Optimizing Mix Proportion of Geopolymer Concrete with Steel Sludge - A Sustainable Approach

M. Selvakumar[1], *S*. Geetha[1*], *Janahar* C[2], *Lakshmi* Krishnan S[2], *Rohith* Kumar R[2]

[1]Professor, Rajalakshmi Engineering College, Chennai, 602105 India
[2]UG Students, Rajalakshmi Engineering College, Chennai, 602105 India

Abstract. As the construction industry is moving towards sustainable infrastructure, the need for green construction materials has gained importance in current scenario. Geopolymer concrete is considered to be an alternate to conventional concrete with cement as cement production is considered to emit more greenhouse gases into the atmosphere. This work has still raised the sustainable part of the geopolymer concrete by using steel sludge generated from automobile industry as partial replacement for fine aggregate. The experimental results were designed using fractional factorial design. The results were analysed for statistical integrity with ANOVA. It has been observed that the maximum compressive strength achieved with steel sludge up to 30% replacement is 48 Mpa with flexural strength of 5.16 Mpa and split tensile strength of 4.6 Mpa. Optimisation was done to find the proportion that gives maximum strength and it was ascertained with experimental validation. XRD and SEM analysis were carried out for studying the microstructure and reaction products formed in the process.

Key words- alkali activation; strength; optimisation; durability; polymerisation

1 Introduction

Cement manufacturing result in emission of high amount of greenhouse gases into the environment. [1,2]. For the production of one ton of cement about 0.87 ton of CO_2 and 3 kg of NO is emitted along with 2 tons of shale & limestone being consumed [3]. However, traditional cement production is associated with a significant carbon footprint, contributing approximately 5% to global CO_2 emissions [4,5]. The widespread carbon emissions associated with ordinary Portland cement concrete are adversely impacting the entire ecosystem. Life cycle inventory data of six cement manufacturing plants in India have been investigated recently in order to access the environmental impacts [6]. Due to rapid industrialization in developing countries like India and more construction activities predicted, alternative cementitious materials replacing cement is required. Geopolymer

* Corresponding Author : geetha.s@rajalakshmi.edu.in

(GPC) is an environmentally friendly solution prepared from a mixture of aluminosilicate materials and alkali activated solution which reduces carbon emission [7,8]. Several researchers in recent times have found that GPC can be formed by using various aluminosilicate materials like fly ash (FA), metakaolin (MK), GGBFS, etc. [9,10,11,12]. High strength is achieved when fly ash is used as binder along with sodium silicate and sodium hydroxide for the production of GPC [13,14, 15, 16]. When geopolymer includes a mix of GGBS (Ground Granulated Blast Furnace Slag), it exhibits up to 110% increase in compressive strength compared to traditional concrete. Additionally, the modulus of elasticity in geopolymer concrete surpasses that of OPC (Ordinary Portland Cement) concrete by 5% to 10%. This suggests that geopolymer concrete not only addresses environmental concerns but also offers improved mechanical properties for construction applications [17]. GPC also possess other properties like low thermal conductivity and sound insulation [18]. Geopolymer concrete composites also utilize waste byproducts such as fly ash, a residue from coal power plants. This approach not only prevents the disposal of fly ash, reducing environmental pollution, but also proves cost-effective as fly ash is a waste product [19]. Industrial activities produce various wastes, and among them, slag from iron industries poses a significant environmental threat [20]. Industries that manufacture products from Iron and Steel industries produce Iron slag in huge quantities and for every ton of steel produced 3-4 tons of Iron Slag is generated. The physical properties of iron slag influence both fresh and hardened characteristics of concrete [21]. Researchers are increasingly focusing on utilizing industrial by-products in concrete, as they enhance the properties of blended cement concrete and contribute to reducing environmental issues.

