GEOPOLYMER CONCRETE

NANO

TIATANIUM DIOXIDE

ZINC OXIDE

SELF-CLEANING GEOPOLYMER CONCRETE WITH NANO-TIO_2/ZNO

A Comprehensive Review of Mechanical, Durability, and Machine Learning-Driven Optimization

B. SRUTHI-23C15A0105

K. LAXMI HARSHITHA-23C15A0102

L. PRASHANTH-21C11A0113

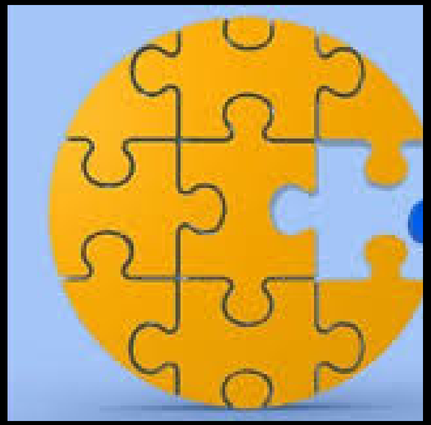
UNDER THE GUIDENCE OF

Mr. S. NARESH

PROBLEM STATEMENT

Ordinary Portland cement concrete is environmentally unsustainable and lacks advanced properties like self-cleaning. Geopolymer concrete (GPC) made with fly ash and GGBS offers a sustainable alternative but faces challenges in achieving optimal mechanical strength, durability, and functionality. Incorporating nano-TiO_2 and ZnO can enhance performance, yet their ideal dosage and long-term behavior are unclear. Additionally, limited use of machine learning restricts mix optimization, highlighting the need for an integrated, data-driven review.

