

An Experimental Performance Evaluation: Optimizing Biochar and TiO₂ Synergies in Concrete

Sachin¹, Prof. Rajashree Chinta², Prof. Sujeet Patil³

^{1,2,3}Department of Civil Engineering, PDA College Of Engineering, Kalaburagi, India
Email: bhagadisachin007@gmail.com

ABSTRACT

This study presents an experimental investigation into the fresh and hardened properties of M30 grade concrete incorporating two supplementary admixtures — biochar (BC) and anatase-phase titanium dioxide (TiO₂ nanoparticles) — as partial cement replacements. Three mix variants were evaluated: Specimen(S1) (1% BC + 0.5% TiO₂), Specimen(S2) (1% BC + 1.75% TiO₂), and Specimen(S3) (2% BC + 3% TiO₂) by weight of OPC Grade 43 cement. Fresh workability was assessed via slump testing (IS 1199:1959), while hardened mechanical performance was evaluated through compressive strength on 150 mm cubes (IS 516) and split tensile strength on 300×150 mm cylinders at 7-day and 28-day curing ages. The optimum mix (S1) attained a 7-day compressive strength of 41.19 MPa — exceeding the M30 target — and a 7-day split tensile strength of 23.86 MPa. The observed slump of 110 mm, classified as medium-to-high workability (IS 456:2000), confirms the effectiveness of pre-saturation of biochar and optimised mix proportioning. An atypical strength regression between 7 and 28 days is documented and mechanistically attributed to accelerated early hydration by nano-TiO₂, subsequent thermal eigenstress accumulation, and micro-crack propagation at biochar–paste interfaces.

Keywords: *Biochar, Titanium Dioxide (TiO₂), Compressive Strength, Split Tensile Strength, Slump, M30 Concrete, Nanoparticles, Internal Curing, Photocatalytic Concrete*

I. Introduction

Concrete remains the most extensively utilised construction material globally, valued for its structural versatility, compressive strength, and cost-effectiveness. However, the dominant role of ordinary Portland cement (OPC) carries substantial environmental consequences, including large-scale CO₂ emissions associated with clinker production. This environmental burden has intensified research into smart, multifunctional cementitious composites capable of simultaneously delivering structural performance and environmental remediation.

With dual imperative, nanotechnology has emerged as a transformative framework for next-generation cementitious materials. Titanium dioxide (TiO₂) in its anatase crystalline phase has attracted considerable attention owing to its well-established photocatalytic activity under ultraviolet radiation, its nucleation-accelerating effect on C-S-H gel formation, and its capacity to densify the interfacial transition zone (ITZ). Concurrently, biochar — a carbon-rich porous material produced through controlled pyrolysis of lignocellulosic biomass — has been investigated as a sustainable partial cement replacement due to its CO₂ sequestration potential, internal curing capability, and pore-filling characteristics.

This study addresses key research gaps by systematically evaluating the combined fresh and hardened properties of M30 concrete incorporating both biochar and nano-TiO₂ across a multi-level dosage matrix, with particular focus on workability (slump), compressive strength, and split tensile strength at 7-day and 28-day curing ages.

1.2 Significance of the study

When nanoparticles are introduced into a cement paste, their extraordinarily high surface-area-to-volume ratio transforms the kinetics and spatial organisation of hydration reactions. Nano-TiO₂ provides heterogeneous nucleation sites upon which calcium silicate hydrate (C-S-H) crystals preferentially precipitate, producing a finer and more uniformly distributed gel network. The interfacial transition zone (ITZ) — the 10–50 µm thick region encircling each aggregate particle — is recognised as the weakest component in conventional concrete. Nanoparticles physically infiltrate and populate this ITZ region, enabling pozzolanic conversion of portlandite into additional C-S-H gel and thereby removing the weakest-link failure mechanism in conventional concrete.

2.Literature Review

Alghwanmeh, Liu, and Zhuge (2025) reviewed the use of biochar in concrete with a focus on production, physical properties, surface area, and porosity, confirming that pre-saturation of biochar with approximately 25% of its mass in water prior to mixing is a widely adopted approach to maintain slump and workability. The review affirmed that the life cycle of biochar-concrete significantly lowers emissions compared to traditional concrete [1].

