*Nanotechnology Perceptions*
*ISSN 1660-6795*
*www.nano-ntp.com*

# Experimental Investigation on Mechanical, Durability, and Microstructural Properties of Mud-Based Geopolymeric Masonry Blocks with Copper Slag, Ggbfs and Groundnut Shell Ash

**K. Infant Xavier[1], K. Mahendran[2]**

[1]*Research Scholar, Centre for Rural Technology, Civil Engineering, The Gandhigram Rural Institute, Deemed to be University, India*
[2]*Professor, Centre for Rural Technology, Civil Engineering, The Gandhigram Rural Institute, Deemed to be University, India.*
*E-mail: infant015@gmail.com*

In corroboration to the process of going green, this investigation provides for the possibility of producing geopolymers from environmentally friendly mud bricks by incorporating red soil, ground granulated blast furnace slag(GGBFS), groundnut shell ash (GNSA), and copper slag instead of the usual traditional components. The basic material used to activate them was 8Molar NaOH, and sodium hydroxide to sodium silicate was 1:2 and cured under ambient conditions. Different mixes were cast to study the performance, with a constant amount of red soil (80%), copper slag (10%), and varying GGBFS and GNSA. Significant findings include dry and wet compressive strength, prism efficiency, ultrasonic pulse velocity (UPV), water absorption, spray erosion, and microstructural analysis. The best Mix comprised of 80% red soil, 6% GGBFS, 4% GNSA, and 10% copper slag, was the most efficient performance. A less porous geopolymer matrix and increased durability resulted from the combined effect of GNSA, GGBFS, and copper slag. That increment in strength and stability suggested that the soil had mineral compounds using copper slag. The workplaces on the table that identified durable alternatives to ensure sustainable masonry in the Mix would necessitate strict guidelines for resource conservation and minimizing the impact of environmental degradation.
**Keywords:** Mud-based Geopolymeric block, red soil, GGBFS, Groundnut shell

ash (GNSA), mechanical, durability, and microstructural Properties.

## 1. Introduction

The building sector plays a significant role in worldwide carbon output because it uses a lot of Portland cement as a regular building material. Hence, we need to find greener options faster to reduce how much construction hurts the environment [1, 2]. Geopolymers, a new eco-friendly material, have caught people's eye because they can use leftovers from factories and farms to make green building materials [3, 4]. Geopolymers are non-organic alumina-silica polymers. People mix silica and alumina-rich stuff with alkaline activators [5]. Geopolymers put out way less $CO_2$ than Portland cement, and they become more assertive and last longer [6, 7]. In addition, using leftovers from factories like GGBFS and farm waste like GNSA helps manage waste and save resources [8, 9]. Red soil, which you can find in many places, can work well as a base for geopolymer blocks. Hence, it has alumina and silica, and it's easy to get [10, 11]. Adding GGBFS makes the geopolymer process work better by bringing in calcium ions, which help make it stronger and last longer [12].In the same way, GNSA, an agro-waste rich in silica, works as a material to supplement cement. It improves the matrix and reduces porosity [13, 14]. Copper slag, a byproduct from industry, has also been found to be of good use in geopolymer mixes. Its high density and pozzolan nature help to improve mechanical properties and resist erosion [15, 16]. Studies show that copper slag makes the matrix denser and withstands weather conditions [17]. The way geopolymer materials are cured has a significant impact on their effectiveness. In particular, Curing at room temperature has proven to be a green and energy-saving option compared to heat curing, which makes it a good fit for building on a large scale [18, 19]. Geopolymer blocks cured at room temperature offer a promising way to reduce the carbon footprint of masonry materials while still meeting modern construction's strength and durability needs [20]. In this study, we made geopolymer masonry blocks using red soil, GGBFS, GNSA, and copper slag. We activated these with an 8-molar sodium hydroxide solution and a sodium hydroxide to sodium silicate ratio of 1:2. We investigated how changing the amounts of GGBFS and GNSA affects several properties of the material, including its strength when dry and wet, the speed with which sound moves through it, its ability to function as a prism, the amount of water it absorbs, and its ability to withstand spraying. We wanted to find the best combination that works well and benefits the environment by reusing waste materials.