RESEARCH GAP



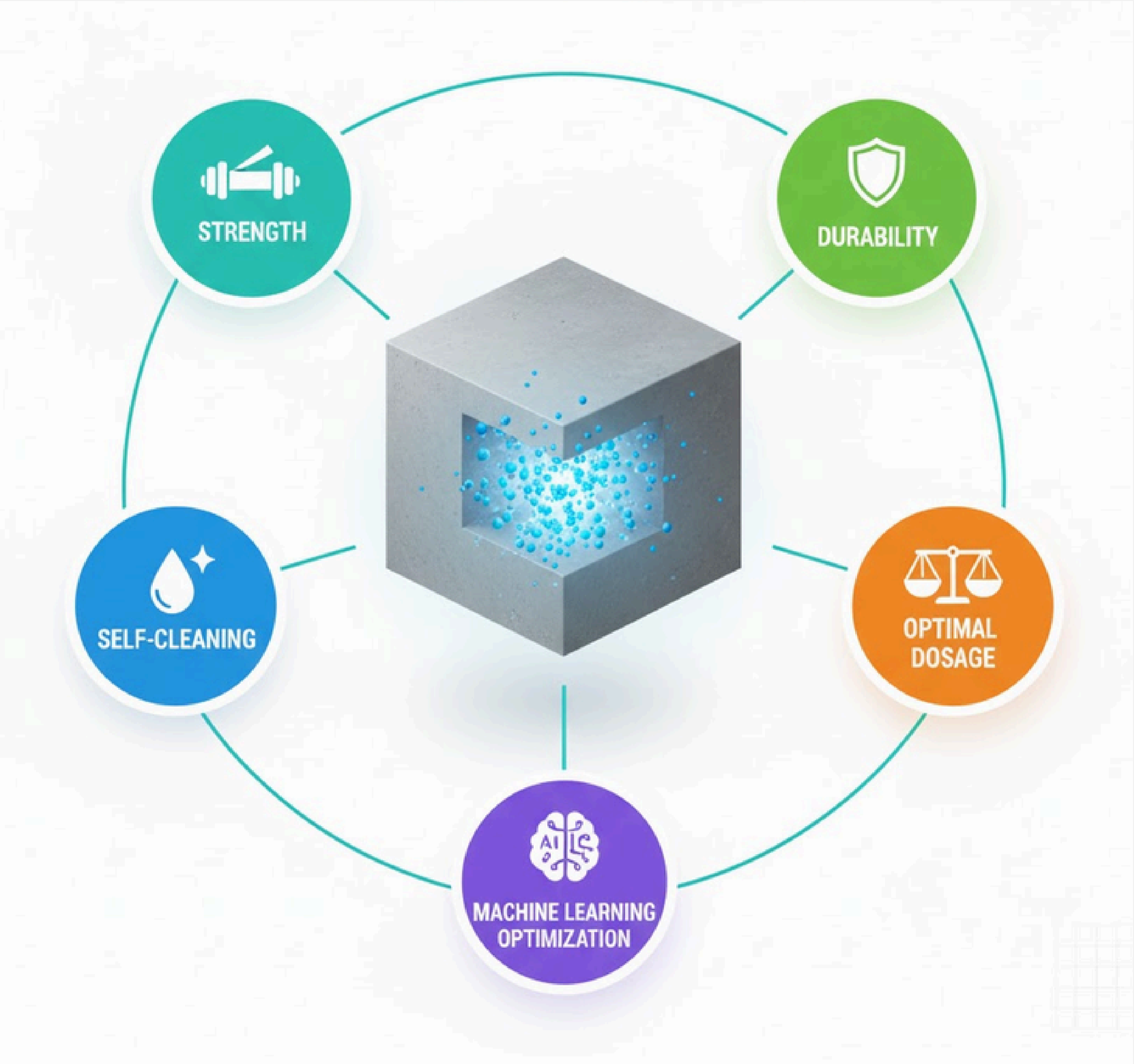
REASEARCH

GAP

- Limited studies on optimal dosage of nano-TiO_2 and ZnO in GPC for balancing strength, durability, and self-cleaning properties.
- Lack of comprehensive evaluation of long-term performance under real environmental conditions.
- Existing research mainly focuses on either mechanical or durability aspects, with fewer works addressing functional self-cleaning efficiency.
- Minimal integration of machine learning techniques to optimize GPC mix design and predict performance accurately.
- Insufficient comparative reviews combining mechanical, durability, and AI-driven optimization in a single framework.

OBJECTIVES

- To review the role of nano-TiO_2 and ZnO in enhancing the properties of geopolymer concrete.
- To evaluate the impact of nano-additives on mechanical strength, durability, and self-cleaning efficiency.
- To identify the optimal dosage levels of nano-materials for balanced performance.
- To explore the integration of machine learning models for accurate prediction and optimization of GPC mix design.
- To establish a framework for developing sustainable, high-performance, and smart construction materials.



ABSTRACT

- Study focuses on self-cleaning Geopolymer Concrete (GPC) using nano-TiO_2 and ZnO as photocatalytic additives.
- Utilized M25-grade mix with 50% Fly Ash and 50% GGBS, activated by 12M NaOH.
- Nano-additives added at 0.5%, 1.0%, and 1.5% by binder weight.
- Optimal dosage (1.0–1.5%) showed:
- Compressive strength up to 35 MPa (28 days) ~30% reduction in water absorption
- High photocatalytic degradation under UV exposure
- Machine Learning model ($R^2 > 0.95$) accurately predicted compressive strength and optimized mix design.
- Concludes that nano-modified GPC is a sustainable, durable, and self-cleaning alternative to ordinary Portland cement.