Barman, Deka, Gogoi, and Das examined partial replacement of cement with biochar at 1, 3, 5, 7, 9, 11, and 13% by weight of cement. Workability decreased with increasing biochar content. The optimal substitution level for compressive strength was identified at 5%, beyond which strength declined [2].

Dhanpal and Saravanan reviewed photocatalytic degradation using TiO_2 concrete. The anatase form was noted for its high surface area, tetragonal crystal structure, and low electron-hole recombination rate. Under UV irradiation, TiO_2 generates reactive oxygen species that convert NO^x to harmless nitrates [3].

Nasikhuddin and Triyana confirmed anatase TiO_2 nanoparticle photocatalytic activity with an average particle size of approximately 27 nm. Under UV irradiation, a dye removal efficiency of 97% was achieved within a 3-hour reaction period, confirming UV light as an indispensable prerequisite for photocatalytic activity.[11]

Ambaye and Charolais (2026) presented a comprehensive sustainability evaluation of MSW-derived biochar as a partial substitute for cement. At a 5 wt.% substitution, biochar concrete exhibited greater compressive strength (45.5 MPa versus 43.3 MPa for the control) and reduced global warming potential.[8]

1.3 Problem statement

Several critical knowledge deficiencies impede the rational application of biochar and TiO_2 as binary additives in structural concrete:

- The interaction mechanism between porous biochar and TiO_2 within the cement matrix has not been clearly characterised, particularly whether biochar's porous structure promotes or retards TiO_2 nanoparticle dispersion or whether synergistic ITZ effects are operative.
- No dosage optimisation framework integrating mechanical performance objectives has been proposed for this binary additive system.
- The workability of concrete incorporating both TiO_2 and biochar at optimum dosage percentages, with expected slump ranges, needs to be determined.

1.4 Objectives

This experimental study is based on the objectives (i) Absence of systematic data on fresh and hardened properties of M30 concrete incorporating biochar and TiO_2 simultaneously across a multi-level factorial design. (ii) workability of concrete at optimum dosage percentages, with expected slump ranges need to be determined. (iii) determining the positive/negative impact of strength for this compound system additives.

2. Materials and Methodology

2.1 Materials

OPC Grade 43 cement (specific gravity 3.15; initial setting time 30 min; final setting time 600 min per IS 4031) was used as the primary binder. River sand conforming to Zone II grading (IS 383:2016; water absorption 1.2%; specific gravity 2.6 and Bulk density 1550 kg/m^3) served as fine aggregate. Crushed granite of 20 mm nominal maximum size (specific gravity 2.85; water absorption 1.2% and Bulk density 1450 kg/m^3) was used as coarse aggregate.

Biochar was incorporated as a direct mass replacement of OPC at 1% and 2% by weight. Prior to mixing, biochar was pre-soaked for 24 hours to eliminate free-water absorption during hydration. Anatase-phase TiO_2 nanoparticles (average particle size 35–80 nm; specific gravity 3.7; purity 99%) were added as an additional filler by mass of the total binder (cement + biochar) at dosages of 0.5%, 1.75%, and 3%.

2.2 Mix Design and Proportions

The control M30 mix was designed in accordance with IS 10262:2019, with a target mean strength of 38.2 N/mm². Three experimental mixes were evaluated:

S1: Normal Mix (NM) + 1% Biochar + 0.5% TiO₂

S2: Normal Mix (NM) + 1% Biochar + 1.75% TiO₂

S3: Normal Mix (NM) + 2% Biochar + 3% TiO₂

A superplasticizer was incorporated to maintain a target slump of 75 ± 25 mm in the control mix. Specimens were cast in 150×150×150 mm steel cube moulds (compressive strength) and 300×150 mm cylindrical moulds (split tensile), demoulded after 24 hours, and cured in clean water tanks for 7 and 28 days in accordance with IS 516.

3. Results: Workability (Slump Test)

3.1 Slump Test Procedure and Observed Values

Workability was assessed immediately after mixing using the standard slump cone test (IS 1199:1959) to capture early fresh concrete behaviour prior to significant hydration. The control M30 mix was designed with a target slump of 75–100 mm (medium workability class), consistent with IS 456:2000 requirements for mechanically vibrated reinforced concrete structural members.