The incorporation of various solid wastes like steel slag and steel sludge as replacements for cement in normal concrete not only improves compressive strength and flexural strength but also facilitates environmental clean-up of hazardous materials and waste disposal concerns [22]. The incorporation of recycled concrete aggregates in aerated geopolymer concrete has increased the initial yield stresses of geopolymer concrete and reduced the defoaming effect [23]. Also waste by-products from steel industry (Steel slag and Iron slag) show significant potential as alternatives to traditional aggregates in concrete up to 30% which improves compressive, flexure and tensile strength [24]. Another study produced geopolymer concrete by using 5% micro silica and 1% waste steel lathe scraps which yielded maximum strength [25]. Replacement of flyash by 15% glass powder and 15% GGBS yielded maximum compressive & split-tensile strength while use of naphthalene based superplasticizer improved both hardened and fresh GPC behaviour [26]. A study found GPC as a good sustainable material since it reduces CO_2 emission by using industrial and agricultural materials like GGBFS, Red mud, silica fume, flyash, sugarcane bagasse, corncob ash and rice-husk ash [27]. GPC in general has been prepared from industrial, municipal and agricultural based waste which can replace the conventional cement concrete [28]. The objective of this paper is to study the strength properties of ambient cured geopolymer concrete with steel sludge as partial replacement of sand.

2 Materials & Methodogy

2.1 Materials

The raw materials used for the production of geopolymer concrete are Si rich material capable of reacting with the alkaline OH for geopolymerization and formation of Si-O-Al bonds which is responsible for the strength gain of the concrete. Class-F flyash procured from North Madras Thermal power plant was used in this study. The curing regime adopted in this work was ambient curing in order to minimise the energy requirement. To facilitate ambient curing ground granulated blast furnace slag (GGBS) which is a by-product from steel industry used as mineral admixture in concrete has been used. The chemical properties of GGBS and fly ash are given in Table-1 which was found using XRF analysis. The alkali activator used in this work is a combination of NaOH and Na_2SiO_3. The molarity of NaOH used is 12M. The ratio of Na_2SiO_3/ NaOH was varied from 0.75 to 1.5. The ratio of alkaline activator/binder was adopted as 0.5. Superplasticiser was used as 0.5% by weight of binder to improve the workability of the concrete.

Table-1. Properties of Fly ash and GGBS

Physical properties	**Class-F fly ash**	**GGBS**
Specific gravity	2.28	2.89
Fineness, (m^2/kg)	287	382
Chemical properties	**% by mass**	**% by mass**
SiO_2	67.4	35.56
CaO	1.52	38.91
Al_2O_3	25.4	18.76
Fe_2O_3	5.12	2.34
MgO	0.3	0.72
Na_2O	0.05	0.44
K_2O	0.02	0.32
SO_3	0.16	1.83
MnO	0.03	1.12
Loss on Ignition, %	1.11	5.12
$SiO_2+Al_2O_3+Fe_2O_3$	97.92	93.42

2.2 Methodology

The experimental investigations were designed using fractional factorial design. Response surface Methodology (RSM) of this design is a tool to analyse the interaction effect of individual factors in influencing the responses. The three variables that were used to design the experimental trails are given in Table 2.

Table 2. The factors and the levels used for experimental runs

Factors	**Units**	**-1 Level**	**+1 Level**
Steel sludge	%	0	30
GGBS	%	10	40
NaOH/Na2SiO3	%	0.75	1.5

Mix design was done using absolute volume method considering the specific gravity of the materials used in the concrete. The particle size distribution of fine aggregate and steel sludge is given in fig.1. The raw materials were mixed in a pan mixer with dry material until the materials are homogenised. Then the alkali activator is used and superplasticiser was added and mixed for 3 to 4 minutes until the mix becomes workable. The fresh concrete was placed in 15 cm cube moulds, prisms of size 10 cm cross section with 50 cm length and cylinder of diameter 10 cm and length of 20 cm. These specimens are as per IS codal specification to test compressive strength, flexural strength and split tensile strength. The moulds were demoulded after 24 hours and exposed to ambient condition facilitating the curing as it is. The samples were cured for 28 days in open air and then tested for strength.