## 2. Materials and Methods:

The soil used to make building blocks originates from the Dindigul district. This soil has unique properties, including a specific gravity of 2.65, a liquid limit of 50%, a plastic limit of 30%, and a shrinkage limit of around 20%. The chemical and physical characteristics of the materials are detailed in Table 1. The GNSA was incinerated at 700°C for six hours to create the necessary reactivity. The resulting ash was then sieved, and only the fine particles were used as a supplementary cementitious material. The detailed mix proportion is shown in Table 2. The blocks were made using a semi-automatic block-making machine like the Hydraform. The red soil and binders were mixed for about 5 minutes, and a geopolymer solution, such as eight molarity sodium hydroxide and a sodium hydroxide-to-sodium silicate ratio of 1:2, was added to the dry Mix until the optimal level was reached. The entire mixture was then thoroughly blended until it became homogeneous and lump-free. Once this batch is ready, it is fed through the hydraulic press. Mixed materials that produce mud blocks measuring 220 x 220 x 115 mm are then expanded from the mould, revealing consistent hydraulic pressure beneath all slabs and a flat surface. The blocks are now designed to withstand typical weather conditions. The compressive strength was determined for the mud blocks at different curing periods, such as 3, 7, 14, and 28 days. The compressive strength of mud blocks is determined by IS 3495 [Part 1] [36]. The strength was evaluated using a CTM of 1000KN. During testing, the loading rate for the mud blocks was 14 $N/mm^2$ per minute. For this mud block, the average dry compressive load was calculated. The mud blocks were then immersed in water for 24 hours for a wet compression test. After that, the blocks were turned back by turning off the water, and the surface moisture on the blocks was dried with a dry cotton cloth. The following experiments to determine wet compressive strength are nearly identical to the previously mentioned dry compressive strength test. The efficiency test on a block is performed using the type of mud block stacking, with three and five number values in each test. The test is more focused on testing the efficiency of these blocks and the strength provision of the blocks in a prismatic manner. Moisture absorption was also measured using IS3495 [Part 2]:1992 [37] for block water absorption. The ultrasonic pulse velocity of cured mud block samples is measured by IS 13311 [Part 1]: 1992[35], based on the principle of homogeneity or voids in solid matter. The erosion rate on each specimen, determined by a spray erosion test, was performed per the procedures outlined in IS1725:2023[34]. A water pressure of 50 kPa was maintained on all mixes to assess the effectiveness of mud blocks based on erosion rate.

Table 1 The chemical and physical properties of Red soil, GGBFS, Groundnut shell ash, and copper slag

| S.NO | Properties | | Red Soil | GGBFS | Groundnut shell ash | Copper slag |
|---|---|---|---|---|---|---|
| 1 | Chemical properties [compositions] | $Al_2O_3$ | 15 | 12 | 12 | 4 |
| | | CaO | 3 | 35 | 5 | 5 |
| | | $Fe_2O_3$ | 10 | 1 | 3 | 53 |
| | | MgO | 4 | 7.5 | 3 | 8 |
| | | $Na_2O$ | 0.6 | 1 | 1 | 2 |
| | | $SiO_2$ | 57 | 41 | 60 | 35 |
| | | $SO_3$ | 0.4 | 1.5 | 1 | 1 |
| | | LOI | 10 | 1 | 15 | 2 |
| 2 | Physical properties | Specific gravity | 2.6 | 3.0 | 2.0 | 3.3 |
| | | Fineness($m^2$/ Kg) | 250 | 400 | 300 | 200 |
| | | Average particle size (µm) | 15 | 11 | 15 | 55 |

Table 2 Mix Proportion

| Mix ID | | 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|---|
| materials | Red Soil | 80% | 80% | 80% | 80% | 80% |
| | Copper slag | 10% | 10% | 10% | 10% | 10% |
| | GGBFS | 10% | 8% | 6% | 4% | 2% |
| | Groundnut shell ash(GNSA) | - | 2% | 4% | 6% | 8% |

**3. Results and Discussions:**

(i) Dry Compressive strength:

Figure. 1 conveys the effects of GGBFS and GNSA on the dry compressive strength of red soil-based geopolymeric blocks. Mix 3 (6% GGBFS, 4% GNSA) showed the best early strength at 3 and 7 days, influenced by the balanced availability of calcium and reactive silica-alumina, thus achieving ideal geopolymerization [21]. Mix 3 resulted in the maximum compressive strength at 28 days, at 15 MPa, highly above other mixes. Excessive GNSA in Mixes 4 and 5 decreased strength because of less calcium and void formation within the matrix [21, 22]. In Mix 3, 4% GNSA provided enough reactive silica for gel formation of the geopolymer, but too much GNSA (6%-8% in Mixes 4 and 5) reduced matrix cohesion and, therefore, strength reduced [21, 22]. Copper slag at 10% in all mixes had improved particle packing, matrix densification, and pozzolanic activity that contributed to higher strength and durability [23]. Ambient curing was found efficient enough for geopolymerization; hence, the system is energy-efficient and sustainable, according to prior findings [22, 23]. Mix 3 achieved the maximum compressive strength at all curing intervals and can be used structurally.

