

Advancements in Geopolymer Concrete: Role of Fly Ash and Nano-TiO₂ in Sustainable Construction

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ABSTRACT

Geopolymer concrete (GPC) has emerged as a sustainable alternative to traditional Portland cement concrete (PCC), offering reduced carbon emissions and improved mechanical and durability properties. Among various industrial by-products and nanomaterials explored for enhancing GPC, fly ash and nano-titanium dioxide (Nano-TiO₂) have shown significant promise. This paper presents a comprehensive review of recent advancements in geopolymer concrete, with a specific focus on the synergistic effects of fly ash and Nano-TiO₂. The discussion covers their influence on workability, setting time, strength development, microstructure, durability, and sustainability metrics. The review aims to guide researchers and engineers towards the effective utilization of these materials for greener construction solutions..

Keywords — Geopolymer Concrete, Fly Ash, Nano-TiO₂, Sustainable Construction, Durability, Mechanical Strength.

I. INTRODUCTION

The construction industry is one of the largest contributors to global CO₂ emissions, primarily due to the extensive use of Ordinary Portland Cement (OPC). To mitigate these environmental impacts, researchers and industry professionals are increasingly focusing on alternative binder systems. Geopolymer concrete (GPC) has emerged as a promising eco-friendly material, offering a lower carbon footprint, superior chemical resistance, and high early strength compared to conventional OPC-based concrete.

Fly ash, a by-product of coal combustion in thermal power plants, is one of the most widely used raw materials in GPC production due to its high aluminosilicate content. Its utilization not only promotes waste management but also significantly reduces CO₂ emissions associated with cement production. Recently, the incorporation of nanomaterials, particularly Nano-TiO₂ (titanium dioxide nanoparticles), has further enhanced the performance characteristics of GPC by improving its mechanical properties, durability, and microstructural density.

The addition of Nano-TiO₂ in cementitious composites has been shown to significantly improve their performance by accelerating hydration reactions, reducing setting time, and enhancing mechanical strength due to its high surface area and nanoscale dimensions. Applied research continues to support the growing adoption of Nano-TiO₂ in the construction industry, where its inclusion has proven beneficial for both fresh and hardened concrete properties. However, excessive addition of Nano-TiO₂ can negatively affect the dimensional stability of cement mixtures, necessitating careful optimization of both particle size and dosage to balance strength, workability, and durability.

This review highlights the critical role of titanium dioxide at the nanoscale, especially in light of the rising global demand for concrete in infrastructure development. While concrete is valued for its toughness and long-term durability, its production is also responsible for substantial environmental pollution through greenhouse gas emissions. To address this, researchers are increasingly replacing portions of traditional cement with eco-friendly additives such as zinc oxide and titanium dioxide.

These nanomaterials have been shown to improve the formation of calcium-silicate-hydrate (C-S-H) gel, enhance bond strength between aggregates, and reduce porosity, all of which lead to improved mechanical performance and durability.

Moreover, nanoparticles such as Nano-TiO₂ also offer environmental benefits beyond structural improvements. Due to their photocatalytic properties, they contribute to air purification by breaking down airborne pollutants like nitrogen oxides (NO_x), thus improving indoor and outdoor air quality. Furthermore, these materials absorb ultraviolet (UV) radiation from sunlight, helping to prevent surface degradation and making structures more aesthetically durable over time.

The strategic use of nanomaterials in cementitious composites not only enhances strength and durability but also addresses issues associated with poor-quality cement, which can compromise structural integrity. Current research focuses on optimizing nano-additive dosage and dispersion techniques to maximize performance gains while minimizing adverse effects on workability and dimensional stability.

In addition to nanomaterials, mineral and chemical additives such as fly ash, silica fume, ground granulated blast furnace slag (GGBS), limestone powder (LSP), and rice husk ash are also widely utilized in concrete to reduce the clinker content and overall CO₂ emissions. These supplementary cementitious materials (SCMs) improve various properties, including strength, durability, and sustainability, while contributing to the reduction of industrial waste.

Overall, the combination of fly ash and Nano-TiO₂ in geopolymer concrete represents a significant advancement towards achieving sustainable, high-performance, and environmentally responsible construction materials. The continued exploration of these materials aligns with global efforts to reduce greenhouse gas emissions and promote green construction technologies.

II. GEOPOLYMER CONCRETE: OVERVIEW AND MECHANISM

Geopolymer Concrete (GPC) represents a significant advancement in sustainable construction materials, offering an eco-friendly alternative to

conventional Ordinary Portland Cement (OPC)-based concrete. Unlike traditional cement concrete, which relies on the hydration of calcium silicates as the primary binding mechanism, GPC utilizes an entirely different chemistry based on alkali activation of aluminosilicate-rich materials.

1. Geopolymerization Mechanism

The core binding process in geopolymer concrete is called geopolymerization, which involves a series of chemical reactions between aluminosilicate source materials and alkaline activators.

