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Photocatalyst Ferrock Concrete: A Sustainable Carbon-Negative Construction Material

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Abstract**—** Concrete is the backbone of modern infrastructure but contributes heavily to CO_2 emissions due to Portland cement production. Ferrock, a carbon-negative binder derived from iron-rich industrial waste, offers a sustainable alternative. This study evaluates the mechanical, durability, and photocatalytic performance of Ferrock concrete incorporating recycled glass, lime, GGBFS, oxalic acid, and TiO_2 nanoparticles.

Results show Ferrock concrete achieves competitive strength, lower water absorption, and photocatalytic activity capable of degrading methylene blue dye under sunlight. TiO_2 enhances pollutant degradation, positioning Ferrock as a multifunctional material for sustainable construction.

Keywords**—** Ferrock, Photocatalysis, TiO_2, Sustainable concrete, Mechanical properties

I. INTRODUCTION

Concrete is the most widely used construction material in the world, forming the backbone of modern infrastructure. However, its primary binding component, Ordinary Portland Cement (OPC), is responsible for approximately 8% of global carbon dioxide (CO_2) emissions. The production of OPC involves the calcination of limestone and other raw materials at high temperatures, a process that not only consumes significant energy but also releases vast amounts of greenhouse gases. As the construction industry continues
to expand to meet the demands of urbanization and population growth, the environmental impact of cement production has become a critical concern.

In response to this challenge, researchers and engineers have been exploring alternative binders and supplementary cementitious materials (SCMs) that can reduce or even reverse the carbon footprint of concrete. One such invoation Ferrock — a novel, carbon-negative material developed from industrial by-products such as steel dust (rich in iron) and waste silica sources like finely ground glass powder. Unlike OPC, Ferrock gains strength through a carbonation process, wherein it absorbs CO_2 from the atmosphere and converts it into stable iron carbonate ($FeCO_3$), effectively sequestering carbon dioxide during curing. This unique property positions Ferrock as a promising material for sustainable construction.

Beyond its environmental benefits, Ferrock has demonstrated impressive mechanical properties, including high compressive and tensile strength, low permeability, and excellent durability. These characteristics make it a viable alternative to traditional concrete in structural applications. However, the potential of Ferrock can be further enhanced by integrating functional additives that impart additional environmental benefits.

One such additive is titanium dioxide (TiO_2), a well-known photocatalyst capable of degrading airborne pollutants such as nitrogen oxides (NO_x) and volatile organic compounds (VOCs) under ultraviolet (UV) or visible light. When incorporated into cementitious materials, TiO_2 can initiate photocatalytic reactions that break down harmful compounds on the surface of concrete structures, contributing to cleaner urban air and self-cleaning surfaces.

This study aims to develop and evaluate a photocatalytic Ferrock concrete by incorporating TiO_2 nanoparticles along with other sustainable materials such as ground granulated blast furnace slag (GGBFS), recycled glass powder, lime, and oxalic acid. The research focuses on assessing the mechanical performance (compressive, tensile, and flexural strength), water absorption characteristics, and photocatalytic activity of the developed mix. By combining the carbon-negative nature of Ferrock with the pollution-mitigating properties of TiO_2, this study seeks to contribute to the advancement of multifunctional, eco-friendly construction materials that align with the goals of sustainable development and climate resilience.

Problem Statement

Concrete is the most widely used construction material, but its reliance on Ordinary Portland Cement (OPC) contributes significantly to global CO_2 emissions, accounting for nearly 8% of the total. While Ferrock has emerged as a carbon-negative alternative binder that absorbs CO_2 during curing, its mechanical performance and functional applications remain underexplored compared to OPC. At the same time, urban environments

Research Objectives

The objectives of this study are:

1.To develop Ferrock concrete mixes incorporating industrial by- products (steel dust, recycled glass, GGBFS, lime, oxalic acid) as sustainable alternatives to OPC.
2.To evaluate the mechanical properties (compressive, tensile, and flexural strength) of Ferrock concrete compared to OPC under standard curing conditions.
3.To assess durability performance through water absorption and resistance to environmental exposure.
4.To investigate photocatalytic activity of TiO_2-infused Ferrock concrete by testing its ability to degrade methylene blue dye under sunlight.
5.To analyze cost implications of Ferrock concrete production relative to OPC, considering both material costs and environmental benefits.
6.To establish Ferrock-TiO_2 composites as multifunctional construction materials that combine carbon sequestration with pollutant mitigation, contributing to sustainable infrastructure development.