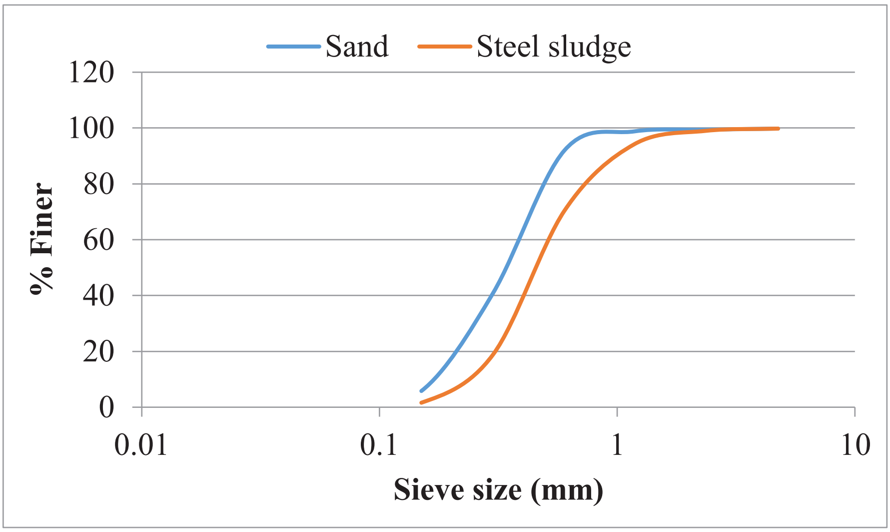

Fig.1. Particle size distribution of sand and steel sludge

3 Results & Discussions

The density of conventional concrete is 2400 kg/m^3 and the geopolymer concrete in this study had density close to conventional concrete. The range of density ranged from 2320 to 2380 kg/m^3. The variation in the density with reference to steel sludge and GGBS is given in fig. 2 and is found to increase as the GGBS and sludge content is increased. A similar attribute was observed with the interaction of alkaline activator and GGBS as given in fig. 3.

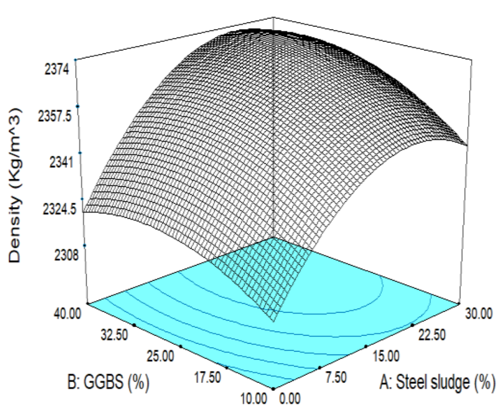

Fig. 2. Variation in Density with steel sludge & GGBS

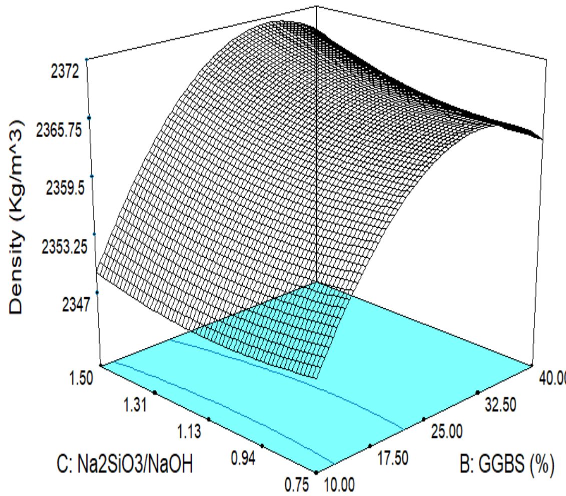

Fig. 3. Variation in Density with GGBS & alkaline solution

The compressive strength of geopolymer concrete was found to increase form 28 Mpa to 46 Mpa with increase in GGBS and steel sludge as given in the response graph of fig. 4. Also as the alkaline activator ratio was increased from 0.75 to 1.5 the compressive strength increased to 45 Mpa as shown in fig.5. This could be attributed to the reactive Si forming strong geopolymer bonds when treated with alkaline activator.