The concrete incorporating both biochar and TiO₂ (optimum design mix S1) recorded an observed slump of 110 mm, classifying the mix within the medium-to-high workability range (100–125 mm) as per IS 456:2000. This value comfortably satisfies the code requirement of 75–150 mm for reinforced concrete applications and indicates a well-balanced water-to-cementitious material ratio, adequate plasticity for complex formwork placement, and no evidence of segregation or excessive bleeding.

Table 1: Slump Classification Reference and Observed Value (IS 456:2000)

Slump Range (mm)	Workability Class	Typical Application	Observed Value / Remark
0 – 25	Very Low	Pavement, Dry Lean	—
25 – 75	Low	Mass Concrete, Foundations	—
75 – 100	Medium	Beams, Slabs	Control M30 target: 75–100 mm
100 – 125	Medium-High	Reinforced Structures	✓ Observed: 110 mm (Biochar + TiO₂ mix)
125 – 175	High	Pumped / Complex Formwork	—

Note: Biochar was pre-soaked 24 hours prior to mixing to eliminate free water absorption. Superplasticizer dosage was marginally adjusted to compensate for the combined rheological effects of biochar porosity and TiO₂ filler action.

3.2 Workability Reduction Mechanisms

Biochar's high specific surface area and intrinsic porosity elevate the internal water demand of the mix. Substituting 1–2% of cement with biochar typically reduces slump by 15–30 mm relative to the control due to increased particle friction and water absorption. The achieved slump of 110 mm demonstrates that pre-saturation of biochar — loading its internal pore network prior to batching — was effective in mitigating this reduction.

Nano-TiO₂ exerts a secondary, more predictable workability influence through its ultrafine filler action and tendency toward agglomeration at the nano-scale. At dosages of 0.5–3%, TiO₂ typically induces a slump reduction of 5–20 mm. Since TiO₂ particles are non-porous and hydrophilic, their water demand is considerably lower than biochar, and their effect can be readily compensated through minor admixture adjustment without altering the overall mix design philosophy.

4. Results: Compressive Strength

4.1 Test Protocol

Compressive strength was determined on 150 mm cubes at 7-day and 28-day curing ages using a Compression Testing Machine (CTM) in accordance with IS 516. Three replicate specimens per mix per curing age were tested. The 28-day strength is the primary design criterion for M30 grade concrete (target ≥ 30 MPa characteristic strength). Results are expressed in MPa computed from the failure load divided by the cross-sectional area ($150 \times 150 \text{ mm} = 22,500 \text{ mm}^2$).

Table 2: Compressive Strength Results — 7-Day and 28-Day Curing Ages

Specimen Group	Mix Composition	7-Day Compressive Strength (MPa)				28-Day Compressive Strength (MPa)			
		S1	S2	S3	Avg.	S1	S2	S3	Avg.
S1	1% Biochar + 0.5% TiO ₂	42.67	40.89	40.00	41.19	35.11	31.11	30.22	32.15
S2	1% Biochar + 1.75% TiO ₂	29.33	27.56	26.67	27.85	28.00	24.00	28.44	26.81
S3	2% Biochar + 3% TiO ₂	21.78	20.00	21.33	21.04	20.00	18.67	19.56	19.41
M30 Target	Control (OPC)	—	—	—	≥ 24.0	—	—	—	≥ 30.0