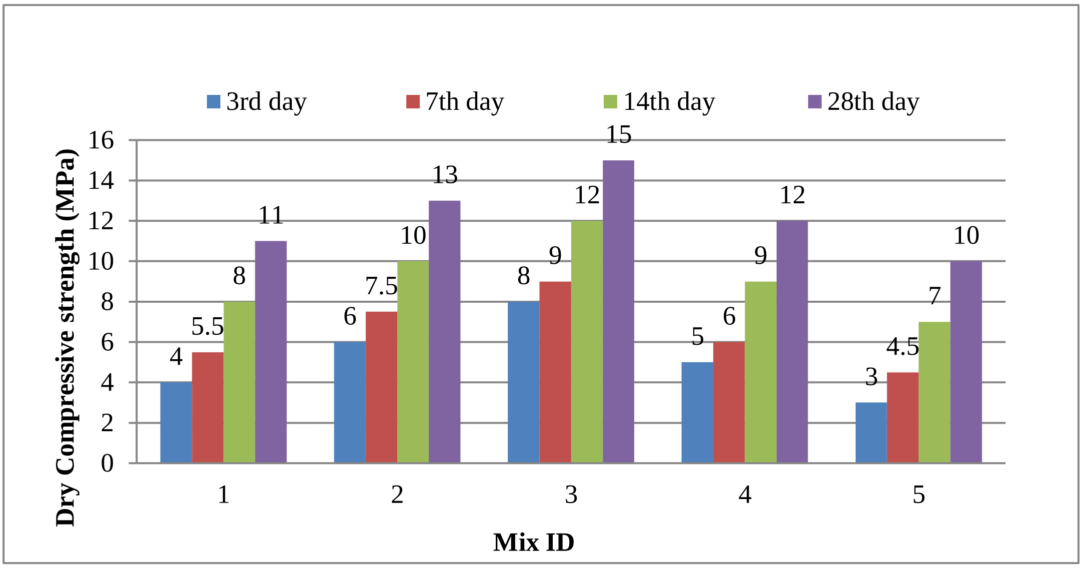


Figure 1. The effects of GGBFS and GNSA on dry compressive strength

(ii) Wet Compressive strength:

Figure 2. depicts the effects of GGBFS and GNSA on the wet compressive strength of mud-based geopolymeric blocks. Mix 3 reached the wet compressive strength of 9 MPa at 28 days. It also exhibited better strength compared to other mixes. The optimized percentage of GNSA was 4%, which enhanced silica-alumina availability in mix 3 to facilitate the strong geopolymer gel while maintaining good water resistance. In Mixes 4 and 5, excessive GNSA diluted the matrix cohesion, thus causing reduced strengths [21, 23]. Higher GNSA content in Mixes 4 and 5 caused unreacted particles and microstructural voids that decreased wet strength (refer.Fig.7). Mix 1 with 10% GGBFS and no GNSA showed moderate wet compressive strength due to inadequate silica-alumina interaction [22, 23]. Copper slag significantly

contributed to wet compressive strength by improving particle packing and providing additional pozzolanic reactions. This enhanced water resistivity and durability in all the mixes [23]. Ambient curing promoted the attainment of wet compressive strength to ensure sustainability without compromising much on energy use and with performance in wet conditions [22, 23].

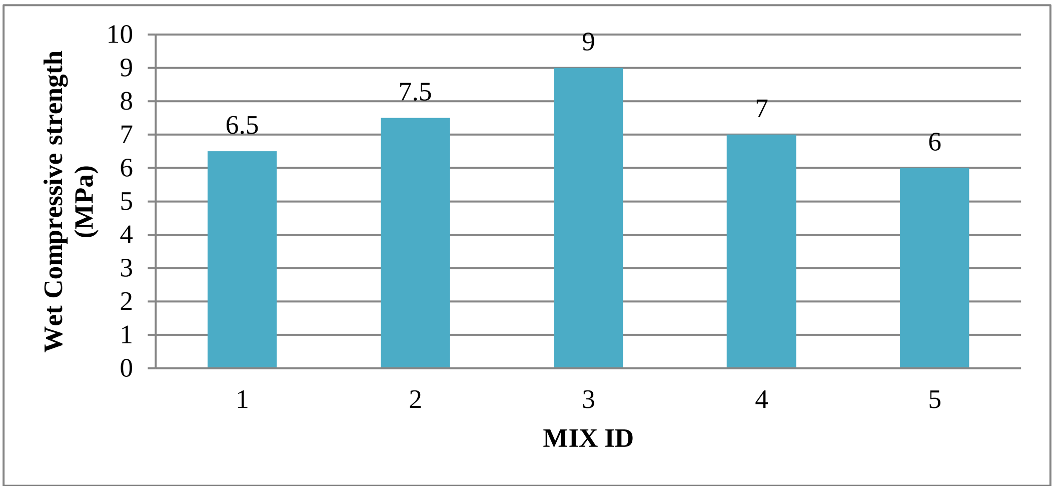


Figure 2. The effects of GGBFS and GNSA on wet Compressive strength

(iii) Ultrasonic Pulse Velocity Test

Figure. 3 represent the effects of GGBFS and GNSA on the UPV of geopolymeric blocks. Mix 3 showed the highest UPV of 4.60 km/s, with excellent matrix density and uniformity, due to the combined effect of 6% GGBFS and 4% GNSA, which provides the optimal calcium and silica-alumina content for dense geopolymerization. The dense microstructure enhanced the propagation of ultrasonic waves through the material [21]. Mixes 4 and 5 obtain lower UPV values due to excess GNSA at 6% and 8%, respectively. Since unreacted ash particles and microstructural voids disrupt the matrix continuity, reducing wave propagation velocity [21, 22]. Mix 1, containing no GNSA and 10% GGBFS, showed a UPV value of 3.6 km/s. The lack of extra silica-alumina from GNSA restricted the formation of geopolymer gel, and hence, the matrix was less dense compared to Mix 3 [22, 23]. Copper slag at 10% contributed positively to UPV as it improved particle packing and densification, which enhanced wave propagation across all mixes [23]. Mix 3 falls into the excellent quality category (above 4.5 km/s) according to IS 13311 [Part 1]: 1992 guidelines, thus confirming its suitability for structural applications. Mixes 1 and 2 are classified as good quality (3.5–4.5 km/s), fulfilling the non-critical application requirement [21]. Also, the mixes 4, 5 are classified as medium quality (3.0–3.5 km/s). The ambient curing process adequately supported the densification of the matrix, which is reflected in the UPV results and helps the sustainability [22, 23]. Mix 3 showed higher UPV values, indicating good structural quality and integrity.

