overall material properties including material damage, chemical ingress, loss of mass, strength (compressive, flexural, tensile) reduction and other durability parameters. An extended study of SCGC reinforced with Basalt FRP bars to be used in reinforced structures is also being investigated to address the corrosion issues of the conventional steel reinforced structures. The initial studies on the bond strength by pull-out tests shows that the Basalt FRP bar reinforced SCGC specimens gave 72% bond strength of that of the steel bar reinforced specimens. This shows promising application of the new mix as sustainable corrosion free alternative to the conventional reinforced structures. However, a conclusive observation can be made only after observing the long-term properties of the new mix.

The current study shows that the use of newly developed self-compacting geopolymer offers a user -friendly mix with the following benefits:

- Zero use of cement and superplasticers
- Made of recycled industrial combustion products as binders reducing the carbon footprint and greenhouse gas emissions.
- Use of one type of solid alkali activator (anhydrous sodium metasilicate).
- Reduced usage of chemicals by limiting alkali activator dosage to 10%.
- Offers self-compacting and flowability properties avoiding the use of vibrators.

- Offers similar mixing procedure reducing the need of skilled labourers or expert knowledge.
- Reduced use of water by eliminating water curing.

3. Conclusion

This paper provides a comprehensive summary of the research on the benefits and challenges of the various geopolymer concrete mixes available with respect to the raw materials, activators and curing regimes. The research also reports the development of new self-compacting geopolymer concrete mix, which is found to be user friendly, sustainable and can replace the conventional OPC. The new mix reports lesser use of chemicals, zero superplasticisers and less water usage. However, a successful implementation of geopolymer concrete in the construction industry will require extensive knowledge of its long-term properties in various environments warranting more studies on successful selection of precursor, optimized alkali content, curing time for adopting the best suited mix of geopolymer concrete.

4. References

1. Adesanya, E. *et al.* (2018) 'One-part geopolymer cement from slag and pretreated paper sludge', *Journal of Cleaner Production*. Elsevier, 185, pp. 168–175.
2. Al-Majidi, M. H. *et al.* (2016) 'Development of geopolymer mortar under ambient temperature for in situ applications', *Construction and Building Materials*, 120, pp. 198–211. doi: https://doi.org/10.1016/j.conbuildmat.2016.05.085.
3. Askarian, M. *et al.* (2019) 'Mix composition and characterisation of one-part geopolymers with different activators', *Construction and Building Materials*. Elsevier, 225, pp. 526–537.
4. Azad, N. M. and Samarakoon, S. M. S. M. K. (2021) 'Utilization of industrial by-products/waste to manufacture geopolymer cement/concrete', *Sustainability (Switzerland)*, 13(2), pp. 1–22. doi: 10.3390/su13020873.
5. Chau, C. K. *et al.* (2017) 'Assessment of CO2 Emissions Reduction in High-Rise Concrete Office Buildings Using Different Material-Use Options', *Handbook of Low Carbon Concrete*, pp. 39–61. doi: 10.1016/B978-0-12-804524-4.00003-8.
6. Chen, K. *et al.* (2021) 'Geopolymer concrete durability subjected to aggressive environments – A review of influence factors and comparison with ordinary Portland cement', *Construction and Building Materials*. Elsevier Ltd, 279, p. 122496. doi: 10.1016/j.conbuildmat.2021.122496.
7. Chopra, D., Siddique, R. and Kunal (2015) 'Strength, permeability and microstructure of self-compacting concrete containing rice husk ash', *Biosystems Engineering*. doi: 10.1016/j.biosystemseng.2014.12.005.
8. Concrete, E. G. *et al.* (2020) 'A Review of Recent Developments and Advances in'.
9. Davidovits, J. (1991) 'Geopolymers - Inorganic polymeric new materials', *Journal of Thermal Analysis*, 37(8), pp. 1633–1656. doi: 10.1007/BF01912193.
10. Davidovits, J. (2013) 'Eopolymer ement', *Institut Geopolymer*, (0), pp. 1–11.
11. Van Deventer, J. S. J., Provis, J. L. and Duxson, P. (2012) 'Technical and commercial progress in the adoption of geopolymer cement', *Minerals Engineering*. Elsevier Ltd, 29, pp. 89–104. doi: 10.1016/j.mineng.2011.09.009.
12. Dhasindrakrishna, K. *et al.* (2021) 'Progress, current thinking and challenges in geopolymer foam concrete technology', *Cement and Concrete Composites*. Elsevier Ltd, 116(November 2020), p. 103886. doi: 10.1016/j.cemconcomp.2020.103886.
13. Diaz, E. I., Allouche, E. N. and Eklund, S. (2010) 'Factors affecting the suitability of fly ash as source material for geopolymers', *Fuel*. Elsevier Ltd, 89(5), pp. 992–996. doi: 10.1016/j.fuel.2009.09.012.
14. Hardjito, D. *et al.* (2003) 'Geopolymer concrete: turn waste into environmentally friendly concrete', *International Conference on Recent Trends in Concrete Technology and Structures (INCONTEST)*, (January 2015), pp. 10–11.
15. Hardjito, D. *et al.* (2004) 'On the development of fly ash-based geopolymer concrete', *ACI Materials Journal*, 101(6), pp. 467–472. doi: 10.14359/13485.
16. Hasnaoui, A., Ghorbel, E. and Wardeh, G. (2021) 'Effect of Curing Conditions on the Performance of Geopolymer Concrete Based on Granulated Blast Furnace Slag and Metakaolin', *Journal of Materials in Civil Engineering*, 33(3), p. 04020501. doi: 10.1061/(asce)mt.1943-5533.0003606.
17. Kashani, A., Ngo, T. D. and Mendis, P. (2019) 'The effects of precursors on rheology and self-compactness of geopolymer concrete', *Magazine of Concrete Research*. doi: 10.1680/jmacr.17.00495.