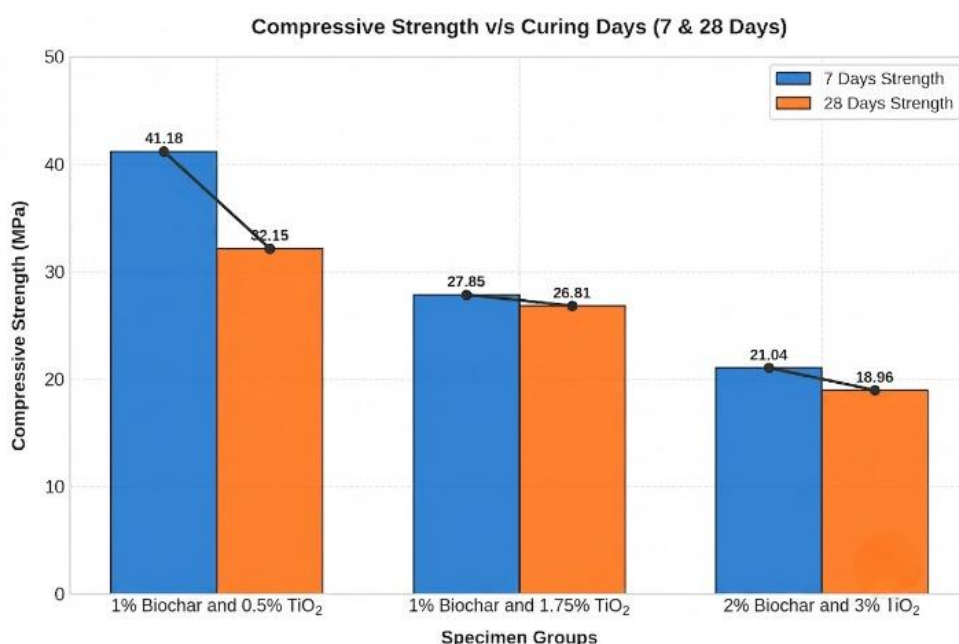


Fig 1: Compressive strength for 7 and 28 days in Mpa

Note: Three specimens per mix labelled S1, S2, S3. Averages computed arithmetically. M30 target 28-day characteristic strength ≥ 30.0 MPa (IS 456:2000). S1 mix meets target at 7 days; all mixes exhibit strength regression at 28 days — see Section 4.3.

4.2 Discussion of Compressive Strength Results

Mix S1 (1% BC + 0.5% TiO₂) attained an average 7-day compressive strength of 41.19 MPa — significantly exceeding the M30 characteristic target of 30 MPa and the target mean strength of 38.2 MPa, identifying it as the optimum early-age combination. Mix S2 (1% BC + 1.75% TiO₂) yielded 27.85 MPa at 7 days, and Mix S3 (2%

BC + 3% TiO₂) achieved 21.04 MPa, demonstrating that increasing additive dosage beyond the S1 threshold is detrimental to early mechanical performance. From results obtained it is concluded the compressive strength of concrete with optimum dosage of biochar and tio2 has found early 7-days strength and a regression after 28-days of curing overtime. This is promoted by compound mechanism observed by incorporating the Tio2 nucleation activity which tend to generate rapid initial strength gain, and in phase encountered by the delayed micro-cracking and internal moisture depletion over the extended curing period

An atypical but documented phenomenon is observed: the 7-day compressive strength exceeds the 28-day compressive strength across all three mixes, contrary to conventional concrete behaviour. This is mechanistically attributed to: (i) accelerated early-age hydration catalysed by nano-TiO₂ nucleation sites producing a rapid, spatially non-uniform heat of hydration; (ii) dissipation of thermal eigenstresses upon cooling that concentrate at biochar–paste interfaces, initiating micro-crack propagation; and (iii) internal moisture depletion from biochar's pore reservoir by 28 days, curtailing further pozzolanic reactivity and hydration progression.

5. Results: Split Tensile Strength

5.1 Test Protocol

Split tensile strength was evaluated on 300×150 mm (height × diameter) cylinders at 7-day and 28-day curing ages. Testing was conducted by applying a diametral compressive load along the longitudinal axis of the cylinder in accordance with IS 5816:1999. Tensile stress was computed as $\sigma_t = 2P/(\pi LD)$, where P is the failure load, L is the cylinder length, and D is the diameter. Results are reported in MPa and kN for correlation with the tabulated load data.

