



A review on study of Mechanical and Durability properties of modified Geopolymer concrete using Nano materials

Mohammed Haseebulla M, Habeebulla Khan, Mahadas Pragna, Sanjana, Tabassum L

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INTRODUCTION

Concrete has long been recognized as the cornerstone of modern infrastructure, playing a critical role in the development of buildings, transportation systems, water supply structures, and other essential facilities. Its widespread use can be attributed to its versatility, availability of raw materials, ease of construction, and ability to withstand high compressive loads. However, the environmental impact associated with concrete production, particularly due to cement manufacturing, has become a major concern in recent years. The process of cement production involves the calcination of limestone at high temperatures, which releases a significant amount of carbon dioxide into the atmosphere. In addition, the process requires substantial energy consumption, contributing further to environmental degradation.

In response to these challenges, researchers and engineers have been actively exploring alternative materials that can reduce the environmental impact of construction activities. Geopolymer concrete has emerged as a promising solution due to its ability to utilize industrial by-products such as fly ash, GGBS, and metakaolin. These materials are rich in silica and alumina, which are essential for the formation of geopolymer binders. The use of these materials not only

reduces the demand for cement but also helps in the effective disposal of industrial waste, thereby addressing two major environmental concerns simultaneously.

The formation of geopolymer concrete is fundamentally different from that of conventional concrete. Instead of hydration reactions, geopolymer concrete undergoes a chemical process known as geopolymerization. This process involves the dissolution of silica and alumina from the source materials in the presence of alkaline activators, followed by polymerization to form a three-dimensional network of aluminosilicate gel. This network provides the necessary strength and durability to the concrete.

Despite its numerous advantages, geopolymer concrete faces certain challenges that limit its widespread application. One of the primary concerns is its brittle nature, which makes it susceptible to sudden failure under tensile stresses. Additionally, the presence of microvoids and pores within the matrix can affect its durability and resistance to environmental degradation. These limitations have prompted researchers to explore the use of advanced materials such as nanomaterials to enhance the performance of geopolymer concrete.

Nanotechnology has emerged as a revolutionary field with applications in various domains, including construction materials. Nanomaterials, due to their extremely small size and high surface area, exhibit unique physical and chemical properties that can significantly influence the behavior of concrete. When incorporated into geopolymer concrete, these materials act as fillers that reduce pore size and improve packing density. They also enhance bonding between particles and improve the overall strength and durability of the material.



Among the various nanomaterials studied, nano-silica has been found to be highly effective in improving compressive strength and reducing porosity. Nano-clay enhances bonding and structural stability, while carbon nanotubes provide exceptional tensile strength and crack resistance. Graphene oxide further improves durability and resistance to environmental degradation. The concept of hybrid nano-modification involves the use of multiple nanomaterials in combination to achieve better performance than individual additives. This approach allows for the integration of multiple mechanisms such as pore filling, nucleation, and crack bridging, resulting in a more compact and durable concrete matrix.

Abstract

Geopolymer concrete has emerged as a sustainable alternative to conventional cement concrete due to its lower carbon emissions and utilization of industrial by-products such as fly ash and Ground Granulated Blast Furnace Slag (GGBS). However, issues related to brittleness, porosity, and durability limit its widespread application. This report focuses on the incorporation of nanomaterials in geopolymer concrete to improve its mechanical and durability properties. Various nanomaterials such as nano-silica, carbon nanotubes (CNTs), nano-alumina, graphene oxide, and nano-clay have been studied based on recent research findings. The study highlights the influence of nanomaterials on compressive strength, split tensile strength, flexural strength, water absorption, permeability, and resistance to chemical attack. The methodology includes selection of raw materials, preparation of alkaline activators, dispersion of nanomaterials, casting of specimens, curing, and performance evaluation through mechanical, durability, and microstructural tests such as SEM and XRD analysis. Literature studies indicate that optimum dosages of nanomaterials significantly enhance geopolymerization, reduce pore structure, and improve bonding within the concrete matrix, resulting in superior strength and durability. The report concludes that nanomaterial-modified geopolymer concrete offers an eco-friendly, high-performance, and durable solution for modern construction applications, although challenges such as nanoparticle dispersion, cost, and large-scale implementation still require further investigation.

2. LITERATURE SURVEY

1. Osama Zaid, et.al. had done work “Sustainability evaluation, engineering properties and challenges relevant to geopolymer concrete modified with different nanomaterials: A systematic review” (2024):

This study presents a comprehensive systematic review on the role of nanomaterials in improving the sustainability, mechanical properties, and durability of geopolymer concrete (GPC). The research identifies a major gap in replacing conventional cement, which contributes approximately 4–7% of global CO₂ emissions, with eco-friendly alternatives. The authors reviewed more than 190 research articles and analyzed the influence of different nanomaterials such as nano-silica, nano-clay, graphene oxide, carbon nanotubes, and nano-alumina on GPC performance. The study considered key parameters including compressive strength, tensile strength, durability, and microstructural characteristics. The results show that nanomaterials significantly enhance compressive strength by approximately 15% to 55%, improve durability by reducing permeability and water absorption, and refine the microstructure through pore filling and increased gel formation (C–S–H and C–A–S–H gels). Nano-silica was found to increase early strength due to its high reactivity, while graphene oxide improved durability and crack resistance, and CNTs enhanced tensile strength through crack-bridging mechanisms. The study also highlights that hybrid nanomaterials provide better performance compared to single nanomaterials due to combined effects. However, challenges such as high cost, dispersion difficulties, lack of standard mix design, and limited field applications are identified. Overall, the study concludes that nanomaterial-modified geopolymer concrete is a high-performance and sustainable construction material with strong potential, but further research is required to address practical implementation challenges and long-term performance.



2. Jamal A. Abdalla, et.al. had done work “Influence of nano-TiO₂, nano-Fe₂O₃, nanoclay and nano-CaCO₃ on the properties of cement/geopolymer concrete” (2022):

This study presents a comprehensive review on the influence of different nanomaterials such as nano-TiO₂, nano-Fe₂O₃, nanoclay, and nano-CaCO₃ on the mechanical, durability, and microstructural properties of cement and geopolymer concrete. The research identifies the need for improving conventional concrete performance due to durability issues and environmental concerns, and highlights nanotechnology as an effective solution. The authors analyzed various experimental studies and reported that nanomaterials significantly enhance compressive strength by approximately **10% to 40%**, depending on the type and dosage. Nano-TiO₂ improves durability and provides photocatalytic properties, while nano-Fe₂O₃ enhances compressive strength and thermal stability. Nanoclay contributes to better pore refinement and can improve strength by about **20–30%**, whereas nano-CaCO₃ acts as a filler material and improves early-age strength by around **15–25%**. The study also highlights that optimum nanoparticle content typically ranges between **1% to 5% by weight of binder**, beyond which agglomeration may reduce performance. Additionally, durability properties such as reduced water absorption, lower permeability, and improved resistance to chemical attack were observed due to the densification of the microstructure. The paper concludes that nanomaterials are highly effective in enhancing concrete performance, but challenges such as dispersion issues, cost, and lack of standardized mix design need further investigation for large-scale applications.