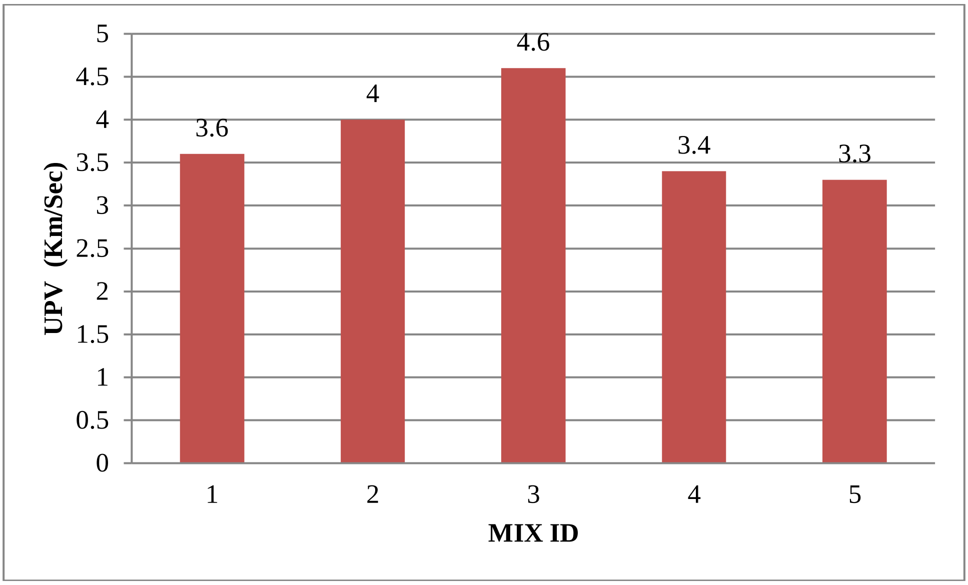


Figure 3. The effects of GGBFS and GNSA on ultrasonic pulse velocity

(iv) Prism test:

Figure. 4 reflect the effects of GGBFS and GNSA on the prism efficiency of red soil-based geopolymeric blocks. Mix 3 showed the highest efficiency, at 0.94, meaning higher load-bearing efficiency. The balanced composition of 6% GGBFS and 4% GNSA fostered optimal geopolymerization and excellent bonding at the blocks-mortar interfaces, reducing microcracks at the interface and, thus, more efficient load-carrying distribution and structural efficiency [21]. Mix 4 with 4% GGBFS and 6% GNSA and Mix 5 containing 2% GGBFS and 8% GNSA had less efficiency than Mix 3. The high proportion of GNSA added creates unwanted particles, which degrade the interfacial transition zone and reduce the mortar-block bond strength [22]. Mix 1 with 10% GGBFS and no GNSA had reasonable efficiency because GNSA deficiency restricted the supply of silica-alumina to the geopolymer gel, reducing the void-filling capability and uniform stress distribution during loading. [23]. 10% copper slag mixed in all blends increased the matrix densification and mechanical interlocking. This effect was most pronounced in Mix 3, where the balanced proportions of the ingredients amplified its positive impact [23]. Ambient curing was sufficient to achieve strength build-up and continued matrix hydration, allowing blocks to gain high prism efficiency without high energy-intensive curing [22, 23]. Mix 3 exhibited the highest prism efficiency and would be most appropriate for structural applications requiring the need to resist high loads. The optimal balance of GGBFS and GNSA combined with copper slag ensured a dense matrix and excellent mortar-block bonding, which supported its use in sustainable masonry systems.

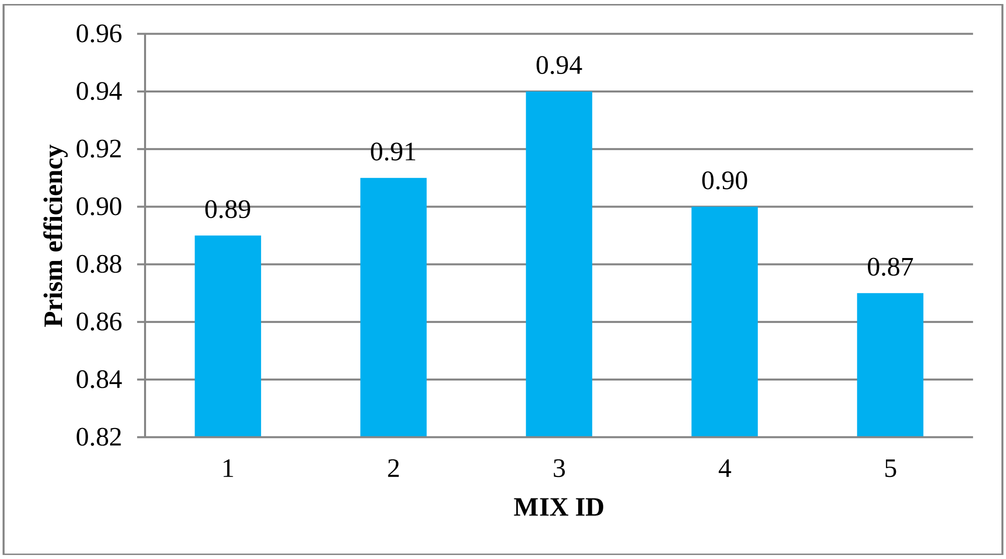


Figure 4. The effects of GGBFS and GNSA on prism efficiency

(v) Water Absorption:

Figure .5 depicts the effects of GGBFS and GNSA on water absorption of red soil-based geopolymeric blocks. Mix 3 showed the lowest water absorption, 8.0%, suggesting a dense matrix with fewer pores. The right proportion of 6% GGBFS and 4% GNSA supported better geopolymerization, resulting in lower pore connectivity. Thus, the block showed lesser water ingress, which enhanced its resistance [21]. Combinations 4 and 5 had more water absorption since the percentage of GNSA was increased at 6% and 8%. Higher GNSA contents brought unreacted particles that filled micro structural voids and consequently increased porosity. This observation showed that ash content is higher than the optimum, which decreases the density of the matrix [22]. Combination 1 had 10% GGBFS with no GNSA and had water absorption at moderate levels of 10.50%. Although GGBFS contributed to the densification of the matrix, the absence of more silica-alumina from GNSA limited the geopolymer gel formation and caused more porosity in the structure [23]. The 10% copper slag was added to improve the particle packing and contributed to the densification of all mixes and diminished water absorption, which was most pronounced in Mix 3 because of the balanced proportions of other ingredients [23]. Ambient curing helped allow adequate geopolymerization time, resulting in better strength with less porosity and producing strong geopolymer materials [22]. Mix 3 had the lowest water absorption, meaning it was the most durable and suitable for applications requiring low porosity, such as masonry blocks for external walls. The balanced composition of 6% GGBFS, 4% GNSA, and 10% copper slag resulted in optimal densification and reduced water ingress.

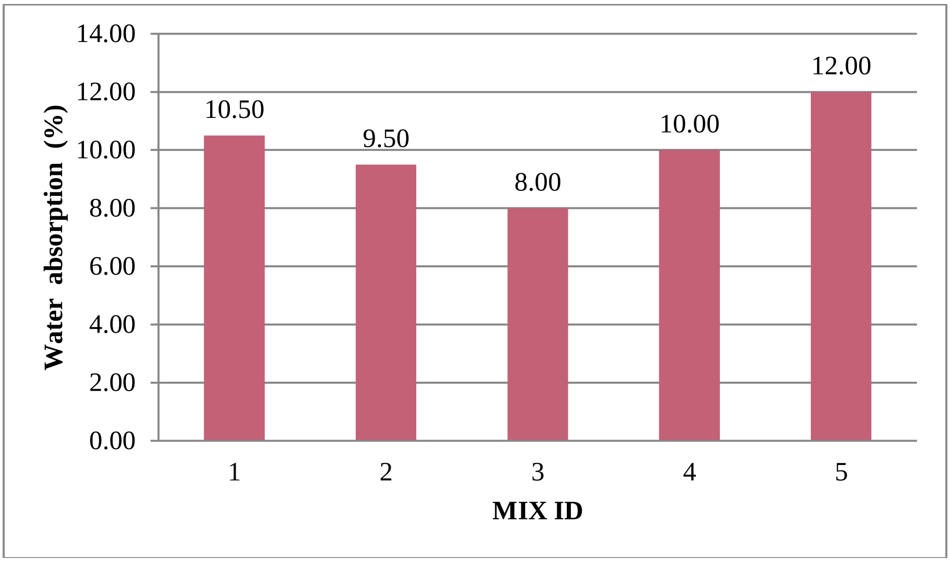


Figure 5. The effects of GGBFS and GNSA on water absorption

(vi) Spray Erosion Test:

Figure 6 illustrates the effects of GGBFS and GNSA on the erosion resistance of geopolymeric blocks. Mix 3 had the lowest erosion rate, 8 mm/hour, which means it is most resistant to spray erosion. The best Mix was 6% GGBFS and 4% GNSA, providing a dense, well-bonded matrix with minimal voids, thereby resisting particle detachment in water spray [21]. Mixes 4 and 5, with higher GNSA content at 6% and 8%, respectively, showed increased erosion rates. Excess unreacted GNSA particles further reduced the cohesion and increased the porosity of the blocks, thus making them vulnerable to erosion [22]. Mix 1, containing 10% GGBFS and no GNSA, presented a moderate erosion rate of 11 mm/hour. Although GGBFS strengthened the matrix, the absence of GNSA reduced the silica-alumina content, limiting the formation of further geopolymer gels [23]. Surface hardness and erosion resistance improved when 10% copper slag was added to all mixes. However, the proportion of ingredients in Mix 3 made copper slag function best in improving erosion resistance [23]. Ambient curing provided enough time to develop strong microstructures via geopolymerization, ensuring that blocks were adequately developed in strength and erosion resistance without needing high-energy curing processes to make them suitable for sustainable applications [22]. Mix 3 had the lowest erosion rate (8 mm/hr), demonstrating superior performance in spray erosion conditions. It was exposed that a balanced composition of 6% GGBFS, 4% GNSA, and 10% copper slag produces a highly dense and cohesive matrix suitable for masonry under outdoor weathering conditions.