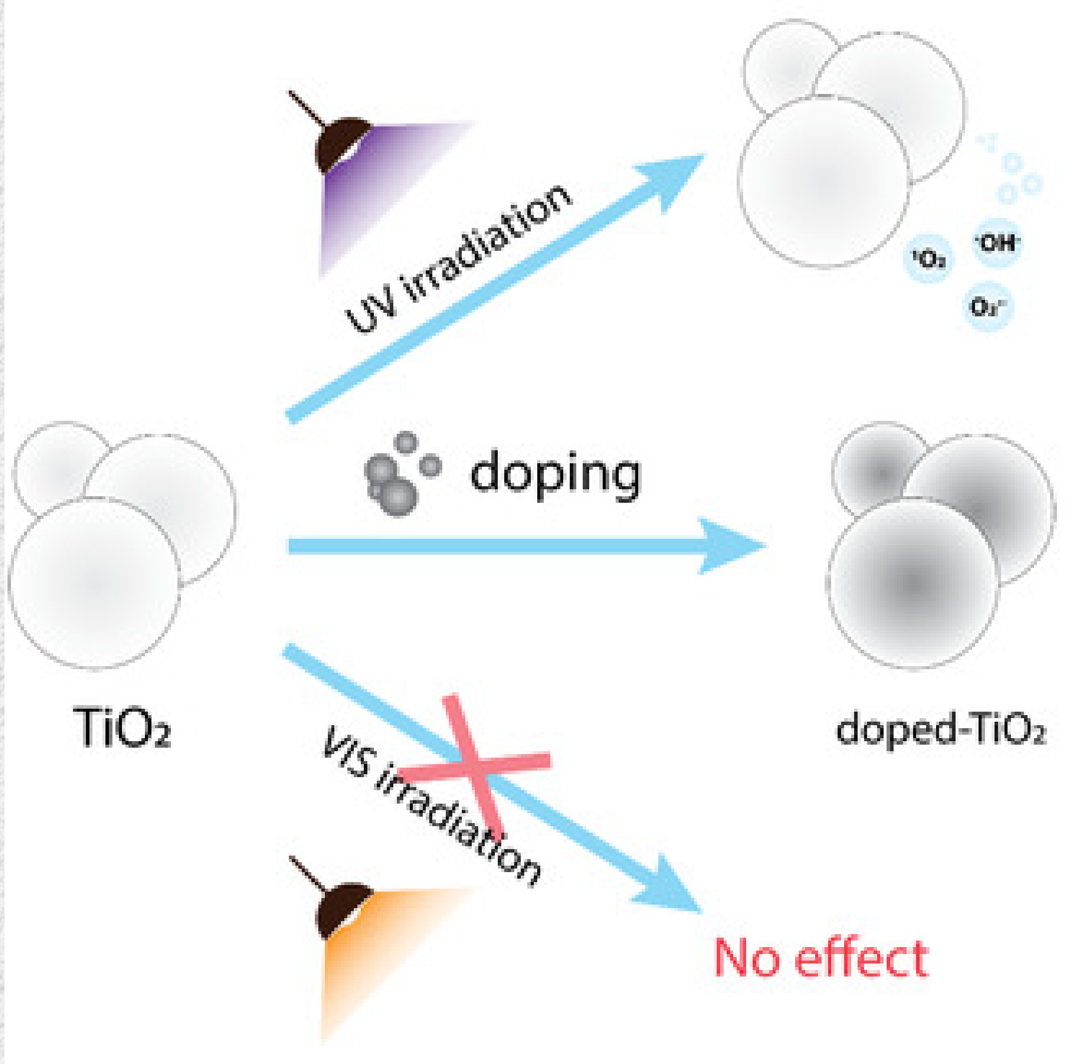


Table of Contents

INTRODUCTION

1.1 Environmental Imperative

- OPC production emits large amounts of CO_2 due to calcination.
- GPC can reduce emissions by up to 80%, supporting carbon neutrality and circular economy by reusing industrial waste (FA & GGBS).
- Nano-additives improve both sustainability and functionality in eco-friendly construction materials.

1.2 Self-Cleaning Mechanism

- TiO_2 and ZnO nanoparticles act as photocatalysts under UV light, generating Reactive Oxygen Species (ROS).
- These radicals decompose pollutants like NO_x and VOCs, maintaining clean surfaces and air quality.
- Optimum nano dosage: 1.0–1.5% by binder weight for peak strength and self-cleaning efficiency.

1.3 Literature Synthesis

- Nano-TiO_2 improves compressive strength by up to 20–30% and reduces water absorption.
- ZnO enhances visible-light responsiveness and photocatalytic activity (~85% dye degradation).
- Research gaps remain in:
  a. Standardizing nano dosages
  b. Durability testing under harsh conditions
  c. ML-driven predictive modeling for GPC optimization.

1.4 Novelty & Objectives

- First integrated study combining Nanotechnology, Durability, and Machine Learning for self-cleaning GPC.