3. R. Samuel Raj, et.al. had done work “Nanomaterials in geopolymer composites: A review” (2023):

This study presents a detailed review on the application of various nanomaterials in geopolymer composites and their influence on fresh, mechanical, durability, and microstructural properties. The research highlights the environmental concern associated with Portland cement, which contributes approximately **5–8% of global CO₂ emissions**, and emphasizes geopolymer composites as a sustainable alternative. The authors reviewed more than **335 research publications** and analyzed a wide range of nanomaterials including nano-silica (NS), nano-alumina (NA), nano-TiO₂ (NT), carbon nanotubes (CNT), graphene oxide (GO), nano-clay (NC), nano-calcium carbonate (NCC), nano zinc oxide (NZ), and nano fly ash. The study found that nanomaterials significantly enhance geopolymerization by increasing reaction rates and forming a denser microstructure. Compressive strength improvements were observed in the range of **15% to 50%**, depending on the type and dosage of nanomaterials. Nano-silica and graphene oxide showed superior performance in improving strength and durability, while CNT improved tensile strength through crack-bridging mechanisms. Additionally, durability properties such as reduced water absorption, permeability, and improved resistance to chemical attack were reported due to pore refinement. The study also notes that optimum nanomaterial dosage typically lies between **0.5% to 3%**, beyond which agglomeration may reduce performance. Overall, the research concludes that nanomaterials play a crucial role in producing high-performance geopolymer composites, but challenges such as dispersion, cost, and large-scale application still need to be addressed for practical implementation.

4. Ayman Ababneh, et.al. had done work “Nano-silica for enhancing corrosion resistance of kaolin-based geopolymer concrete” (2025):

This study investigates the effectiveness of nano-silica (SiO₂) in improving the corrosion resistance and mechanical performance of kaolin-based geopolymer concrete (GPC). The research addresses the critical issue of steel reinforcement corrosion in concrete structures and the need to reduce CO₂ emissions associated with conventional cement. Nano-silica was added in varying percentages of **0%, 4%, 6%, and 8% by weight of kaolin**, and its effect was evaluated under accelerated corrosion conditions using techniques such as ultrasonic pulse velocity (UPV), half-cell potential (HCP), visual inspection, and pull-out tests. The results showed that the optimum nano-silica content was **7%**, which provided the highest corrosion protection efficiency of approximately **48%**, significantly reducing steel degradation. Additionally, nano-silica coating improved mechanical properties, with **UPV increasing by about 82%**, stiffness improving by **75%**, and overall damage index reducing by **45%** compared to uncoated specimens. The study also observed reduced permeability and



enhanced microstructure due to pore refinement and improved bonding. Overall, the research concludes that nano-silica is highly effective in enhancing both durability and corrosion resistance of geopolymer concrete, making it suitable for reinforced concrete structures exposed to aggressive environments, although optimization of dosage is essential for maximum performance.

5. Zhong Xu, et.al. had done work “Mechanical properties and durability of geopolymer concrete based on fly ash and coal gangue under different dosage and particle size of nano silica” (2023):

This study investigates the influence of nano-silica (NS) dosage and particle size on the mechanical and durability properties of geopolymer concrete prepared using fly ash and coal gangue. The research addresses the environmental concern of CO₂ emissions from cement production, which is approximately **1.01 tons of CO₂ per ton of cement**, and promotes geopolymer concrete as a sustainable alternative with significantly lower emissions (about **1/10 to 1/5 of OPC emissions**). Nano-silica was incorporated in varying dosages of **0–1.5%** and particle sizes of **20 nm and 100 nm** to evaluate its effect on performance. The results showed that the appropriate dosage of nano-silica significantly improved compressive strength and durability, while excessive dosage resulted in negative effects due to agglomeration. Smaller particle size nano-silica (**20 nm**) exhibited better performance in enhancing mechanical properties and reducing water absorption due to higher surface area and improved nucleation effect, whereas larger particle size (**100 nm**) showed better resistance to sulfate attack. Microstructural analysis using SEM, XRD, and image analysis confirmed that nano-silica improved density and reduced porosity, leading to enhanced bonding and strength. The study concludes that optimal nano-silica content (around **1%**) with smaller particle size provides the best overall performance, improving both strength and durability of geopolymer concrete while maintaining sustainability.

6. Jayant M. Raut, et.al. had done work “Performance optimization of hybrid nano-engineered geopolymer binders-based ultra-high-performance concrete” (2025):

This study focuses on the development and optimization of hybrid nano-engineered geopolymer binders for ultra-high-performance concrete (UHPC), aiming to achieve superior mechanical strength, durability, and sustainability. The research incorporates hybrid nanomaterials such as nano-silica and graphene oxide using optimized dispersion techniques like ultrasonication and mechanical milling. The results show that the developed geopolymer composite achieved a high compressive strength exceeding **120 MPa at 28 days**, along with very low water absorption of less than **3%**, indicating a highly dense and durable microstructure. The study also highlights that microwave-assisted curing significantly enhances geopolymerization, achieving strength gains of approximately **70% within 4 hours**, demonstrating rapid early-age strength development. Additionally, hybrid nano-additives improved bonding and microstructural refinement, resulting in enhanced durability, impact resistance, and crack resistance. The incorporation of doped carbon nanotubes further provided self-sensing capabilities, increasing structural monitoring efficiency by over **25%**. Microstructural analysis using XRD and molecular dynamics indicated improved crystallinity of about **50%** and bond strength

enhancement exceeding **320 kJ/mol**, confirming strong interfacial bonding. The study concludes that hybrid nano-engineered geopolymer concrete offers a high-performance, durable, and energy-efficient solution suitable for advanced construction applications such as infrastructure, aerospace, and defense, while emphasizing the importance of optimized dispersion and curing techniques for achieving maximum performance.