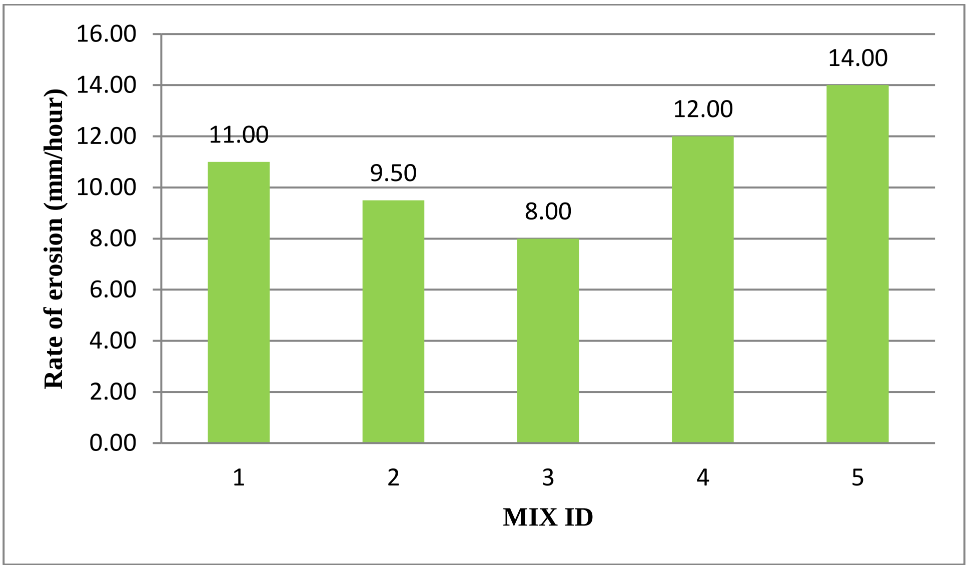


Figure 6. The effects of GGBFS and GNSA on the rate of erosion

(vii) Scanning Electron Microscopic (SEM) Analysis:

Figure. 7 indicate the SEM images of the geopolymeric blocks. SEM was used to study the microstructural characteristics of the geopolymer matrix for all mixes tested at 28 days. The optimum blend, which is Mix 3 (80% red soil, 6% GGBFS, 4% GNSA, and 10% copper slag), showed excellent polymerization, which was essential for improving the mechanical and durability properties of the geopolymer. Micrographs of Mix 3 show dense and compact geopolymer matrices with very few microcracks and pores that confirm the geopolymerization process had been carried out efficiently (Ref.Fig.7). The addition of 6% GGBFS significantly contributed because calcium ions leached during the reaction helped to form the C-A-S-H gel in addition to the main geopolymeric gel phases, improving the cohesion and strength of the matrix [24, 25]. GNSA, rich in reactive silica, was fully involved in the geopolymerization reaction, thereby further minimizing the microstructure and porosity [26, 27]. Mixes consisting of a higher percentage of GGBFS (as in Mix 1: 10% GGBFS) manifested the presence of unreacted particles in the matrix, indicating partial geopolymerization. Again, this will be attributed to the lack of alkaline activators compared to the reactant material, thus less homogenized [28]. Mixes with lower GGBFS and higher GNSA content, such as Mix 5: 2% GGBFS and 8% GNSA, demonstrated a more porous structure, compromising mechanical integrity and durability [29]. This concentration of 10% copper slag in Mix 3 has majorly contributed towards the densification of the matrix. The excellent pozzolanic activity, combined with the very high specific gravity of copper slag, results in better bonding within the geopolymer structure, as evidenced by the well-integrated particles in the SEM images. This integration improved not only the density of the matrix but also its resistance to environmental degradation, such as erosion [30, 31]. SEM analysis shows Mix 3 has a dense and well-formed geopolymer matrix, indicating an optimized synergy between red soil, GGBFS, GNSA, and copper slag. The microstructure aligns with superior mechanical and a durability characteristic obtained for the Mix and supports its sustainability and feasibility for high-performance masonry applications [32, 33].