Table 3: Split Tensile Strength Results — 7-Day and 28-Day Curing Ages

Cylinder Group	Mix Composition	7-Day Split Tensile Strength (MPa)				28-Day Split Tensile Strength (MPa)			
		C1	C2	C3	Avg.	C1	C2	C3	Avg.
Batch 1	1% Biochar + 0.5% TiO ₂	21.57	23.54	26.48	23.86	21.57	20.59	18.63	20.26
Batch 2	1% Biochar + 1.75% TiO ₂	19.61	22.56	20.59	20.92	16.67	14.71	16.67	16.02
Batch 3	2% Biochar + 3% TiO ₂	18.63	21.57	19.61	19.94	10.79	13.73	17.65	14.06

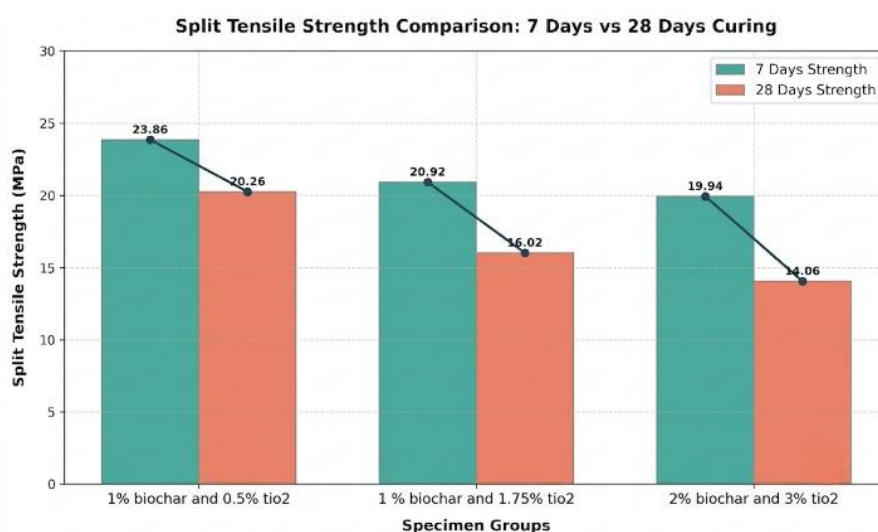


Fig 1: Split Tensile strength for 7 and 28 days in Mpa

Note: Three replicate cylinders per batch. Batch designations correspond to mix compositions: Batch 1 = S1, Batch 2 = S2, Batch 3 = S3. Load values at failure: Cylinder 1.1 = 220 kN (stable), Cylinder 1.2: 240 → 210 kN, Cylinder 1.3: 270 → 190 kN (peak 7d value in dataset).

5.2 Discussion of Split Tensile Strength Results

Batch 1 (1% BC + 0.5% TiO₂) exhibited the best overall performance. Cylinder 1.3 achieved the highest 7-day tensile strength in the entire dataset (26.48 MPa / 270 kN), attributed to maximally effective activation of synergistic internal curing and nano-TiO₂ heterogeneous nucleation. Cylinder 1.1 demonstrated the most stable behaviour, maintaining 21.57 MPa at both curing ages, indicating minimal microstructural degradation over the curing period and illustrates the increasingly effective activation of synergistic internal curing and heterogeneous nucleation mechanisms.

Batch 2 exhibited moderate 7-day strengths (19.61–22.56 MPa) with consistent 28-day regression to 14.71–16.67 MPa, suggesting ongoing ITZ microstructural deterioration as biochar's internal moisture reservoir was depleted. Batch 3 recorded the lowest values overall, with Cylinder 3.1 achieving only 10.79 MPa at 28 days — the minimum in the experimental dataset — indicative of ITZ instability from excessive additive loading and inadequate microstructural densification at higher dosages.

The widening divergence between 7-day and 28-day tensile strength envelopes across Batches 1 through 3 provides compelling evidence that the 1% biochar – 0.5% nano-TiO₂ binary system functions as an early-strength-optimised cementitious formulation, most mechanically productive within the first seven days of curing.