7. F.S. Frieda, et.al. had done work “Effects on the strength and durability of graphene oxide modified geopolymer concrete using industrial waste bauxite tailings” (2025):

This study investigates the effect of graphene oxide (GO) on the mechanical, durability, and microstructural properties of geopolymer concrete prepared using industrial waste bauxite tailings (BT) and ground granulated blast furnace slag (GGBS), aiming to promote sustainable construction by reducing reliance on conventional



cement. The research highlights that geopolymer concrete is a low-carbon alternative with improved durability, and the addition of GO further enhances its performance. Different dosages of GO (**0.025%, 0.05%, 0.075%, 0.1%, and 0.125%**) were studied under ambient curing conditions using sodium hydroxide (4M) and sodium silicate solution (ratio 2.5). The results showed that an optimum GO content of **0.1%** provided the highest improvement in compressive strength, with an increase of **44.52%**, while other mixes showed improvements of **31.95% and 10.22%** depending on binder ratios ($A/B = 0.45$ and 0.5). Durability tests such as Rapid Chloride Penetration Test (RCPT), Water Permeability Test (WPT), Surface Resistivity (SR), and Ultrasonic Pulse Velocity (UPV) indicated significant improvements, including reduced chloride ion penetration and water absorption, along with increased surface resistivity and UPV values. The addition of GO also enhanced microstructural properties by reducing porosity and improving bonding, as confirmed by SEM analysis. Overall, the study concludes that graphene oxide significantly enhances both strength and durability of geopolymer concrete, making it highly suitable for high-performance and sustainable construction applications, particularly when used at optimized low dosages.

8. Aissa Rezzoug, et.al. had done work “Sustainable ultra-high-performance basalt fiber-reinforced geopolymer concrete incorporating carbon nanotubes and treated recycled aggregates” (2025):

This study investigates the development of sustainable ultra-high-performance geopolymer concrete (UHPGC) incorporating basalt fibers, carbon nanotubes (CNTs), and treated recycled aggregates to enhance mechanical and durability performance while reducing environmental impact. The research highlights that Portland cement production contributes approximately **7% of global CO₂ emissions**, emphasizing the need for sustainable alternatives like geopolymer concrete. CNTs were added in varying dosages of **0.05%, 0.1%, and 0.15%**, and the results showed that the optimum dosage was **0.05% CNT**, which provided the highest improvement in compressive strength and overall performance. The combined effect of CNTs, basalt fibers, and calcium silicate hydrate (CSH) treatment significantly enhanced mechanical properties, interfacial bonding, and durability. The study also reported improved sulfate resistance and high-temperature resistance, with specimens tested at temperatures ranging from **200°C to 1000°C**, showing good thermal stability. Treated recycled aggregates improved internal curing and interfacial transition zones, resulting in better strength and durability. Microstructural analysis confirmed that the addition of CNTs and fibers led to a denser matrix with reduced porosity. Overall, the study concludes that the hybrid use of CNTs, basalt fibers, and treated recycled aggregates can significantly enhance the performance of geopolymer concrete, making it suitable for high-strength, durable, and sustainable construction applications.

9. Menatalah A. Kotop, et.al. had done work “Engineering properties of geopolymer concrete incorporating hybrid nano-materials” (2021):

This study investigates the effect of hybrid nanomaterials, specifically nano-clay (NC) and carbon nanotubes (CNTs), on the mechanical and durability properties of geopolymer concrete as a sustainable alternative to conventional cement-based materials. The research highlights that the cement industry contributes approximately **7% of global greenhouse gas emissions**, emphasizing the importance of eco-friendly alternatives such as geopolymer concrete. In this study, slag was used as the primary aluminosilicate source, and alkaline activators such as sodium silicate (Na_2SiO_3) and sodium hydroxide (NaOH) were used for geopolymerization. The results showed that the incorporation of hybrid nanomaterials significantly improved compressive and flexural strength, with the optimum mix achieving maximum strength when **2.53% nano-clay was combined with 0.01% CNTs**. The addition of CNTs enhanced tensile strength through crack-bridging mechanisms, while nano-clay improved compressive strength due to its high pozzolanic activity and filler effect. The hybrid system also improved durability properties such as reduced chloride ion penetration and lower water permeability.



Microstructural analysis confirmed that nanomaterials refined the pore structure and enhanced bonding within the matrix. However, the study also identified challenges such as dispersion difficulties of CNTs due to their high surface area. Overall, the research concludes that hybrid nanomaterials provide a synergistic effect, significantly enhancing both strength and durability of geopolymer concrete, making it suitable for high-performance construction applications.

10. Said A. Saeid, et.al. had done work “Nanomaterials in Geopolymers for Refractory Applications: Trends, Mechanisms, and Challenges” (2026):

This study presents a comprehensive review on the role of nanomaterials in enhancing geopolymer-based refractory materials for high-temperature applications, focusing on their mechanical, thermal, and microstructural performance. The research highlights that geopolymer refractories offer a sustainable alternative to conventional ceramics by significantly reducing embodied energy and CO₂ emissions while maintaining high-temperature stability. The authors analyzed various nanomaterials such as nano-silica, nano-alumina, TiO₂, ZnO, carbon nanotubes (CNTs), graphene derivatives, and nanoclays, and found that these materials act as nucleation centers and pore refiners, leading to a denser microstructure and improved performance. The study reports that nanomaterial incorporation can enhance strength retention by approximately **70–85% at high temperatures ranging from 1000°C to 1200°C**, along with improved thermal shock resistance and reduced thermal shrinkage. Advanced synthesis techniques such as sol-gel, hydrothermal methods, ultrasonication, and mechanical milling were identified as effective for improving nanoparticle dispersion and reactivity. Additionally, the study highlights improvements in interfacial transition zone (ITZ) densification and crack-bridging mechanisms, which enhance durability and structural stability under extreme conditions. However, challenges such as nanoparticle agglomeration, high cost, variability in precursor materials, and lack of standardized mix design were identified. Overall, the research concludes that nanomaterials significantly improve the high-temperature performance of geopolymer refractories, making them suitable for industrial and energy-intensive applications, although further optimization and cost reduction are required for large-scale implementation.