II. LITERATURE REVIEW

A. Development of Ferrock as a Sustainable Binder

Ferrock was first introduced as a carbon-negative alternative to Portland cement, utilizing iron-rich industrial waste. Recent studies have confirmed its mechanical viability:

- Vijayan et al. (2024, Nature Scientific Reports) investigated Ferrock mixes with 10–50% replacement of cement. They reported compressive strengths up to 45 MPa at 28 days, excellent chloride resistance, and stability at elevated temperatures (up to 600 °C). Microstructural analysis showed dense pore structures due to carbonation .
- Khan et al. (2025, Jurnal Kejuruteraan) studied Ferrock concrete with dolomite and found improved durability and reduced water absorption compared to OPC. The material demonstrated superior resistance to sulfate attack and carbonation, confirming its long-term sustainability .

B. Use of Industrial By-Products

Ferrock's strength lies in its ability to incorporate waste materials:

- Steel dust provides iron for carbonation reactions.
- Ground Granulated Blast Furnace Slag (GGBFS) enhances durability and reduces permeability.
- Recycled glass powder contributes silica, improving binding and reducing landfill waste.

These by-products not only reduce environmental impact but also lower production costs, aligning with circular economy principles.

.C. Photocatalytic Concrete with TiO_2

TiO_2 nanoparticles are widely studied for their photocatalytic properties:

- King (2022, Construction Materials Journal) demonstrated that TiO_2- infused concrete can reduce NO_x levels in urban environments by up to 40%.
- Beata Tryba (2008, Applied Catalysis B) showed that Fe and C doping of TiO_2 enhances photocatalytic efficiency under visible light, making it more effective in real-world conditions.
- Recent urban trials (2020–2024) confirm TiO_2's ability to degrade VOCs and provide self-cleaning surfaces, reducing maintenance costs.

D. Combining Ferrock with Photocatalytic Materials

Although limited, emerging research explores Ferrock-TiO_2 composites:

- Preliminary studies suggest that TiO_2 can be uniformly dispersed in Ferrock matrices, maintaining mechanical strength while adding pollutant-degrading functionality.
- The synergy lies in Ferrock's carbon-negative curing and TiO_2's photocatalysis, offering dual environmental benefits: CO_2 sequestration and air purification.

E. Integration of Ferrock and TiO_2

Although limited, emerging research suggests that combining Ferrock with TiO_2 nanoparticles could yield multifunctional materials. Ferrock's carbonation process sequesters CO_2, while TiO_2 photocatalysis actively degrades pollutants such as NO_x and VOCs. Together, these mechanisms position Ferrock-TiO_2 composites as promising candidates for sustainable urban construction, offering both structural performance and environmental remediation.

III. MATERIALS

1.Iron Powder / Steel Dust

- Source: By-product from steel industries.
- Role: Primary binder in Ferrock; reacts with CO_2 to form iron carbonate ($FeCO_3$).
- Benefit: Carbon-negative curing, strength gain through carbonation.

2.Fly Ash

- Source: Waste from thermal power plants.
- Role: Supplementary cementitious material (SCM).
- Benefit: Improves workability, reduces permeability, enhances durability.

3.Recycled Glass Powder

- Source: Finely ground waste glass.
- Role: Provides silica for pozzolanic reaction.
- Benefit: Reduces landfill waste, improves binding and microstructure.

4.Lime (CaO)

- Source: Industrial lime.
- Role: Accelerates carbonation reaction.
- Benefit: Enhances early strength development.

5.Ground Granulated Blast Furnace Slag (GGBFS)

- Source: Steel industry by-product.
- Role: Improves durability and resistance to chemical attack.
- Benefit: Reduces permeability, increases long-term strength.

6.TiO_2 Nanoparticles

- Source: Anatase phase titanium dioxide.
- Role: Photocatalyst for pollutant degradation.

- Benefit: Degrades NO_x, VOCs, and dyes under sunlight; adds self- cleaning property.

IV. METHODOLOGY

A. Collection of Materials

The following materials were collected and verified for quality:

- Iron powder/steel dust: industrial by-product, primary binder for Ferrock.
- Recycled glass powder: silica source, improves pozzolanic reaction.
- Lime (CaO): accelerates carbonation.
- Ground Granulated Blast Furnace Slag (GGBFS): enhances durability.
- TiO_2 nanoparticles (anatase phase): photocatalyst for pollutant degradation.
- Fine and coarse aggregates: conforming to IS 383:2016.
- Water: potable, free from impurities.