Objectives:

1. Assess the influence of nano-TiO_2/ZnO (0.5–1.5%) on strength, durability, and photocatalytic properties.
2. Develop an ML model ($R^2 > 0.95$) for accurate compressive strength prediction.
3. Propose guidelines for industrial application and sustainable concrete design.

LITERATURE REVIEW

Author & Year	Title	Objective	Methodology	Key Findings	Relevance to Present Study
Wang et al. (2024)	*Multi-performance optimization of low-carbon geopolymer considering mechanical, cost, and CO_2 emission based on experiment and interpretable learning*	To optimize geopolymer performance considering strength, cost, and emissions.	Experimental study with interpretable ML model integration.	Balanced strength, cost, and low CO_2 footprint; ML improved optimization.	Demonstrates ML's role in optimizing mix design of GPC.
Saranya et al. (2020)	*Behaviour of GGBS–Dolomite Geopolymer Concrete Short Column under Axial*	To examine structural performance of GGBS–Dolomite GPC under	Axial loading tests on GPC short columns.	Improved compressive strength and load-bearing capacity vs OPC.	Validates structural performance of geopolymer concrete mixes.

Author & Year	Title	Objective	Methodology	Key Findings	Relevance to Present Study
Gad et al. (2024)	*Predicting the compressive strength of engineered geopolymer composites using automated machine learning*	To develop ML models for predicting GPC strength.	Automated ML applied on experimental dataset.	Achieved $R^2 > 0.95$ in compressive strength prediction.	Strengthens the use of ML in mix optimization for nano-GPC.
Almutairi et al. (2021)	*Potential applications of geopolymer concrete in construction: A*	To explore real-world use and sustainability of GPC.	Review of construction case studies using GPC.	GPC identified as eco-efficient, durable, and sustainable.	Reinforces real-world application of self-cleaning GPC systems.

MATERIALS AND MIX

1. Binder Materials

- Fly Ash (FA):
  - A Class F low-calcium industrial by-product obtained from coal combustion.
  - Acts as a primary aluminosilicate source in geopolymerization.
  - Provides long-term strength, reduces heat of hydration, and promotes sustainability.
- Ground Granulated Blast Furnace Slag (GGBS):
  - A by-product from the steel industry, rich in calcium and silica.
  - Enhances early strength, durability, and workability of GPC.
  - Together with fly ash (50:50 ratio), it forms a balanced binder offering strength and sustainability.

BINDER RATIO: FA : GGBS = 50 : 50 (BY WEIGHT) → ACHIEVES M25-GRADE GPC MIX.

2. Alkaline Activator Solution

- Sodium Hydroxide (NaOH):
  - Used at 12M concentration to initiate the dissolution of aluminosilicate particles.
  - Provides necessary alkalinity for polymer chain formation.
- Sodium Silicate (Na_2SiO_3):
  - Acts as a source of soluble silica, improving binding and strength.
  - Promotes rapid setting and better gel formation in GPC.

MIX RATIO: NA_2SIO_3 : NAOH = 2.5 : 1 → ENSURES EFFECTIVE ACTIVATION AND MECHANICAL STABILITY.

3. Nano-Additives

- Nano Titanium Dioxide (TiO_2):
  - Provides photocatalytic and self-cleaning properties by decomposing organic pollutants under UV light.
  - Enhances compressive strength and surface durability.
  - Effective in air-purifying concrete applications.

I DOSAGE: 0.5%, 1.0%, AND 1.5% BY BINDER WEIGHT .

4. Aggregates & Water

- Fine Aggregate:
  - River sand (as per IS 383) used for smooth texture and uniform compaction.
- Coarse Aggregate:
  - Crushed granite (max 20 mm) ensures structural stability and strength.