6. Integrated Strength Summary

Table 4: Integrated Compressive and Split Tensile Strength Summary (Average Values)

Mix ID	Composition	Comp. Avg. (MPa) 7d	Comp. Avg. (MPa) 28d	Split Avg. (MPa) 7d	Split Avg. (MPa) 28d	Strength Trend
S1 / B1	1% BC + 0.5% TiO ₂	41.19	32.15	23.86	20.26	Regression (7d > 28d)
S2 / B2	1% BC + 1.75% TiO ₂	27.85	26.81	20.92	16.02	Moderate regression
S3 / B3	2% BC + 3% TiO ₂	21.04	19.41	19.94	14.06	Significant regression

Note: Strength trend classification — 'Regression (7d > 28d)' indicates atypical strength loss between curing ages, documented across all three mixes. S1 (1% BC + 0.5% TiO₂) is identified as the optimum mix for early-age structural applications.

8. Conclusions

This experimental investigation into M30 concrete incorporating biochar and TiO₂ nanoparticles yields the following principal conclusions:

1. The optimum mix S1 (1% BC + 0.5% TiO₂) achieved a 7-day compressive strength of 41.19 MPa and a 7-day split tensile strength of 23.86 MPa, both exceeding the M30 design benchmark, classifying it as a high-performance early-strength-optimised formulation.
2. An atypical strength regression from 7 to 28 days is documented across all mixes, mechanistically attributed to nano-TiO₂-accelerated early hydration, thermal eigenstress accumulation, and biochar-induced moisture depletion inhibiting late-age hydration continuation.

3. The observed slump of 110 mm confirms medium-to-high workability (IS 456:2000), demonstrating that biochar pre-saturation and targeted superplasticizer dosage effectively compensate for the combined rheological effects of biochar porosity and TiO₂ filler action.
4. The S1 binary additive system demonstrates suitability for time-critical structural applications — precast concrete, rapid formwork removal, emergency infrastructure repair — where maximised early-age mechanical performance is the primary design objective.

References

1. Alghwanmeh, H., Liu, Y., & Zhuge, Y. (2025). Biochar Concrete: A state-of-the-art review. *Journal of Asian Concrete Federation*.
2. Barman, P. J., Deka, M. P., Gogoi, A., & Das, G. Comprehensive study of partial replacement of cement with biochar in concrete.
3. Dhanpal, J., & Saravanan, S. Photocatalytic degradation of concrete containing TiO₂ nanoparticles. [Review Paper].
4. Srivastava, A., Mishra, A., & Kumar, S. (2025). Mechanical and durability study of Nano-SiO₂ and nano-TiO₂ on fibre reinforced concrete.
5. Sumil Kumaran, A., & Judes Sujatha, S. (2024). CO₂-sequestering ability of M20 grade concrete with biochar and iron ore tailing powder.
6. Mekky, K. M., Sharobim, K., & Ibrahim, M. G. A biochar-based framework integrating life cycle assessment and socio-economic impacts.
7. Barbhuiya, S., & Das, B. B. Biochar-concrete: A comprehensive review of properties, production and sustainability.
8. Ambaye, T. G., et al. (2026). Decarbonizing concrete with biochar: Insights from life cycle sustainability assessment.
9. Hylton, J. Relevant biochar characteristics influencing compressive strength of biochar cement mortars.
10. Patel, R., & Acharya, B. Study of biochar in cementitious materials for developing green concrete composites.
11. Nasikhuddin & Triyana, K. Study on photocatalytic properties of TiO₂ nanoparticle in various pH conditions.
12. Kumar, R., Chandgude, G., & Jadhav, S. Titanium dioxide — an experimental study of self-cleaning concrete (M25 grade). *IJCRT*.
13. IS 456:2000 — Plain and Reinforced Concrete — Code of Practice (4th revision). Bureau of Indian Standards, New Delhi.
14. IS 1199:1959 — Methods of Sampling and Analysis of Concrete. Bureau of Indian Standards, New Delhi.
15. IS 10262:2019 — Concrete Mix Proportioning — Guidelines (2nd revision). Bureau of Indian Standards, New Delhi.
16. IS 383:2016 — Coarse and Fine Aggregate for Concrete — Specification (3rd revision). Bureau of Indian Standards, New Delhi.
17. IS 2386 (Part I–III) — Methods of Test for Aggregates for Concrete. Bureau of Indian Standards, New Delhi.
18. IS 4031 (Part 5 & 11) — Methods of Physical Tests for Hydraulic Cement. Bureau of Indian Standards, New Delhi.