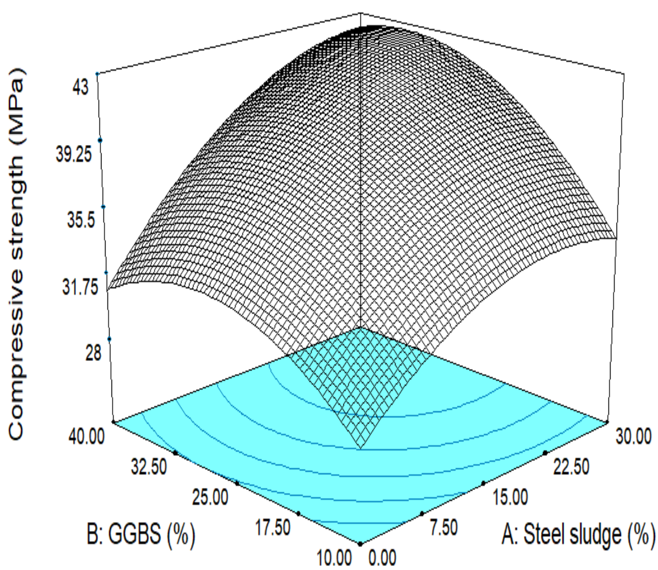

Fig. 4. Variation in Compressive strength with steel sludge & GGBS

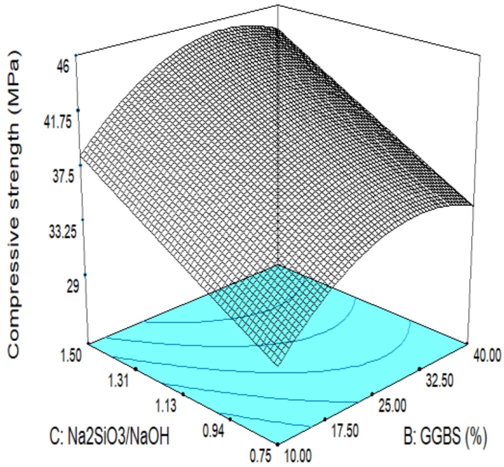

Fig. 5. Variation in Compressive strength with GGBS & alkaline solution

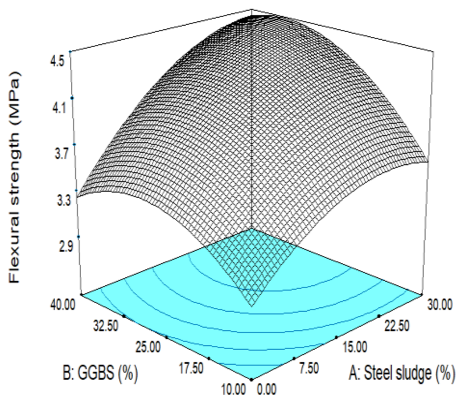

Fig. 6. Variation in flexural strength with steel sludge & GGBS

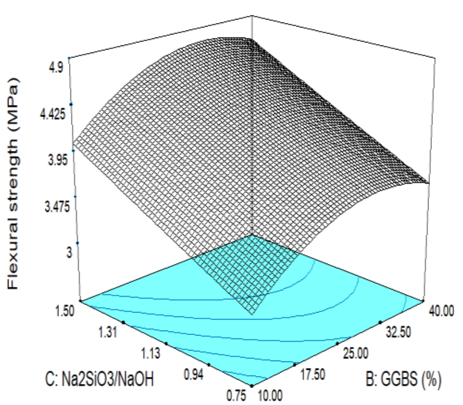

Fig. 7. Variation in flexural strength with GGBS & alkaline solution

The major factor in the entire process is the alkaline activators which consist of metal hydroxides and silicates. These elements react with the silicate rich raw material resulting in the formation of strong 3-dimensional Si-O-Al bonds. As the concentration of alkaline solution increases the interlocking of bonds gets stronger resulting in high strength.
The same trend of increase in flexural strength and split tensile strength was observed as the contents of raw material and alkaline solution was increased. The flexural strength ranged from 2.6 to 4.9 as shown in the response surface graphs given in fig. 6 and fig. 7. And the split tensile strength was found to increase from 2.4 to 4.4 Mpa as given in graphs in fig. 8 and fig. 9.