MIX DESIGN

Step-1: Target strength Fck = fck + 1.65x S Where,
S = 4.0 N/mm
Fck = 25 + 1.65 x 4.0
Fck = 31.6 N/mm2

Step-2: Approximate air content
IS – 10262;2019, table – 3, pg.no.3

- 10mm nominal maximum size of aggregate entrapped air, as percentage of volume of concrete 1.5%
- 20mm nominal maximum size of aggregate entrapped air, as percentage of volume of concrete 1.0%

We take,
10mm and 20mm nominal maximum size of aggregates – entrapped air, as percentage of volume of concrete 1.5% and 1.0% So that average value (1.5 %+ 1.0%) / 2 = 1.25%

Step-3: water-cement ratio

 From, IS – 456;2000, table – 5, pg.no.20

For M25 – maximum water cement ratio 0.50 (moderate)

Step-4: Selection of water content

From, IS -10262;2019; table – 4, pg.no.5

Water content = 186kg (for 50mm slump)

Estimated water content for 75mm slump

From, (IS -10262 -CL.5.3) for every 25mm – add 3%

= 3 x 186 / 100 = 192 kg/M3

Water content = 192 kg /m3

Step-5: Calculation of cement content

Water-cement ratio = 0.55

Water content = 192 kg

Cement content = water content/water cement ratio

Cement content =192 / 0.55 = 349 kg/m3

Minimum cement content for moderate condition

= 300 kg/m3 (IS – 456;2000, table-5)

Maximum cement content = 450 kg/m3

(IS – 456;2000)

Cement content = 349 > 300 kg/m3

Hence,ok

Step-6: Proportion of volume of coarse aggregate and fine aggregate content

From, IS – 10262;2019, table – 5,

The volume of coarse aggregate corresponding to 20mm size aggregate and fine aggregate (Zone II) for water cement ratio of 0.50 = 0.62.

cement ratio of 0.50 = 0.62.

In the present case water-cement ratio is 0.55.

For every 0.05 increase then substract the 0.01. and also the for every 0.05 decreases then add the 0.01. ± 0.05 W/C = ± 0.01

As the water-cement ratio is higher by 0.05 The proportion of volume of coarse aggregate is decreases by 0.01

Corrected proportion of volume of coarse aggregate for the water-cement ratio of 0.55 = 0.62 – 0.01 = 0.61. Volume of fine aggregate content = 1 - 0.61 = 0.39

Step-7: Mix calculation. The mix calculations per unit volume of concrete shall be as follows;

a. Total volume = 1 m3

b. Volume of entrapped air in wet concrete = 0.0125 m3

c. Volume of cement = mass of cement/ specific gravity of cement x 1/1000 349/3.10 x 1/1000 = 0.112 m3

d. Volume of water = mass of water/specific gravity of water x 1/1000 =192/1 x 1/1000 = 0.192 m3

e. Volume of all in aggregate

[(a-b)(c+d)] = [(1-0.0125)(0.112+0.192)] = 0.683 m3

f. Mass of coarse aggregate = g x volume of coarse aggregate x specific gravity of coarse aggregate x 1000
=0.683 x 0.61 x 2.89 x 1000 = 1204.06 kg - 1204 kg.

g. Mass of fine aggregate = g x volume of fine aggregate x specific gravity of fine aggregate x 1000
= 0.683 x 0.39 x 2.56 x 1000 681.90-682 kg

Step-8: Mix proportions for trial (Wet)

Cement = 349 kg/m3

Water 192 kg/m3

Fine aggregate = 682 kg/m3

Coarse aggregate = 1204 kg/m3

W/C ratio = 0.55

C/C F.A/C: C.A/C: W/C

1:1.95: 3.44: 0.55

For one cube :

Cement: 0.15 x 0.15 x 0.15 x 349 = 1.177 kg/m3

Fine aggregate: 0.15 x 0.15 x 0.15 x 682 2.301 kg/m3

Coarse aggregate: 0.15 x 0.15 x 0.15 x 1204 = 4.063 kg/m3

Water: 0.15 x 0.15 x 0.15 x 192 = 0.648 kg/m3

Step-9: Adjustment on water, fine aggregate and coarse aggregate:

a) Fine aggregate:

= mass of fine aggregate in SSD condition / 1 + water absorption/100 682/1+1/100 = 675 kg/m3

b) Coarse aggregate

= mass of coarse aggregate in SSD condition /

1+ water absorption/100

1204/1+0.405/100 = 1199 kg/m3

The extra water to be added for absorption by coarse and fine aggregate,

1) For coarse aggregate:

= mass of coarse aggregate in SSD condition -mass of coarse aggregate in dry condition 1204-1199 = 5 kg

2) For fine aggregate:
=mass of fine aggregate in SSD condition-mass of fine aggregate in dry condition 682-675=7 kg
The estimated requirement for added water, therefore, 192+5+7 = 204 kg/m3

Step-10: Mix proportions after adjustment for dry aggregates
Cement=349 kg/m3 Water (to be added) = 204 kg/m3
Fine aggregate (dry) = 675 kg/m3
Coarse aggregate (dry) = 1199 kg/m3
W/C ratio 0.58

Grade of concrete: M25 [1:1:2]

(CEMENT=50:50 FLYASH AND GGBS)

Mix Proportion:

For one cube:

Flyash and GGBS: 1.177kg

Fine aggregate: 2.301kg

Coarse aggregate:4.063kg

Distilled Water: 0.648 liters

EXPERIMENTAL DETAILS

Category	Test Name	Purpose / Description
Mechanical Properties	Compressive Strength	Measured at 7, 14, and 28 days to evaluate load-bearing capacity of GPC.
	Split Tensile Strength	Determines bonding and ductility between geopolymer matrix and aggregates.
	Flexural Strength	Assesses the bending resistance and toughness of GPC beams.
Durability Studies	Water Absorption Test	Measures porosity and permeability reduction in nano-modified mixes.
	Acid & Sulphate Resistance	Evaluates the chemical stability and degradation under harsh environmental exposure.
Functional (Self-Cleaning) Properties	Photocatalytic Activity	Tested via methylene blue dye degradation under UV light to determine self-cleaning efficiency.
	Surface Morphology (SEM/EDS)	Analyzes particle dispersion, surface texture, and microstructural densification.

Expected Conclusion

- The incorporation of nano-TiO_2 and ZnO is expected to enhance the mechanical strength, durability, and self-cleaning efficiency of Geopolymer Concrete (GPC).
- Optimum nano-additive dosage is anticipated around 1.0–1.5%, improving compressive strength and reducing water absorption significantly.
- Photocatalytic activity is expected to demonstrate effective degradation of surface pollutants under UV exposure, validating the self-cleaning property.
- The integration of Machine Learning models is expected to provide accurate prediction and optimization of mix designs ($R^2 > 0.95$).
- Overall, the study aims to establish Nano-GPC as a sustainable, smart, and high-performance material suitable for future eco-friendly construction.

REFERENCES

1. Bélaïd, F. (2022). How does concrete and cement industry transformation contribute to mitigating climate change challenges? Resources, Conservation and Recycling Advances, 15, Article 200084. https://doi.org/10.1016/j.rcradv.2022.200084
2. Rihan, M. A. M., Onchiri, R., Gathimba, N., & Sabuni, B. (2024). Mix design approaches of eco-friendly geopolymer concrete: A critical review. Hybrid Advances, 7, Article 100290. https://doi.org/10.1016/j.hybadv.2024.100290
3. Duan, P., Yan, C., Luo, W., & Zhou, W. (2016). Effects of adding nano-TiO_2 on compressive strength, drying shrinkage, carbonation and microstructure of fluidized bed fly ash-based geopolymer paste. Construction and Building Materials, 106, 115–125. https://doi.org/10.1016/j.conbuildmat.2015.12.095
4. Wilson, J., Ke, X., Maskell, D., & Ball, R. J. (2025, May 21). Evaluation of photocatalytic ZnO-geopolymer composites: Degradation of methylene blue and α-pinene. Cement and Concrete Composites, Advance online publication. https://doi.org/10.1016/j.cemconcomp.2025.106125
5. Huo, Y., Sun, H., Chen, Z., & Yang, Y. (2022). Mechanical properties and its reliability prediction of engineered/strain-hardening cementitious composites (ECC/SHCC) with different moisture contents at negative temperatures. Cement and Concrete Composites, 134, Article 104812. https://doi.org/10.1016/j.cemconcomp.2022.104812

Thank You!