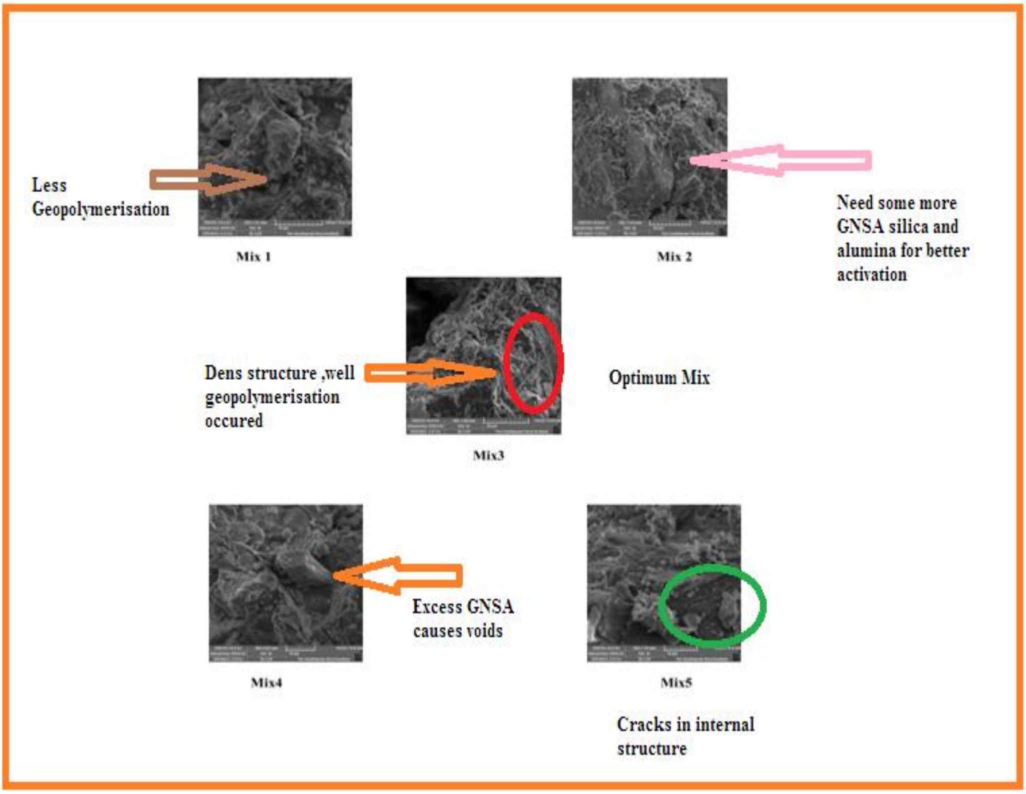


Figure 7. SEM images of the geopolymeric blocks

## 4. Conclusions:

The third Mix (mix.3), consisting of 80% red soil, 6% GGBFS, 4% GNSA, and 10% copper slag, produced the maximum compressive strength value at all the curing ages; values reached 8.00 MPa, 9.00MPa, 12.00 MPa, and 15.00 MPa at ages 3, 7, 14, and 28 days, which could be primarily attributed to an appropriate proportioning of 6% GGBFS with 4% GNSA that produced the highest rate of geopolymerization that provided a stronger dense matrix. Mix 3 possessed a more incredible wet compressive strength of 9Mpa at 28 days. High retention in water degradation signifies excellent resistance for such mixes toward wet environments. The highest UPV achieved by mix 3 is 4.6 km/s at 28 days. The outcome shows it possesses excellent homogeneity and has dense microstructure, corresponding to high compressive strength and durable properties. The highest prism efficiency0.94 was recorded by Mix 3, effectively distributing the load and maintaining minimal stress concentration in the masonry applications. The water absorption of Mix 3 was the lowest at 8.00% and thus showed a very dense and less porous structure. The optimal combinations of GGBFS and GNSA minimized porosity and improved durability. Mix 3 had the lowest erosion rate, 8 mm/hour, in the spray erosion test, which indicates the excellent weathering and erosion resistance of this geopolymer for masonry in aggressive environments. Ambient curing on geopolymer blocks has been less energy-intensive and reduces the carbon footprint. Another advantage is that industrial byproducts (GGBFS, GNSA, and copper slag) were used sustainably to conserve resources. Thus, Mix 3 (80% red soil, 6% GGBFS, 4% GNSA, and 10% copper slag) was the best Mix, showing strength, durability, and good erosion resistance at ambient curing. These properties make Mix 3 the ideal blend for geopolymer masonry block applications in construction, particularly in areas requiring environmentally friendly and long-lasting materials.

Acknowledgement

The authors thank the Department of Science and Technology- Science and Engineering Research Board (DST-SERB) for funding a research project titled "Design……Agro wastes." Furthermore, we thank the Gandhigram Rural Institute (DTBU)-Dindigul for facilitating the experimental project work.