- **Source Materials:** These are rich in silicon (SiO₂) and aluminum (Al₂O₃), typically obtained from industrial by-products like fly ash, Ground Granulated Blast Furnace Slag (GGBS), metakaolin, or rice husk ash.
 - **Alkaline Activators:** The commonly used activators include sodium hydroxide (NaOH), sodium silicate (Na₂SiO₃), potassium hydroxide (KOH), or combinations thereof. These activators provide the necessary alkaline environment to initiate the dissolution of silica and alumina from the raw material.
- The geopolymerization reaction proceeds through the following main stages:
- **Dissolution:** Under the influence of the alkaline activator, the aluminosilicate particles dissolve, releasing Si⁴⁺ and Al³⁺ ions into the solution.
 - **Polycondensation:** The dissolved silica and alumina species undergo polycondensation reactions, forming a three-dimensional Si-O-Al-O polymeric network.
 - **Setting and Hardening:** The polymerization process results in a hardened matrix that binds the aggregates together, similar to how hydrated calcium silicate (C-S-H gel) binds particles in OPC-based concrete.

This Si-O-Al framework gives GPC its unique properties, including enhanced chemical resistance, high mechanical strength, and durability.

2. Key Benefits of Geopolymer Concrete

GPC offers multiple advantages over traditional OPC-based concrete, making it highly suitable for modern, sustainable construction:

- **Low Carbon Footprint:** GPC production significantly reduces CO₂ emissions because it does not require high-temperature calcination like OPC manufacturing. By using industrial by-products like fly ash, it promotes waste utilization and reduces reliance on virgin raw materials.
- **High Early Strength:** GPC can achieve rapid strength gain at early ages, making it suitable for precast elements and projects with fast-track construction schedules.
- **Superior Chemical Resistance:** Geopolymer concrete exhibits excellent resistance to acid attacks, chloride penetration, sulphate attacks, and alkali-silica reactions (ASR), making it ideal for aggressive environments such as marine structures, sewage systems, and chemical plants.
- **Durability and Longevity:** The dense microstructure and low permeability of GPC enhance its resistance to environmental degradation, freeze-thaw cycles, and long-term chemical exposure.
- **Reduced Water Demand:** The geopolymer mix typically requires less water compared to OPC concrete, contributing to better durability and reduced porosity.
- **Waste Utilization:** GPC promotes the circular economy by effectively utilizing industrial by-products like fly ash, slag, and other aluminosilicate-rich materials, reducing landfill waste.

III. ROLE OF FLY ASH IN GEOPOLYMER CONCRETE

Fly ash plays a pivotal role in the production of geopolymer concrete (GPC) by acting as the primary source of alumina (Al₂O₃) and silica (SiO₂), which are essential for the geopolymerization process. It is a by-product generated from the combustion of pulverized coal in thermal power plants, making it an environmentally sustainable material for large-scale concrete applications.

Types of Fly Ash Used in GPC

Fly ash is broadly classified into two categories based on its chemical composition and physical properties, as per ASTM C618:

Class F Fly Ash: This type contains low calcium content (<10%), making it rich in silica and alumina. Class F fly ash is highly pozzolanic and is especially suitable for producing geopolymer concrete with improved long-term strength, low heat of hydration, and enhanced durability in aggressive environments.

Class C Fly Ash: Class C fly ash has a higher calcium content (>20%), making it both pozzolanic and self-cementing. Its higher calcium oxide (CaO) content can accelerate early strength gain, making it suitable for fast-track construction projects. However, excessive calcium can sometimes interfere with the geopolymerization mechanism, affecting long-term durability.

Effects of Fly Ash on Geopolymer Concrete Properties

Workability: Fly ash particles are generally spherical in shape, which acts as tiny ball bearings within the mix, improving the flowability and reducing water demand. This characteristic makes GPC mixes with fly ash more workable compared to conventional OPC mixes.

Mechanical Strength: Fly ash contributes significantly to the compressive strength of GPC through enhanced geopolymerization. Optimum fly ash replacement levels, typically in the range of 60% to 80% (by binder weight), can result in compressive strengths exceeding 40 MPa at 28 days of curing, depending on curing conditions and activator concentrations.

Durability Performance: Geopolymer concrete incorporating fly ash demonstrates excellent resistance to chemical attacks, including sulphate attack, acidic environments, and chloride ion penetration. It also shows reduced susceptibility to alkali-silica reaction (ASR), making it suitable for marine and chemically aggressive exposure conditions.

Sustainability: Utilizing fly ash reduces the consumption of virgin raw materials and minimizes CO₂ emissions by avoiding cement clinker production. It also helps in reducing fly ash disposal challenges faced by thermal power plants.

IV. INFLUENCE OF NANO-TiO₂ ON GEOPOLYMER CONCRETE

The integration of nanotechnology into concrete materials has opened new pathways for enhancing concrete performance at the microstructural level. Among the various nanomaterials explored, Nano-Titanium Dioxide (Nano-TiO₂) has gained significant attention in the field of geopolymer concrete research.