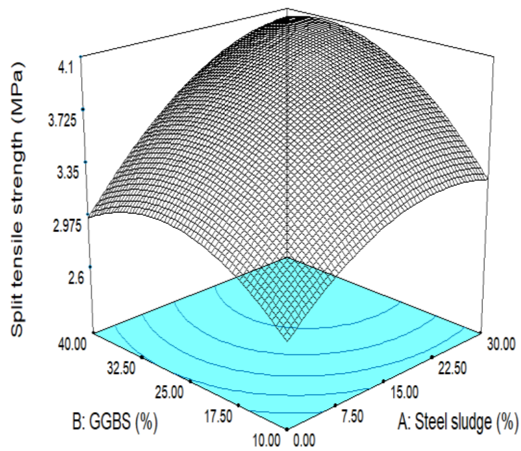

Fig. 8. Variation in split tensile strength with steel sludge & GGBS

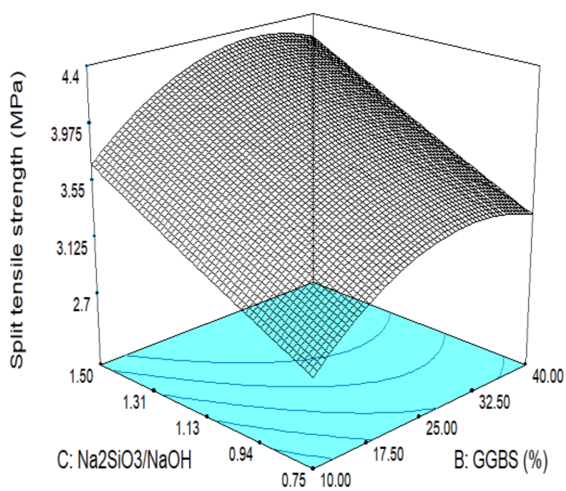

Fig. 9. Variation in split tensile strength with GGBS & alkaline solution

The advantage of using GGBS along with fly ash is that the chemical composition of the materials as given in Table-1 shows that class-F fly ash is rich in Si and GGBS has substantial amount of Ca. The presence of Ca and Si facilitate the formation of CSH and CAH-the hydration products named calcium silicate hydrate and calcium aluminate hydrate contributing to strength enhancement. These hydration products participate in the geopolymerization process as well forming stronger bonds making the interlocking system intact. And as time of curing is increased the strength enhancement is improved as the pozzolanic reaction takes long time.