11. B. Middendorf, et.al. had done work “Nanomaterials in geopolymer concrete: revolutionizing sustainable cement solutions” (2025):

This study presents a detailed review on the role of nanomaterials in improving the performance of geopolymer concrete (GPC) as a sustainable alternative to Ordinary Portland Cement (OPC), emphasizing environmental and mechanical benefits. The authors highlight that OPC production contributes approximately **7–8% of global CO₂ emissions**, with global production reaching about **4.5 billion metric tons in 2023**, whereas geopolymer concrete significantly reduces carbon footprint and energy consumption. The incorporation of nanomaterials such as nano-silica, nano-alumina, carbon nanotubes (CNTs), and graphene oxide enhances the microstructural densification, accelerates geopolymerization, and improves resistance to chemical and thermal degradation. Among these, nano-silica and graphene oxide showed the most consistent improvements in compressive strength and durability, while CNTs contributed to multifunctional performance but faced dispersion challenges. The study also indicates that geopolymer systems can reduce global warming potential by approximately **26–45% compared to OPC**, depending on raw materials and production methods. Additionally, nanomaterials refine pore structure, enhance bonding, and improve long-term durability, making GPC suitable for advanced construction applications. However, issues such as high cost, dispersion difficulties, and scalability remain significant challenges. Overall, the study concludes that nanomaterial-modified geopolymer concrete offers a promising, eco-friendly, and high-performance solution for sustainable construction, with further research required to optimize large-scale implementation.



12. Balamurali Kanagaraj, et.al. had done work “Influence of Multi-walled Carbon Nanotube (MWCNT) on flexural behavior and microstructure characteristics of geopolymer concrete beams” (2024):

This experimental study investigates the effect of Multi-Walled Carbon Nanotubes (MWCNTs) on the mechanical and flexural performance of geopolymer concrete (GPC) beams, focusing on compressive strength, load-deflection behavior, and microstructural characteristics. The study used MWCNT concentrations ranging from **0.02% to 0.16%** and tested beam specimens of size **1500 mm × 150 mm × 150 mm**. The results revealed that the optimum MWCNT dosage was **0.12%**, achieving a compressive strength of **29.78 MPa** with a significant **26.62% increase** compared to control specimens, while higher concentrations led to strength reduction due to agglomeration. In terms of structural performance, the energy absorption capacity (EAC) increased with MWCNT addition, reaching a peak value of **6116 kN·mm at 0.12%**, and maintained consistent improvement up to **0.06%** dosage. The stiffness and ductility behavior followed a similar trend, showing improvement up to **0.1% MWCNT**, beyond which performance decreased. The density index also improved up to **0.1%**, and the flexural toughness factor remained stable up to **0.06%** before declining at higher concentrations. Microstructural analysis using SEM confirmed a denser and more compact matrix at the optimum dosage, whereas excessive MWCNT content resulted in particle agglomeration and reduced performance. Overall, the study concludes that controlled incorporation of MWCNTs significantly enhances the strength, ductility, and energy absorption capacity of geopolymer concrete beams, with **0.12% identified as the optimal dosage** for achieving superior performance.

13. Mehmet Serkan Kirgiz, et.al. had done work “Modification mechanism of silver nanoparticles-functionalized MW-CNT and GGBFS and CQDs on the structural properties of geopolymer reinforced-composite beam” (2025):

This study investigates the combined effect of silver nanoparticle-functionalized multi-walled carbon nanotubes (Ag-PM-MWCNT), ground granulated blast furnace slag (GGBFS), and carbon quantum dots (CQDs) on the structural performance of geopolymer reinforced composite beams (GR-CBs). The experimental analysis was conducted over extended curing periods of **7, 28, 90, 180, 365, 2185, and 4370 days**, evaluating properties such as compressive strength, shear strength, bending strength, Young’s modulus, porosity, and fluidity. The results showed that incorporating **0.5–0.7 wt% Ag-PM-MWCNT and 2.5 wt% CQD** significantly reduced fluidity and porosity while enhancing mechanical performance. Notably, the compressive, bending, and shear strengths increased by more than **180%, 160%, and 104%**, respectively, compared to conventional mixes. The maximum recorded strengths after **4370 days** were **75 MPa (compressive strength), 10.6 MPa (bending strength), and 9.5 MPa (shear strength)**. Additionally, the Young’s modulus showed significant improvement due to enhanced microstructural densification, as confirmed by SEM analysis. The inclusion of GGBFS further contributed to improved bonding and long-term durability. The study concludes that the synergistic use of nanomaterials and industrial by-products leads to a highly dense and durable geopolymer matrix, making it suitable for long-term structural applications and infrastructure development, with substantial improvements in strength and durability characteristics.

14. Gaurav Thakur, et.al. had done work “Nano-Transition Metal Oxide-Modified Geopolymer Concrete: A Comprehensive Review on Mechanisms, Performance, and Sustainability” (2026):

This study provides a comprehensive review of nano-transition metal oxide (NTMO) modified geopolymer concrete (GPC), focusing on their mechanisms, performance enhancement, and sustainability aspects. The research highlights the incorporation of nano-oxides such as **TiO₂, ZnO, Fe₂O₃, ZrO₂, CuO, NiO, and MnO₂** into geopolymer matrices derived from industrial by-products like fly ash, GGBFS, and metakaolin. These nanomaterials act as nano-fillers, nucleation sites, and functional activators, leading to improved microstructural densification and enhanced mechanical properties. The study reports that NTMO incorporation can significantly improve compressive strength and durability, while also imparting multifunctional properties such as **self-cleaning, antibacterial behavior, electromagnetic shielding, and thermal stability**. Additionally, optimized



nano-oxide dosage is critical, as excessive content can lead to agglomeration and reduced performance. The review also emphasizes that geopolymer concrete can reduce CO₂ emissions significantly compared to conventional cement-based materials, contributing to sustainable construction. Furthermore, the study identifies that NTMO-modified GPC enhances life-cycle performance and stability, making it suitable for advanced infrastructure applications. Overall, the research concludes that NTMO-based geopolymer concrete is a next-generation smart material with improved mechanical performance, durability, and environmental benefits, although further work is needed in dosage optimization and large-scale implementation.

15. Anil Kumar, et.al. had done work “Advancements in Geopolymer Concrete: A Detailed Review of Engineering Properties with Nanomaterial Integration” (2024):

This study presents a comprehensive review on the advancements in geopolymer concrete (GPC) with the integration of various nanomaterials, focusing on improving mechanical properties, durability, and sustainability. The research highlights that GPC utilizes industrial by-products such as **fly ash (FA), bottom ash (BA), ground granulated blast furnace slag (GGBFS), and rice husk ash (RHA)** as primary binders, significantly reducing dependence on Ordinary Portland Cement (OPC) and lowering environmental impact. The incorporation of nanomaterials like **carbon nanotubes (CNT), nano-silica (NS), nano-alumina (NA), nano-titanium dioxide (NT), nano-clay (NC), and graphene oxide (GO)** enhances inter-particle packing and microstructural densification, leading to improved strength and durability. The study reports that the addition of nano-silica at an optimum dosage of **2%** yielded the most favorable results in terms of compressive strength and durability. Furthermore, nanomaterial incorporation eliminates the need for thermal curing in many cases, reducing energy consumption during production. The TOPSIS analysis conducted in the study identified nano-silica as the most effective nanomaterial among those evaluated. The review concludes that nanomaterial-modified GPC exhibits superior engineering properties, enhanced durability, and improved sustainability performance, although challenges related to cost, large-scale application, and optimal dosage selection still need to be addressed for practical implementation.