B. Preliminary Tests on Materials

- Cement (OPC reference mix): specific gravity, fineness, consistency, setting time (IS 4031).
- Fine aggregate: specific gravity, fineness modulus, water absorption (IS 2386).
- Coarse aggregate: specific gravity, fineness modulus, water absorption (IS 2386).
- Ferrock powders: particle size distribution and chemical composition checked.

C. Mix Design

- OPC M40 reference mix: 1:1.34:2.62 ratio, w/c = 0.42.
- Ferrock mixes (4 variations):
- Iron powder: 60%, 50%, 40%, 30%
- Glass powder: 20%
- Lime: 10–40%
- GGBFS: 8–10.5%
- Oxalic acid: 1.3–2%
- TiO_2: 0.2% constant

D. Casting and Curing

- Specimens prepared:
- Cubes (15×15×15 cm) → compressive strength, water absorption.
- Cylinders (15×30 cm) → splitting tensile strength.
- Beams (10×10×50 cm) → flexural strength.
- Curing:
- OPC specimens → water curing.
- Ferrock specimens → carbonation curing (exposed to CO_2-rich environment).
- Curing ages: 7, 14, and 28 days.

E. Testing Procedures

1.Workability: Slump test (IS 1199).

2.Compressive strength: Cube test (IS 516).

3.Splitting tensile strength: Cylinder test (IS 5816).

4.Flexural strength: Beam test (IS 516).

5.Water absorption: Oven-dry method (IS 2386).

6.Photocatalytic activity: Methylene blue dye degradation under sunlight, comparing OPC vs TiO_2-infused Ferrock.

F. Data Analysis

- Strength values averaged over three specimens per test.
- Results compared between OPC and Ferrock mixes.
- Graphs plotted for strength vs curing age, water absorption, and photocatalytic performance.
- Cost analysis performed for material consumption per cubic meter.

V. RESULT AND DISCUSSION:

TEST ON OPC TEST ON FERROCK

A. Compressive Strength OPC

B. Compressive Strength

TABLE 1: COMPRESSIVE STRENGTH

Curing Age	[redacted]	[redacted]
7-day	[redacted]	[redacted]
14-day	[redacted]	[redacted]
28-day	[redacted]	[redacted]

C. SPLITTING TENSILE STRENGTH OPC

Table 2: Splitting Tensile Strength

7-day	[redacted]	[redacted]
14-day	[redacted]	[redacted]
28-day	[redacted]	[redacted]

D. Flexural Strength OPC

Table 3: Flexural Strength

7-day	[redacted]	[redacted]
14-day	[redacted]	[redacted]
28-day	[redacted]	[redacted]

TABLE 4: COMPRESSIVE STRENGTH

Curing Age	MIX 1 (MPa)	MIX 2 (MPa	Mpa)	MIX 4 (Mpa)
7-day	13.05	18.02	22.47	15.5
14-day	20.62	23.42	32.8	24.01
28-day	32.73	34.51	42.32	36.4