18. Liew, K. M., Sojobi, A. O. and Zhang, L. W. (2017) 'Green concrete: Prospects and challenges', *Construction and Building Materials*. Elsevier Ltd, 156, pp. 1063–1095. doi: 10.1016/j.conbuildmat.2017.09.008.
19. Lloyd, N. and Rangan, V. (2009) 'Geopolymer concrete - Sustainable cementless concrete', *American Concrete Institute, ACI Special Publication*, (261 SP), pp. 33–53.
20. Luukkonen, T. *et al.* (2018) 'One-part alkali-activated materials: A review', *Cement and Concrete Research*. Elsevier, 103, pp. 21–34.
21. Mohajerani, A. *et al.* (2019) 'Recycling waste materials in geopolymer concrete', *Clean Technologies and Environmental Policy*. Springer Berlin Heidelberg, 21(3), pp. 493–515. doi: 10.1007/s10098-018-01660-2.
22. Nagajothi, S. and Elavenil, S. (2020) 'Effect of GGBS Addition on Reactivity and Microstructure Properties of Ambient Cured Fly Ash Based Geopolymer Concrete', *Silicon*. Silicon. doi: 10.1007/s12633-020-00470-w.
23. Nematollahi, B., Sanjayan, J. and Shaikh, F. U. A. (2015) 'Synthesis of heat and ambient cured one-part geopolymer mixes with different grades of sodium silicate', *Ceramics International*. Elsevier, 41(4), pp. 5696–5704.
24. Part, W. K., Ramli, M. and Cheah, C. B. (2015) 'An overview on the influence of various factors on the properties of geopolymer concrete derived from industrial by-products', *Construction and Building Materials*. Elsevier Ltd, 77, pp. 370–395. doi: 10.1016/j.conbuildmat.2014.12.065.
25. Patel, Y. J. and Shah, N. (2018) 'Development of self-compacting geopolymer concrete as a sustainable construction material', *Sustainable Environment Research*. doi: 10.1016/j.serj.2018.08.004.
26. Phoo-Ngernkham, T. *et al.* (2015) 'Effects of sodium hydroxide and sodium silicate solutions on compressive and shear bond strengths of FA-GBFS geopolymer', *Construction and Building Materials*. Elsevier Ltd, 91, pp. 1–8. doi: 10.1016/j.conbuildmat.2015.05.001.
27. Rahman, S. K. and Al-Ameri, R. (2021) 'A newly developed self-compacting geopolymer concrete under ambient condition', *Construction and Building Materials*, 267. doi: 10.1016/j.conbuildmat.2020.121822.
28. Razak, S. A. A., Zainal, F. F. and Shamsudin, S. R. (2020) 'Effect physical and mechanical properties of fly ash-based geopolymers on corrosion reinforcement bar: A review', *AIP Conference Proceedings*, 2291(November). doi: 10.1063/5.0023113.
29. Sandanayake, M. *et al.* (2018) 'Greenhouse gas emissions of different fly ash based geopolymer concretes in building construction', *Journal of Cleaner Production*. Elsevier Ltd, 204, pp. 399–408. doi: 10.1016/j.jclepro.2018.08.311.
30. Shehata, N., Sayed, E. T. and Abdelkareem, M. A. (2021) 'Recent progress in environmentally friendly geopolymers: A review', *Science of the Total Environment*. Elsevier B.V., 762, p. 143166. doi: 10.1016/j.scitotenv.2020.143166.
31. Singh, B. *et al.* (2015) 'Geopolymer concrete: A review of some recent developments', *Construction and Building Materials*. Elsevier Ltd, 85, pp. 78–90. doi: 10.1016/j.conbuildmat.2015.03.036.
32. Tao, Z. and Pan, Z. (2019) 'Geopolymer Concrete At Ambient and Elevated Temperatures: Recent Developments and Challenges', *NED University Journal of Research*, 2(Special Issue on First SACEE'19), pp. 113–128. doi: 10.35453/nedjr-stmech-2019-0007.
33. Tennakoon, C. *et al.* (2016) 'Thermal effects of activators on the setting time and rate of workability loss of geopolymers', *Ceramics International*. Elsevier, 42(16), pp. 19257–19268.
34. Xu, G. and Shi, X. (2018) 'Characteristics and applications of fly ash as a sustainable construction material: A state-of-the-art review', *Resources, Conservation and Recycling*. Elsevier, 136(August 2017), pp. 95–109. doi: 10.1016/j.resconrec.2018.04.010.
35. Zakka, W. P., Abdul Shukor Lim, N. H. and Chau Khun, M. (2021) 'A scientometric review of geopolymer concrete', *Journal of Cleaner Production*. Elsevier Ltd, 280, p. 124353. doi: 10.1016/j.jclepro.2020.124353.
36. Zannerni, G. M., Fattah, K. P. and Al-Tamimi, A. K. (2020) 'Ambient-cured geopolymer concrete with single alkali activator', *Sustainable Materials and Technologies*, 23. doi: 10.1016/j.susmat.2019.e00131.
37. Zhuang, X. Y. *et al.* (2016) 'Fly ash-based geopolymer: Clean production, properties and applications', *Journal of Cleaner Production*. Elsevier Ltd, 125, pp. 253–267. doi: 10.1016/j.jclepro.2016.03.019.