## References

[1]. Turner, L. K., & Collins, F. G. (2013). Carbon dioxide equivalent (CO2-e) emissions: A comparison between geopolymer and OPC concrete. Construction and Building Materials, 43, 125-130.
[2]. Andrew, R. M. (2018). Global $CO_2$ emissions from cement production. Earth System Science Data, 10(1), 195-217.
[3]. Provis, J. L., & Bernal, S. A. (2014). Geopolymers and related alkali-activated materials. Annual Review of Materials Research, 44, 299-327.
[4]. Davidovits, J. (2011). Geopolymer chemistry and applications. Geopolymer Institute.
[5]. Duxson, P., et al. (2007). Geopolymer technology: The current state of the art. Journal of Materials Science, 42(9), 2917-2933.
[6]. Hardjito, D., & Rangan, B. V. (2005). Development and properties of low-calcium fly ash-based geopolymer concrete. Research Report GC-1.
[7]. Nath, P., & Sarker, P. K. (2014). Effect of GGBFS on durability of fly ash-based geopolymer concrete. Materials and Structures, 47(4), 605-616.
[8]. Siddique, R. (2008). Waste materials and byproducts byproducts in concrete. Springer-Verlag London.
[9]. Hossain, K. M. A., & Anwar, M. S. (2019). Agro-waste materials as supplementary cementitious materials: A review. Journal of Cleaner Production, 238, 117889.
[10]. Kumar, R., & Bhattacharjee, B. (2003). Porosity, pore size distribution and in situ strength of concrete. Cement and Concrete Research, 33(1), 155-164.
[11]. Mehta, A., & Siddique, R. (2017). Sustainable geopolymer concrete using ground granulated blast furnace slag and rice husk ash: Strength and permeability properties. Journal of Cleaner Production, 149, 821-831.
[12]. Roy, D. M. (1999). Alkali-activated cements: Opportunities and challenges. Cement and Concrete Research, 29(2), 249-254.
[13]. Singh, S. P., et al. (2015). Properties of geopolymer concrete prepared using ground granulated blast furnace slag and groundnut shell ash. Construction and Building Materials, 82, 258-267.
[14]. Ramachandran, V. S., et al. (2001). Handbook of thermal analysis of construction materials. William Andrew Publishing.
[15]. Al-Jabri, K. S., et al. (2009). Copper slag as sand replacement for high-performance concrete. Cement and Concrete Composites, 31(7), 483-488.
[16]. Shi, C., Meyer, C., & Behnood, A. (2008). Utilization of copper slag in cement and concrete.

Resources, Conservation and Recycling, 52(10), 1115-1120.
[17]. Poon, C. S., et al. (2003). Performance of metakaolin concrete at elevated temperatures. Cement and Concrete Research, 33(4), 593-597.
[18]. Sarker, P. K. (2011). Bond strength of reinforcing steel embedded in fly ash-based geopolymer concrete. Materials and Structures, 44(5), 1021-1030.
[19]. Palomo, A., et al. (1999). Alkaline activation of fly ashes: NMR study of the reaction products. Cement and Concrete Research, 29(7), 1323-1329.
[20]. Rovnaník, P. (2010). Effect of curing temperature on the development of hard structure of metakaolin-based geopolymer. Construction and Building Materials, 24(7), 1176-1183.
[21]. Singh, S., Kumar, R., & Bhattacharyya, S. K. (2020). Utilization of industrial byproducts byproducts in geopolymer concrete: Strength and microstructural analysis. Construction and Building Materials, 233, 117161.
[22]. Nath, P., & Sarker, P. K. (2014). Effect of GGBFS on the durability of fly ash-based geopolymer concrete. Materials and Structures, 47(4), 605-616.
[23]. Hossain, K. M. A., & Anwar, M. S. (2019). Agro-waste materials as supplementary cementitious materials: A review. Journal of Cleaner Production, 238, 117889.
[24]. Xu, H., & Van Deventer, J. S. J. (2000). Geopolymerization of alumino-silicate minerals. International Journal of Mineral Processing, 59(3), 247–266.
[25]. Provis, J. L., & Bernal, S. A. (2014). Geopolymers and related alkali-activated materials. Annual Review of Materials Research, 44, 299–327.
[26]. Khale, D., & Chaudhary, R. (2007). Mechanism of geopolymerization and factors influencing its development: A review. Journal of Materials Science], 42(3), 729–746.
[27]. Hardjito, D., Wallah, S. E., & Rangan, B. V. (2005). Factors influencing the compressive strength of fly ash-based geopolymer concrete. Civil Engineering Dimension, 7(2), 88–93.
[28]. Davidovits, J. (1994). Properties of geopolymer cements. First International Conference on Alkaline Cements and Concretes.
[29]. Mehta, A., & Siddique, R. (2017). Properties of low-calcium fly ash-based geopolymer concrete incorporating OPC as partial replacement of fly ash. Construction and Building Materials, 150, 792–807.
[30]. Hwang, C. L., & Laiw, J. C. (1989). Durability design and copper slag in concrete. Cement and Concrete Research, 19(5), 747–758.
[31]. Shi, C., Meyer, C., & Behnood, A. (2008). Utilization of copper slag in cement and concrete. Resources, Conservation and Recycling, 52(10), 1115–1120.
[32]. Rangan, B. V. (2008). Fly ash-based geopolymer concrete. Indian Concrete Journal, 82(5), 41–48.
[33]. Kong, D. L. Y., & Sanjayan, J. G. (2008). Damage behavior of geopolymer composites exposed to elevated temperatures. Cement and Concrete Composites, 30(10), 986–991.
[34].IS 1725:2023 Stabilized soil Block Used in General Building Construction Specification.
[35].IS 13311 [Part 1]: 1992 Non-destructive testing of concrete Part 1: Ultrasonic pulse velocity.
[36].IS 3495 [Part 1]: 2019 Burnt Clay Building Bricks -Methods of Tests Part 1 Determination of Compressive Strength [Fourth Revision].
[37].IS 3495 [Part 2]: 2019Burnt Clay Building Bricks - Methods of Tests Part 2 Determination of Water Absorption [Fourth Revision].