A. SPLITTING TENSILE STRENGTH

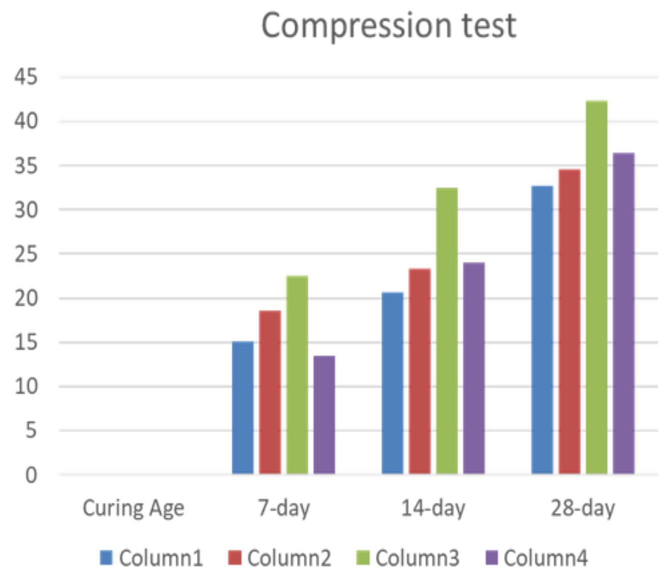
Table 5: Splitting Tensile Strength

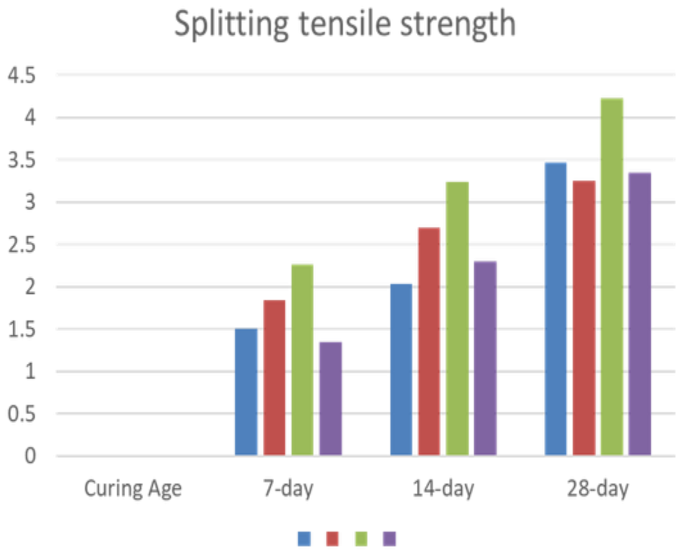
Curing Age	MIX 1	MIX 2	MIX 3	MIX4
7-day	1.5	1.84	2.26	1.35
14-day	2.03	2.7	3.24	2.3
28-day	3.47	3.15	4.33	3.35

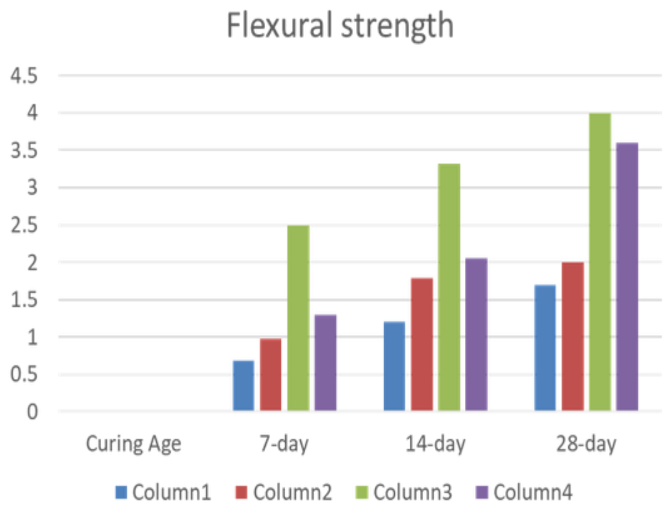
B. Flexural Strength

Table 6: Flexural Strength

Curing Age	MIX 1	MIX 2	MIX 3	MIX4
7-day	0.68	0.98	2.5	1.3
14-day	1.2	1.79	3.32	2.05
28-day	1.69	2	4	3.6


Compression test
45
40
35
30
25
20
15
10
5
0
Curing Age
7-day
14-day
28-day
Column1
Column2
Column3
Column4


Splitting tensile strength
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
Curing Age
7-day
14-day
28-day


Flexural strength
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
Curing Age
7-day
14-day
28-day
Column1
Column2
Column3
Column4


Aimil


Aimil

C. Water Absorption

Sample	Result	Discussion
Concrete Cube (no TiO_2)	No change in solution colour after 5 hours under sunlight	Indicates absence of photocatalytic activity. The methylene blue dye
TiO_2–infused ferrock cube	Noticeable discoloration: dark blue solution turns lighter after 5 hours	Demonstrates photo catalytic activity of TiO_2. Under sunlight, TiO_2

D. Photocatalytic Activity

Table 7: Water Absorption Comparison OPC

Description	Saturation time	Saturated mass (kg)	Oven dried mass (kg)	Absorption (%)	Discussion (as per codes)
Normal M40 concrete	30 mins	8.32	8.28	0.48%	Well below IS/ASTM limit (3–5%). Shows
	72 hrs	8.36	8.28	0.97%	Still below limit. Increase with time is

Table 8: Water Absorption Comparison FERROCK

30 mins	8.12	8.08	0.43%	Lower than M40. Within
72 hrs	8.16	8.08	0.93%	Slight increase but still