16. Jiarong Shi, et.al. had done work “Effects of three different nanomaterials on the properties and microstructure of sludge based geopolymers” (2024):

This study investigates the influence of three nanomaterials—nano-silica (NS), nano-calcium carbonate (NCC), and graphene nanoplatelets (GNPs)—on the mechanical properties and durability of sludge-based geopolymers. The results demonstrated that nano-silica exhibited the most significant improvement in strength, with the addition of **2% NS leading to a compressive strength increase of up to 108.2%**, outperforming NCC and GNPs. The early reaction rate of geopolymerization was enhanced due to the nucleation effect of NS, NCC, and GNPs. After **28 days**, the mass loss for geopolymer samples improved with nanomaterial incorporation, with values recorded at **15.06% (reference), 14.78% (NS), 14.85% (NCC), and 14.55% (GNPs)**, indicating improved durability. Furthermore, the modified geopolymers showed enhanced resistance to pore structure degradation, erosion, and freeze–thaw cycles. The improvements were attributed to the ability of nanomaterials to fill pores, accelerate gel formation, and promote denser microstructure development. Microstructural analysis confirmed better gel connectivity and reduced porosity in nanomodified samples. Overall, the study concludes that the incorporation of nanomaterials, particularly nano-silica at **2% dosage**, significantly enhances both mechanical strength and durability of sludge-based geopolymers, making them a viable solution for sustainable waste utilization and construction applications.



17. Menatalah A. Kotop, et.al. had done work “Engineering properties of geopolymer concrete incorporating hybrid nano-materials” (2021):

This study investigates the effect of hybrid nanomaterials, specifically carbon nanotubes (CNTs) and nano-clay (NC), on the mechanical and durability properties of geopolymer concrete (GPC) produced using fly ash and slag as aluminosilicate sources. The research utilized alkaline activators composed of **sodium silicate (Na_2SiO_3) and sodium hydroxide (NaOH)** and evaluated properties such as compressive strength, flexural strength, bond strength, chloride resistance, and water penetration. The results indicated that the optimal mix containing **2.5% nano-clay combined with 0.01% CNTs** achieved superior compressive strength compared to other mixes, demonstrating the synergistic effect of hybrid nanomaterials. The incorporation of CNTs enhanced tensile strength and crack resistance due to their high surface area, while nano-clay improved pozzolanic activity and reduced porosity, leading to better durability performance. Additionally, improvements were observed in resistance to chloride penetration and reduced water permeability, indicating enhanced long-term durability. However, excessive CNT content caused dispersion issues and reduced workability. Overall, the study concludes that hybrid nanomaterials significantly improve the engineering properties of geopolymer concrete, with **2.5% NC + 0.01% CNT identified as the optimal combination** for achieving enhanced strength and durability.

18. B. Middendorf, et.al. had done work “Nanomaterials in geopolymer concrete: revolutionizing sustainable cement solutions” (2025):

This study presents a systematic review on the impact of nanomaterials in enhancing the performance and sustainability of geopolymer concrete (GPC) as an alternative to Ordinary Portland Cement (OPC). The research highlights that OPC production contributes approximately **7–8% of global CO_2 emissions**, with global production reaching around **4.5 billion metric tons**, whereas geopolymer concrete significantly reduces carbon footprint and energy consumption. The incorporation of nanomaterials such as **nano-silica, nano-alumina, carbon nanotubes (CNTs), and graphene oxide** improves microstructural densification, accelerates geopolymerization, and enhances resistance to chemical and thermal degradation. Among these, nano-silica and graphene oxide showed the most consistent improvements in compressive strength and durability, while CNTs contributed to multifunctional properties but faced dispersion challenges. The study further indicates that geopolymer systems can reduce global warming potential by approximately **26–45% compared to OPC**, depending on raw materials and production conditions. Additionally, nanomaterials refine pore structure, improve bonding, and enhance long-term durability, making GPC suitable for advanced construction applications. However, challenges such as high cost, dispersion issues, and large-scale implementation remain. Overall, the study concludes that nanomaterial-modified geopolymer concrete offers a highly sustainable and high-performance solution for future construction with significant environmental and mechanical advantages.

19. Koti Chiranjeevi, et.al. had done work “Enhancing the properties of geopolymer concrete using nano-silica and microstructure assessment: a sustainable approach” (2023):

This study investigates the effect of nano-silica incorporation on the mechanical and durability properties of geopolymer concrete (GPC) prepared using fly ash, ground granulated blast furnace slag (GGBS), and sugarcane bagasse ash. The research explored different mix combinations, including a ternary blend of **25% GGBS, 65% fly ash, and 10% bagasse ash**, along with varying nano-silica dosages. The results demonstrated that the addition of **4% nano-silica** significantly enhanced both strength and durability characteristics, achieving a maximum compressive strength of **41.33 MPa** and split tensile strength of **2.91 MPa** for the optimized GCBA-N4 mix. Durability tests such as rapid chloride permeability, water absorption, and sulfate attack showed improved resistance, with minimum permeability and mass loss observed at the optimum nano-silica content. The study also highlights that geopolymer concrete reduces CO_2 emissions compared to Ordinary Portland Cement (OPC), where OPC production emits approximately **600–800 kg of CO_2 per ton**, while GPC reduces emissions by about **22–72%**. Microstructural analysis confirmed improved densification and reduced porosity due to nano-silica acting as a filler and nucleation agent. Overall, the study concludes that the incorporation of nano-silica at **4% dosage**



significantly improves the strength, durability, and sustainability of geopolymer concrete, making it a viable alternative for eco-friendly construction.