Properties of Nano-TiO₂

Nano-TiO₂ is characterized by:

- **Extremely Fine Particle Size:** Typically in the range of 10–100 nanometers, allowing it to penetrate and modify the microstructure of the concrete matrix at a molecular level.
- **High Specific Surface Area:** Due to its nanoscale size, Nano-TiO₂ offers an extensive surface area, which increases its reactivity and interaction with other cementitious materials.
- **Photocatalytic Activity:** Nano-TiO₂ exhibits strong photocatalytic properties, especially under UV light, enabling it to break down organic pollutants and airborne contaminants, making the concrete self-cleaning and air-purifying.
- **Good Dispersion:** Proper dispersion of Nano-TiO₂ in the concrete mix enhances uniformity and minimizes particle agglomeration, which is critical for optimal performance.

Effects of Nano-TiO₂ on Geopolymer Concrete Performance

- **Microstructure Densification:** Nano-TiO₂ acts as an efficient filler material, reducing micro-voids and pore spaces within the geopolymer matrix. This refinement leads to a denser, less permeable concrete, enhancing both mechanical and durability properties.
- **Compressive Strength Improvement:** Numerous studies have reported that the addition of 1–2% Nano-TiO₂ (by weight of binder) can lead to a 15–20% increase in compressive strength at 28 days. The nanoparticles act as nucleation sites for geopolymeric gel formation, accelerating the geopolymerization process.
- **Enhanced Durability:** Nano-TiO₂ improves the concrete's resistance to water permeability,

chloride ion diffusion, and freeze-thaw cycles. Its ability to fill pores and cracks reduces pathways for harmful agents, thereby extending the service life of structures.

- **Self-Cleaning and Air Purification:** One of the unique benefits of Nano-TiO₂ addition is the photocatalytic effect, which enables the concrete surface to break down organic contaminants and NO_x gases when exposed to sunlight. This property contributes to improved aesthetic appearance and better air quality around buildings.

V. LITERATURE REVIEW

Recent research highlights the significant role of nanomaterials in enhancing the mechanical and durability properties of concrete, especially geopolymer concrete (GPC). Alghairi et al. (2025) reported that nanomaterials like nanosilica, nanoalumina, nanoclay, and carbon-based nanomaterials improved compressive (12–50%), tensile (16–107%), and flexural strength (2–90%), along with durability due to microstructural refinement [1]. Bheel et al. (2025) demonstrated that incorporating TiO₂ nanoparticles and PVA fibers in ECC enhanced chemical resistance and mechanical properties, with optimal results at 1.5% TiO₂ and 1% PVA [2]. Dhanashire et al. (2024) and Amarender et al. (2024) showed that nano-silica, combined with optimized NaOH molarity (up to 14M), significantly improved GPC strength and microstructure through accelerated geopolymerization [4][5]. Rani et al. (2024) found that 2% nano-alumina addition enhanced strength and durability in fly ash-GGBS-based GPC [6]. Rihan et al. (2024) confirmed GPC's superior high-temperature resistance up to 1200°C, making it suitable for fire-resistant structures [7]. Dhanapal et al. (2024) highlighted the photocatalytic and self-cleaning benefits of nano-TiO₂ in concrete, while Elhadi et al. (2024) observed that 2% nano-silica optimized mechanical performance in micro-glass fiber-reinforced GPC [8][9]. Khan et al. (2024) reviewed the broad potential of nanomaterials for multifunctional concrete applications, addressing challenges like dispersion and health concerns [10]. Ashwini et al. (2024) recommended 1.75% nano-silica and 35% fly ash replacement for improved

strength [11]. Kishore et al. (2023) and Jandial et al. (2023) emphasized the environmental benefits of GPC and the role of nanomaterials like TiO₂ and black ash in improving durability, workability, and resistance to aggressive environments [13][14].

VI. CONCLUSIONS

The growing environmental concerns and the need for sustainable construction practices have accelerated research into alternative cementitious materials like Geopolymer Concrete (GPC). This comprehensive review highlights the critical role of fly ash and Nano-TiO₂ in enhancing the mechanical, durability, and microstructural properties of GPC. Fly ash, with its high aluminosilicate content, serves as an effective binder precursor, reducing CO₂ emissions and promoting industrial waste utilization. Simultaneously, the incorporation of Nano-TiO₂ has shown considerable promise in improving compressive strength, durability, and microstructure densification while also offering self-cleaning and air-purifying properties due to its photocatalytic action.

Research findings indicate that the synergistic use of fly ash and Nano-TiO₂ significantly enhances GPC's performance in terms of strength gain, reduced permeability, chemical resistance, and sustainability metrics. However, the optimum dosage of Nano-TiO₂ needs careful control, as excessive addition can adversely affect workability and dimensional stability.

Overall, the combined application of fly ash and Nano-TiO₂ in GPC represents a sustainable, eco-friendly, and high-performance solution for modern infrastructure needs. Future research should focus on large-scale field trials, long-term durability assessment under various environmental conditions, and cost-benefit analyses to facilitate broader industrial adoption.

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