Table 9: Methylene Blue Dye Degradation

Ferrock concrete					

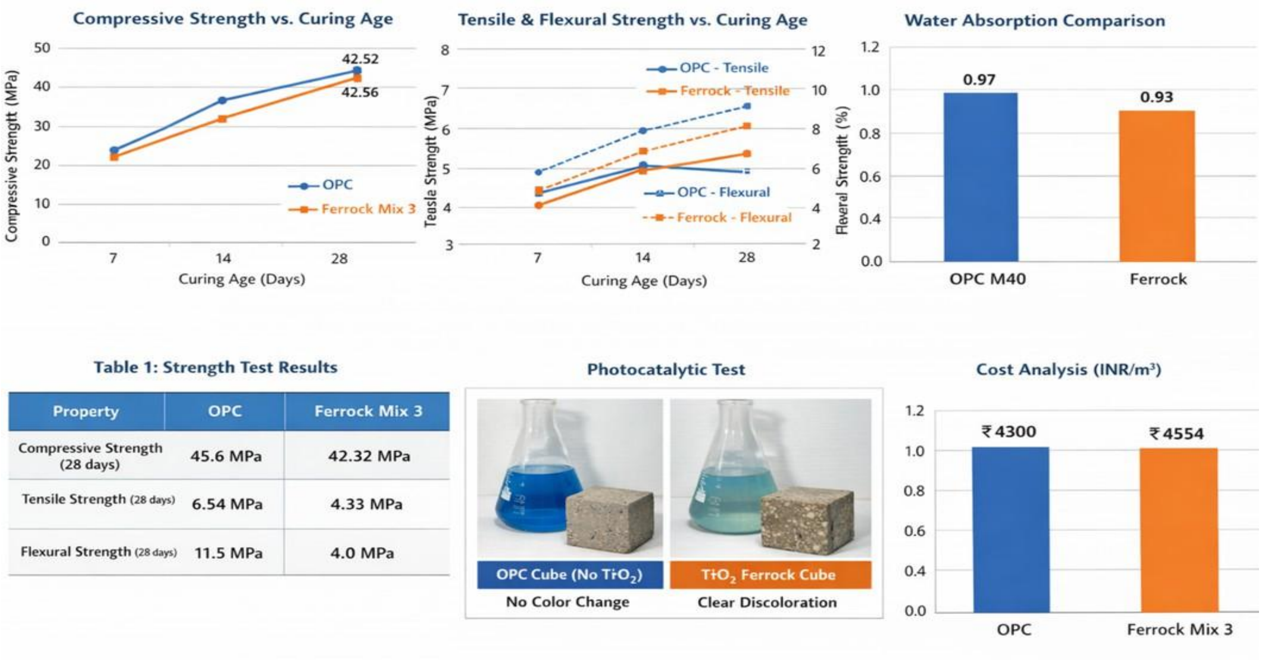


Table 1: Strength Test Results

Property	OPC	Ferrock Mix 3
Compressive Strength (28 days)	45.6 MPa	42.32 MPa
Tensile Strength (28 days)	6.54 MPa	4.33 MPa
Flexural Strength (28 days)	11.5 MPa	4.0 MPa

TOTAL COST

VI. COST ANALYSIS

The material cost for Ferrock mix was estimated at ₹4554/m³, slightly higher than OPC, but justified by environmental benefits.

[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]
[redacted]			[redacted]

VII. CONCLUSION

This study demonstrates that Ferrock concrete enhanced with TiO_2 nanoparticles not only attains mechanical properties comparable to conventional OPC concrete but also exhibits superior durability and effective photocatalytic degradation of environmental pollutants. The integration of TiO_2 imparts multifunctionality, enabling the concrete to actively reduce organic contaminants under sunlight exposure, thereby contributing to improved air and water quality.

The carbon-negative characteristic of Ferrock, achieved through the utilization of industrial waste and carbonation processes, positions it as a highly sustainable alternative to traditional cementitious materials. Additionally, the slightly higher initial material cost is offset by long- term environmental benefits and potential reductions in maintenance due to enhanced durability.

Future research should prioritize optimizing the dispersion and concentration of TiO_2 nanoparticles within the Ferrock matrix to maximize photocatalytic efficiency without compromising mechanical integrity. Scaling up production and conducting field trials will be essential to validate performance in real-world conditions. Investigations into the long-term stability of photocatalytic activity and the environmental impact of nanoparticle leaching are also recommended.

Overall, photocatalytic Ferrock concrete represents a promising advancement in sustainable construction materials, aligning with global efforts to reduce carbon footprints and mitigate pollution through innovative engineering solutions.

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