20. Manas Sarkar, et.al. had done work “ZnO-SiO₂ nanohybrid decorated sustainable geopolymer retaining anti-biodeterioration activity with improved durability” (2018):

This study investigates the development of ZnO-SiO₂ nanohybrid incorporated geopolymer as a sustainable construction material with enhanced durability and anti-biodeterioration properties. The research utilized industrial by-products such as fly ash combined with alkaline activators to produce geopolymer composites, where ZnO-SiO₂ nanohybrids were synthesized via chemical precipitation and uniformly coated over ZnO nanorods. The results indicated that the incorporation of ZnO-SiO₂ significantly improved both mechanical strength and durability, while also imparting strong antimicrobial properties. The study demonstrated that the nanohybrid-modified geopolymer exhibited improved resistance to microbial growth, with enhanced antibacterial efficiency due to the generation of reactive oxygen species. Additionally, durability tests showed reduced permeability and improved resistance against environmental degradation. The material also maintained comparable strength to conventional geopolymer while improving functional performance. The study highlights that geopolymer materials can reduce greenhouse gas emissions by approximately **75% compared to Ordinary Portland Cement (OPC)**, making them highly sustainable. Microstructural analysis using SEM, TEM, and XRD confirmed improved densification and uniform distribution of nanomaterials within the matrix. Overall, the study concludes that ZnO-SiO₂ nanohybrid incorporation significantly enhances durability, antimicrobial resistance, and sustainability, making it suitable for infrastructure applications exposed to harsh environmental and biological conditions.

21. Nada Hadi Jumaa, et.al. had done work “Strength and microstructural properties of binary and ternary blends in fly ash-based geopolymer concrete” (2022):

This study investigates the effect of binary and ternary blends incorporating nanomaterials on the strength and microstructural properties of fly ash-based geopolymer concrete (GPC). The mixes were prepared using industrial waste fly ash (FA) with nano-clay (NC) and nano-titanium dioxide (NT) at varying proportions of **40%, 45%, and 50% FA**, while maintaining a constant water-to-FA ratio of **0.12**. Three groups were studied: control (FA only), binary blends (FA+NC and FA+NT), and ternary blends (FA+NC+NT). Mechanical properties such as compressive strength, tensile strength, and density were evaluated, along with microstructural analysis using XRD and SEM. The results showed that the addition of nanomaterials significantly improved the density and reduced pore structure of GPC. Compressive strength increased by **up to 38% with nano-clay and 24% with nano-TiO₂ in binary mixes**, while the ternary blend exhibited the highest improvement of **up to 55%**, indicating a synergistic effect of combined nanomaterials. The improved performance is attributed to enhanced geopolymerization and pore-filling effects of nanoparticles, resulting in a denser matrix and better durability characteristics. Overall, the study concludes that ternary blends (FA+NC+NT) provide superior mechanical and microstructural performance compared to binary and control mixes, making them highly effective for sustainable and high-performance geopolymer concrete applications.

22. Kamal Kishore, et.al. had done work “Technological challenges in nanoparticle-modified geopolymer concrete: A comprehensive review on nanomaterial dispersion, characterization techniques and its mechanical properties” (2023):

This review paper examines the role of nanomaterials in improving the mechanical and durability properties of geopolymer concrete (GPC), while also highlighting key technological challenges such as nanoparticle dispersion and characterization. The study emphasizes that geopolymer concrete, derived from industrial waste materials, significantly reduces carbon emissions compared to conventional concrete and can lower CO₂ emissions by **approximately 25–45%** depending on raw materials and processing. The incorporation of nanomaterials such as



nano-silica, carbon nanotubes (CNTs), graphene oxide (GO), and nano-alumina enhances compressive strength, reduces porosity, and improves crack

resistance; however, improper dispersion leads to agglomeration, negatively affecting performance. The review highlights that optimized nanoparticle content (generally **1–5% by weight**) improves microstructure densification and mechanical strength, while excessive dosage reduces workability and strength. Various advanced characterization techniques such as **SEM, TEM, XRD, FTIR, and NMR** are discussed for analyzing microstructural changes and geopolymerization mechanisms. The paper also identifies challenges such as cost, large-scale application, and long-term durability performance, despite the observed improvements in mechanical properties. Overall, the study concludes that while nanomaterials can significantly enhance GPC performance, achieving uniform dispersion and optimal dosage is critical for realizing improvements of up to **20–50% in strength and durability properties**, making it a promising yet technically challenging advancement in sustainable construction materials.

2. OBJECTIVES

- ▮ To study the effect of nano-materials on the mechanical properties of concrete, such as compressive strength, split tensile strength, and flexural strength.
- ▮ To evaluate the durability properties of modified concrete containing nano-materials, including water absorption, permeability, and resistance to chemical attack.
- ▮ To determine the optimum percentage of nano-materials to be added in concrete for achieving improved strength and durability.
- ▮ To analyze the influence of nano-materials on the microstructure and overall performance of concrete, leading to improved long-term serviceability.