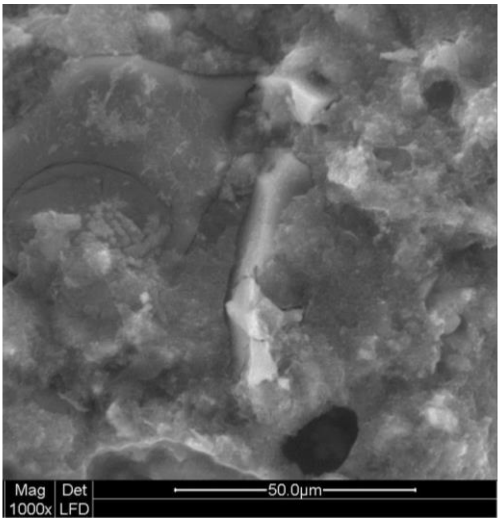

Fig. 10. SEM image with 0.75 alkaline activator

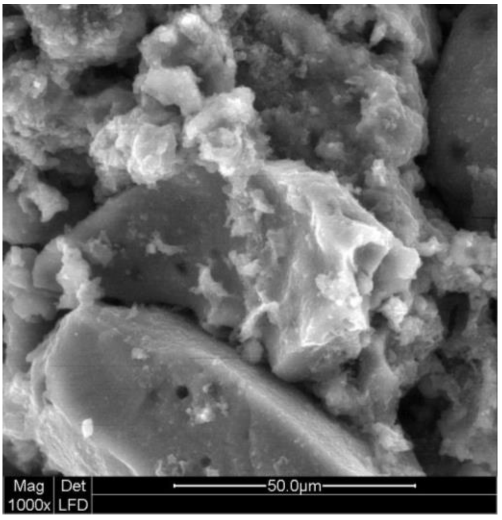

Fig. 11. SEM image with 1.5 alkaline activator

The SEM image was taken on 1 cm cubes of geopolymer concrete at the end of the curing period. The SEM images given in fig-10 and fig-11 for different dosages of alkaline activators have clear polymerised reaction products in the form of gel and crystals of $CaOH_2$. Similarly XRD was taken on powdered samples passing 75 µm sieve. The graph in fig-12 gives the composition of raw flyash and the geopolymer concrete activated with two different activators.

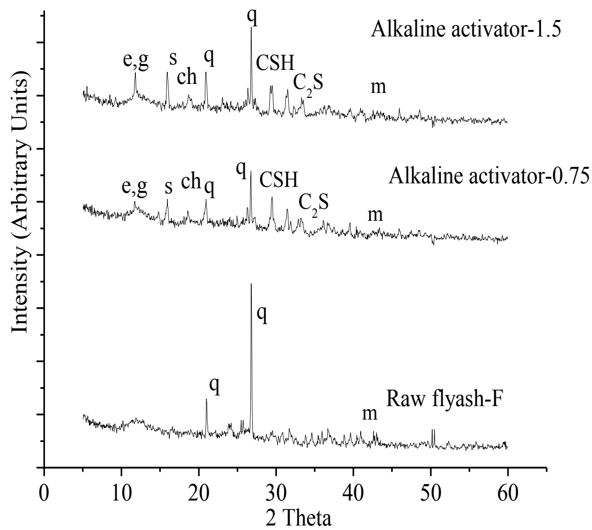

Fig. 12. XRD of raw flyash and geopolymer concrete activated with 0.75 and 1.5 alkaline activators

4 Multiple Optimization

The advantage of using Design expert software to design the trials will facilitate to validate the experimental data and also arrive at the optimised mix ratio considering the desirable parameters. The optimisation was done considering high strength and density. Based on the experimental investigations the optimised mix proportion as given by ANOVA analysis is given in Table-3. Experimental trials were conducted for the proposed mix proportion and the results were compared with the predicted values given by the software. The consolidated predicted and observed values are given in Table-4

Table. 3. Optimised mix ratio

Steel sludge	GGBS	Na2SiO3/NaOH
30	19.53	1.5

Table-4 Results of Optimised mix ratio

	Density (kg/m^3)	Compressive strength (Mpa)	Flexural strength (Mpa)	Split Tensile strength (Mpa)
Predicted	2360.06	44.83	4.71	4.29
Observed	2382.4	42.36	4.48	4.09

5 Conclusion

In Conclusion the results of experimental investigation for this study are summarized as:

- This study shows that steel sludge powder has particle size similar to sand and it can be a potential replacement for the fine aggregate in the production of geopolymer concrete.
- The ambient cured geopolymer concrete has produced strength on par with conventional geopolymer concrete cured in oven thereby proving energy efficient sustainable material.
- The strength increase in terms of compressive, flexural and split tensile is evident that there is a good enhancement due to the addition of steel sludge powder.
- The SEM and XRD results are evident of the reaction products that contribute to the strength improvement.
- Finally, the study reveals that steel sludge as a fine aggregate replacement in geopolymer concrete offers a promising avenue for the construction industry to address environmental concerns.