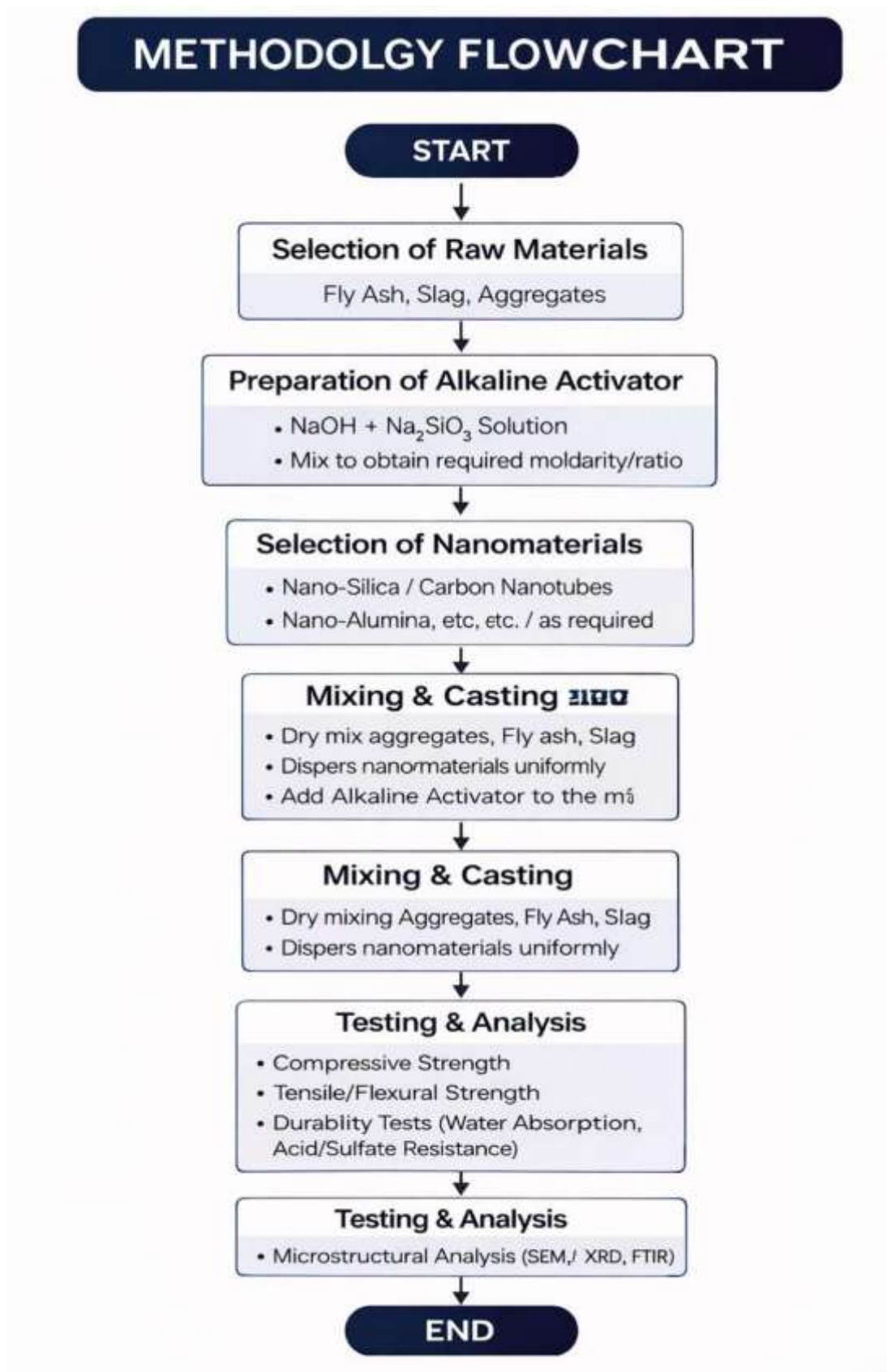
Materials Used

MATERIALS USED
(Geopolymer Concrete Study)

Sl. No.	Material / Data Used	Source	Purpose
1	Fly Ash (Class F)	Thermal Power Plants / Industrial Waste	Used as primary aluminosilicate source for geopolymer formation
2	Ground Granulated Blast Furnace Slag (GGBS)	Steel Industry By-product	Enhances strength and accelerates geopolymerization reaction
3	Fine Aggregates (Sand)	Natural Sources	Provides workability and fills voids in concrete mix
4	Coarse Aggregates (Gravel)	Quarry Sources	Provides bulk strength and structural stability
5	Sodium Hydroxide (NaOH) Solution	Chemical Suppliers	Acts as alkaline activator for geopolymer reaction
6	Sodium Silicate (Na ₂ SiO ₃) Solution	Chemical Suppliers	Enhances binding and improves strength of geopolymer matrix
7	Nano-Silica (NS)	Nanomaterial Suppliers	Improves compressive strength and reduces porosity
8	Carbon Nanotubes (CNTs)	Laboratory / Nanotech Sources	Enhances tensile strength and crack resistance
9	Nano-Clay (NC)	Nanomaterial Suppliers	Improves bonding and pozzolanic activity
10	Nano-Titanium Dioxide (TiO ₂)	Nanomaterial Suppliers	Enhances durability and microstructure density
11	Mixing Water	Laboratory Supply	Used for solution preparation and workability
12	Testing Equipment (Compression Testing Machine, SEM, XRD)	Laboratory Equipment	Used to evaluate mechanical and microstructural properties
12	Testing Equipment (Compression Testing Machine, SEM, XRD)	Laboratory Equipment	Used to evaluate mechanical and microstructural properties



METHODOLOGY





Selection of Raw Materials

(Fly Ash, Slag, Aggregates)

This is the first important practical step because the performance of geopolymer concrete depends strongly on the quality and type of raw materials used.

Fly Ash

Fly ash is a by-product obtained from thermal power plants during coal combustion. It is rich in silica and alumina, which are the main ingredients required for geopolymerization. In geopolymer concrete, fly ash acts as the main binder source instead of cement. Low-calcium fly ash is commonly preferred because it gives better geopolymer reaction and better long-term strength, though high-calcium fly ash may also be used depending on the purpose of the study.

Slag

Slag, especially Ground Granulated Blast Furnace Slag (GGBS), is obtained from the iron and steel industry. It contains calcium, silica, and alumina. Slag is added to increase early-age strength, improve setting behavior, and enhance durability. In many geopolymer mixes, slag is combined with fly ash because fly ash alone may react slowly at room temperature, while slag improves reactivity and makes the concrete stronger at earlier ages.

Aggregates

Aggregates form the bulk of the concrete and provide strength, volume stability, and economy.

- **Fine aggregate** usually means sand.
- **Coarse aggregate** usually means gravel or crushed stone.

They must be clean, hard, well graded, and free from organic impurities. Proper grading helps in reducing voids, improving workability, and increasing density. The size and proportion of aggregates directly affect the final strength and durability of the geopolymer concrete.

Why this step is important

If the raw materials are not selected properly, the geopolymer reaction may be weak, the mix may become unworkable, and the final concrete may show poor strength and durability.

Preparation of Alkaline Activator

(NaOH + Na₂SiO₃ solution, mixed to obtain required molarity/ratio)

The alkaline activator is the chemical solution that starts and supports the geopolymerization reaction. Unlike ordinary concrete, where cement reacts with water, geopolymer concrete needs an alkaline medium to activate the silica and alumina present in fly ash and slag.

Sodium Hydroxide (NaOH)

NaOH is a strong alkali. It dissolves silica and alumina from fly ash and slag, making them available for chemical reaction. The concentration of NaOH is generally expressed in **molarity**, such as 8M, 10M, 12M, or 14M.

- Lower molarity may give slower reaction and lower strength.
- Higher molarity usually increases reaction and strength, but too high a concentration may reduce workability and increase cost.

Sodium Silicate (Na₂SiO₃)

Sodium silicate is added to provide extra soluble silica, which helps in forming a stronger geopolymer gel network. It improves bonding, density, and strength.

Mixing of Activators

NaOH solution and sodium silicate solution are mixed in a required ratio. This ratio is very important. Commonly used ratios may vary depending on the mix design. The mixed alkaline solution is often prepared in advance and allowed to cool because dissolving NaOH in water releases heat.

Why this step is important

The strength, setting time, workability, and durability of geopolymer concrete depend heavily on:

- NaOH molarity
- Na₂SiO₃ / NaOH ratio



- total alkaline solution quantity

If the activator is not prepared properly, geopolymerization will be incomplete and the concrete will not perform well.

Selection of Nanomaterials

(Nano-silica / Carbon Nanotubes / Nano-alumina etc. as required)

This step involves choosing the nanomaterial to be added to the geopolymer concrete to improve its properties. Nanomaterials are extremely fine particles, usually in the nanometer range. Because of their very small size and high surface area, they react quickly and strongly influence the concrete structure.

Nano-silica

Nano-silica is one of the most commonly used nanomaterials. It fills very tiny pores in the concrete matrix, improves packing density, accelerates geopolymerization, and increases strength. It is especially effective for improving compressive strength and reducing permeability.

Carbon Nanotubes (CNTs)

CNTs are tube-shaped carbon materials with very high tensile strength. They help bridge microcracks and improve crack resistance, tensile strength, flexural strength, and ductility. However, they are difficult to disperse uniformly because they tend to clump together.

Nano-alumina

Nano-alumina improves reactivity, densifies the matrix, and can enhance strength and durability. It may also help improve thermal stability in some applications.

Other possible nanomaterials

Depending on the study, other materials such as graphene oxide, nano-clay, nano-TiO₂, nano-CaCO₃, nano-Fe₂O₃, and ZnO-based nanomaterials may also be selected.

Basis of selection

The nanomaterial is selected according to the objective:

- For compressive strength: nano-silica, nano-alumina
- For tensile/flexural strength: CNTs, graphene oxide
- For durability: nano-silica, nano-TiO₂, nano-clay
- For thermal or special properties: nano-alumina, ZnO hybrids, graphene-based materials

Why this step is important

The correct type and dosage of nanomaterial can significantly improve geopolymer concrete, but excess dosage may cause agglomeration, poor workability, and lower performance.

Mixing & Casting

(Dry mix aggregates, fly ash, slag; disperse nanomaterials uniformly; add alkaline activator to the mix)

This is the main preparation stage of the geopolymer concrete.

Step 1: Dry Mixing

First, all dry ingredients such as:

- fly ash
- slag
- fine aggregate
- coarse aggregate

are mixed thoroughly. This ensures even distribution of all solid materials.

Step 2: Dispersion of Nanomaterials

Nanomaterials must be spread uniformly throughout the mix. This is one of the most critical steps in the entire methodology.

Because nanomaterials are very fine and have high surface energy, they tend to form lumps or clusters. If they are



not properly dispersed, they will not improve the concrete effectively.

Dispersion may be done by:

- dry blending with binder materials
- mixing in liquid activator
- ultrasonication
- mechanical stirring
- using surfactants in advanced

studies Uniform dispersion ensures that nanomaterials can:

- fill micro voids
- improve bonding
- refine the matrix
- bridge cracks effectively

Step 3: Addition of Alkaline Activator

After dry mixing and nanomaterial dispersion, the alkaline activator is added gradually. The full mix is then blended until a uniform, workable geopolymer concrete is obtained.

Step 4: Casting

The fresh mix is placed into moulds of required sizes:

- cubes for compressive strength
- cylinders for split tensile strength
- prisms or beams for flexural strength
- other shapes for durability and microstructural studies

The moulds are usually compacted by tamping, vibrating table, or standard compaction methods to remove entrapped air.

Why this step is important

Improper mixing or poor nanomaterial dispersion can lead to:

- weak zones
- air voids
- non-uniform microstructure
- inaccurate test results

This step determines whether the concrete produced is reliable and reproducible.

Mixing & Casting

The flowchart shows “Mixing & Casting” twice. This usually means the process is emphasized in two parts, or one of the boxes may represent the continuation of the same stage.

In practical terms, the repeated part can be understood as:

- first box: preparing the mix and dispersing nanomaterials
- second box: final mixing, pouring into moulds, compaction, and finishing

Finishing after casting

After casting:

- the surface is levelled
- specimens are marked for identification
- moulds are kept undisturbed for initial setting

Then specimens are demoulded after the required time and transferred for curing.

Testing & Analysis

(Compressive strength, tensile/flexural strength, durability tests such as water absorption and acid/sulfate resistance)



Once the specimens are cast and cured, they are tested to evaluate performance.

Compressive Strength Test

This is the most basic and important test for concrete. Cube or cylinder specimens are placed in a compression testing machine and loaded until failure.

This test shows:

- the load-carrying capacity of the concrete under compression
- how much strength improvement is obtained by adding nanomaterials

Split Tensile Strength Test

Concrete is weak in tension, so this test is important. A cylindrical specimen is loaded across its diameter until it splits. This helps determine:

- resistance to cracking
- improvement in tensile behaviour

Flexural Strength Test

Beam or prism specimens are tested under bending. This shows how well the concrete resists bending stresses. This is especially important when nanomaterials like CNTs or graphene oxide are used because they often improve flexural behaviour through crack-bridging action.

Durability Tests

(Water absorption, acid resistance, sulfate resistance)

Durability tests measure how the concrete behaves in aggressive environments over time.

Water Absorption Test

This measures the amount of water the concrete can absorb. Lower water absorption means:

- fewer pores
- denser structure
- better long-term durability

Acid Resistance Test

Concrete specimens are exposed to acidic solutions. The test checks:

- loss in weight
- loss in strength
- surface damage

Nanomaterials often improve acid resistance by making the matrix denser and less permeable.

Sulfate Resistance Test

Sulfates attack concrete and can cause expansion, cracking, and deterioration. In this test, specimens are exposed to sulfate solutions and their behavior is monitored.

Improved sulfate resistance means the concrete is suitable for harsh soil or wastewater environments.

Why these tests are important

Mechanical strength alone is not enough. A concrete mix must also survive in actual service conditions. Durability tests show whether the nanomaterial-modified geopolymer concrete is suitable for real construction use.

Testing & Analysis

(Microstructural analysis: SEM, XRD,)

After mechanical and durability testing, the internal structure of the concrete is studied using advanced instruments. This helps explain **why** the concrete behaved the way it did.

SEM – Scanning Electron Microscopy

SEM gives highly magnified images of the surface and microstructure. It helps observe:

- pore structure
- cracks



- gel formation
- nanomaterial distribution
- densification of matrix

For example, a denser matrix with fewer voids usually explains higher strength and lower permeability.

XRD – X-ray Diffraction

XRD is used to identify crystalline and amorphous phases present in the material. It helps determine:

- reaction products formed during geopolymerization
- degree of crystallinity
- changes due to nanomaterial addition

This shows whether the geopolymer gel network has developed properly.

Why microstructural analysis is important

These techniques provide the scientific explanation behind improvements in:

- strength
- durability
- bonding
- crack resistance

Without microstructural analysis, we know only the result; with it, we understand the mechanism.

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