Acknowledgement: The authors acknowledge the funding received from DST-WMT research project with sanction No: DST/TDT/WM/2019/85

References

1. Fateh Belaid, How does concrete and cement industry transformation contribute to mitigating climate change challenges? RCR Advances. 15, 200084 (2022) DOI:10.1016/j.rcradv.2022.200084
2. Hrvoje Miikulcic, Jiri Jaromir Kleme, Milan Vujanovic, Krzysztof Urbaniec, Neven Duic, Reducing greenhouse gasses emissions by fostering the deployment of alternative raw materials and energy sources in the cleaner cement manufacturing process, J. Clean. Prod. 136(B), 119-132 (2016) DOI:10.1016/j.jclepro.2016.04.145
3. Ahmad L. Almutairi, Bassam A. Tayeh, Adeyemi Adesina, Haytham F. Isleem, Abdullah M. Zeyad, Potential applications of geopolymer concrete in construction: A review., Case Stud. Constr. Mater. 15, e00733 (2021)DOI:10.1016/j.cscm.2021.e00733
4. Tengfang Xu, Tjebbe Galama, Jayant Sathaye, Reducing carbon footprint in cement material making: Characterizing costs of conserved energy and reduced carbon emissions., Sustain. Cities Soc. 9, 54-61 (2013) DOI:10.1016/j.scs.2013.03.002
5. Juan Cagiao, Breixo Gómez, Juan Luis Domenesh, Salvador Gutierrez Mainar, Hortensia Gutierrez Lanza., Calculation of the corporate carbon footprint of the cement industry by the application of MC3 methodology, Ecol. Indic.11(6), 1526-1540 (2011) DOI:10.1016/j.ecolind.2011.02.013
6. Anusha S. Basavaraj, Ravindra Gettu., Primary life cycle inventory data for cement production, with relevance to sustainability assessment–Indian cases., Data Br. 110258 (2024 to be published) DOI:10.1016/j.dib.2024.110258
7. Y.M. Liew, C.Y. Heah, A.B.M. Mustafa, H. Kamarudin, Structure and properties of clay-based geopolymer cements: a review, Prog. Mater. Sci. 83, 595–629 (2016) DOI:10.1016/j.pmatsci.2016.08.002
8. Siba Sankar Chanda, Shyamal Guchhait., A comprehensive review on the factors influencing engineering characteristics of lightweight geopolymer concrete., J. Build. Eng. 108887 (2024 to be published) DOI:10.1016/j.jobe.2024.108887
9. Thong M. Pham, Wensu Chen, Abdul M. Khan, Hong Hao, Mohamed Elchalakani, Tung M. Tran., Dynamic compressive properties of lightweight rubberised geopolymer concrete, Constr. Build. Mater. 238, 117705 (2020) DOI:10.1016/j.conbuildmat.2019.117705
10. Yijiang Wang, Tong Zheng, X.F. Zheng, Yifei Liu, Jo Darkwa, Guo-ging Zhou., Thermo-mechanical and moisture absorption properties of fly ash-based lightweight

geopolymer concrete reinforced by polypropylene fibers, Constr. Build. Mater. 251, 118960 (2020) DOI:10.1016/j.conbuildmat.2020.118960
11. Ehsan Mohseni, MahyarJafar Kazemi, Mahdi Koushkbaghi, Behnam Zehtab, Babak B ehforouz., Evaluation of mechanical and durability properties of fiber-reinforced lightweight geopolymer composites based on rice husk ash and nano-alumina, Constr. Build. Mater. 209, 532-540 (2019) DOI:10.1016/j.conbuildmat.2019.03.067
12. K. Neupane, Fly ash and GGBFS based powder-activated geopolymer binders: a viable sustainable alternative of Portland cement in concrete industry, Mech. Mater. 103, 110–122 (2016) DOI:10.1016/j.mechmat.2016.09.012
13. Besarion Meskhi, Alexey Beskopylny, Sergei Stel'makh, Evgenii Shcherban., Analytical Review of Geopolymer Concrete: Retrospective and Current Issues, Materials. 16(10), 3792 (2023) DOI:10.3390/ma16103792
14. M. Amin, I.Y. Hakeem, A.M. Zeyad, B.A. Tayeh, A.M. Maglad, I.S. Agwa., Influence of recycled aggregates and carbon nanofibres on properties of ultra-high-performance concrete under elevated temperatures, Case Stud. Constr. Mater. 16, e01063 (2022) DOI:10.1016/j.cscm.2022.e01063
15. Shamsad Ahmad, Ahmed Zubair, Mohammed Maslehuddin., Effect of key mixture parameters on flow and mechanical properties of reactive powder concrete, Constr. Build. Mater. 99, 73-81 (2015) DOI:10.1016/j.conbuildmat.2015.09.010
16. Ali İhsan Çelik and Yasin Onuralp Özkılıç., Geopolymer concrete with high strength, workability and setting time using recycled steel wires and basalt powder, Steel Compos. Struct., 46(5) (2023) DOI:10.12989/scs.2023.46.5.689
17. Subhankar Chowdhury, Subhashree Mohapatra, Ambar Gaur, Gaurav Dwivedi, Archana Soni., Study of various properties of geopolymer concrete – A review, Mater. Today: Proc. 46(12) (2020) DOI:10.1016/j.matpr.2020.09.835
18. Ping Duan, Luxia Song, Chunjie Yan., Novel thermal insulating and lightweight composites from metakaolin geopolymer and polystyrene particles, Ceram. Int. 43(6) (2017) DOI:10.1016/j.ceramint.2017.01.025
19. P.M. Rameshwaran and T. Ch. Madhavi., Flexural behaviour of fly ash based geopolymer concrete, Mater. Today: Proc. 46(9), 3423–3425 (2021) DOI:10.1016/j.matpr.2020.11.755
20. Ragini Dutt Sharma and Navdeep Singh., Evaluation of strength and absorption behaviour of iron slag and recycled aggregates concrete and its comparative environmental estimation by life cycle assessment, Clean. Mater. 10, 100210 (2023) DOI:10.1016/j.clema.2023.100210
21. Shuvom Dutta and Navdeep Singh., A brief review on workability characteristics of iron slag concrete, Mater. Today: Proc. (2023) to be published DOI:10.1016/j.matpr.2023.04.042
22. Nurul Hidayah Roslan, Mohammad Ismail, Zaiton Abdul-Majid, Seyedmojtaba Ghoreishiamiri, Bala Muhammad., Performance of steel slag and steel sludge in concrete, Constr. Build. Mater. 104, 16–24 (2016) DOI:10.1016/j.conbuildmat.2015.12.008
23. Kirubajiny Pasupathy, Sayanthan Ramakrishnan, Jay Sanjayan., Influence of recycled concrete aggregate on the foam stability of aerated geopolymer concrete, Constr. Build. Mater. 271, 121850 (2021) DOI:10.1016/j.conbuildmat.2020.121850
24. Abhishek Kumar and Navdeep Singh., Mechanical performance of steel and iron slag concretes: A brief review, Mater. Today: Proc. 93, Part 3, 62-70 (2023) DOI:10.1016/j.matpr.2023.06.463

25. Ali İhsan Çelik, Yasin Onuralp Özkılıç, Alireza Bahrami, Ibrahim Y. Hakeem., Mechanical performance of geopolymer concrete with micro silica fume and waste steel lathe scrap, Case Stud. Constr. Mater. 19, e02548 (2023) DOI:10.1016/j.cscm.2023.e02548
26. I.R. Mithanthaya*, Shriram Marathe , N B S Rao, Veena Bhat., Influence of superplasticizer on the properties of geopolymer concrete using industrial wastes, Mater. Today: Proc. 4, 9803–9806 (2017) DOI:10.1016/j.matpr.2017.06.270
27. H.M. Tanu and Sujatha Unnikrishnan., Utilization of industrial and agricultural waste materials for the development of geopolymer concrete- A review, Mater. Today: Proc. 65(2), 1290-1297 (2022) DOI:10.1016/j.matpr.2022.04.192
28. Shimol Philip and M. Nidhi., A review on the material performance of geopolymer concrete as green building materials, Mater. Today: Proc. 2023 (to be published) DOI:10.1016/j.matpr.2023.04.110