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ARTICLE

Experimental Study on the Influence of TiO_2 and GGBS on Concrete Durability and Impact Strength

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ABSTRACT

The paper examines the improvements in M40 and M50 grade concrete properties resulting from adding nano-titania and using ground granulated blast-furnace slag as a replacement for cement in an effort to produce an environmentally friendly concrete substitute. The concrete mixes were formulated by following IS 10262:2019 and the different mix combinations comprised 0.5% to 2% nano-TiO_2 as well as up to 40% replacement of cement with ground granulated blast-furnace slag. Tests were performed to analyze the behavior of the mixes under mechanical loads, abrasion and impact, as well as freezing and thawing conditions. Mixes containing 1% nano-TiO_2 and either 30% GGBS or recycled glass powder yielded better results than reference mixes. This series of modified concretes demonstrated superior performance through lower abrasion loss, higher resistance to compression and compression forces similar to impact and enhanced freeze–thaw durability substantiated by the preservation of dynamic modulus, density and UVD values. The improvements are a direct consequence of the strengthening effect produced by the combined presence of nano- and pozzolanic materials. Experiments demonstrate that incorporating nano- and pozzolanic components simultaneously enhances durability, mechanical performance and lowers the amount of cement required. This method enables both sustainable and durable performance in concrete that can withstand various rigorous applications.

Keywords: Concrete Pavement; Nano Titanium Dioxide (TiO_2); Ground Granulated Blast Furnace Slag (GGBS); Freeze-Thaw Resistance; Impact Strength; Cantabro Abrasion Test; Durability

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1. Introduction

Concrete remains one of the most widely used construction materials due to its excellent compressive strength, durability, and adaptability to various structural applications [1]. However, its long-term performance and structural integrity are often compromised under harsh environmental conditions, such as freeze-thaw cycles, chemical exposure, impact loading, and surface abrasion [2,3]. These aggressive factors can lead to premature deterioration, surface scaling, strength loss, and reduced service life of concrete structures [4]. As a result, enhancing the durability and mechanical performance of concrete has become a critical area of research in recent years [5,6].

Advancements in material science, particularly in nanotechnology and the use of supplementary cementitious materials (SCMs), have shown great promise in overcoming the limitations of conventional concrete [7,8]. Among these innovations, Nano-Titanium Dioxide (Nano-TiO_2) has gained attention for its ability to improve the microstructure of concrete by refining pore structure, accelerating hydration reactions, and contributing to early-age strength development [9,10]. In parallel, Ground Granulated Blast Furnace Slag (GGBS), an industrial by-product of the steel manufacturing process, has been successfully utilized as a partial replacement for Portland cement [11]. GGBS contributes to increased workability, reduced permeability, and enhanced resistance to sulfate and acid attack, making it an environmentally friendly and performance-enhancing alternative [12,13].

The synergistic use of Nano-TiO_2 and GGBS is anticipated to produce a dense and durable concrete matrix with superior resistance to both physical and chemical degradation [14,15]. This research aims to investigate the combined effect of these two materials on the strength, acid resistance, and chloride ion permeability of concrete, thereby contributing to the development of sustainable, long-lasting construction materials for aggressive service environments [16].

Several studies have explored the effects of incorporating nano-titanium dioxide (nano-TiO_2) and ground granulated blast furnace slag (GGBS) on the strength and durability of concrete [17]. Vaid & Lallotra (2024) provided a comprehensive review highlighting the benefits of partially replacing cement with nano-TiO_2 and GGBS to enhance mechanical properties and durability while also reducing carbon emissions from the cement industry [18]. Maniseresht, through a response surface methodology (RSM) approach [19], demonstrated that while early strength may decrease with combined use, long-term properties improved significantly, particularly at 90 days with optimal mixes of 10% TiO_2 and 30–39.3% GGBS, which showed the lowest porosity and water absorption. Sastry et al. (2021) investigated geopolymer concrete and observed improved resistance to sulphate and chloride attacks with increased nano-TiO_2 content, supported by SEM and XRD analyses [20].

Baikerikar et al. (2024) found that the synergistic use of waste glass powder and nano-TiO_2 enhanced both mechanical and durability properties [21], though workability decreased with higher nano-TiO_2 content. Microstructural analysis of geopolymer concrete revealed that 2–3% nano-TiO_2 in fiber-reinforced mixes significantly improved compressive, flexural, and impact strength [22]. Zhang et al. (2021) examined the effect of a novel TiO_2-graphene composite in alkali-activated slag mortar and reported densified microstructures with reduced meso-capillary porosity, although excessive dosage caused agglomeration and reduced performance [23]. Hemalatha & Ramujee (2021) work on self-compacting geopolymer concrete incorporating fly ash, GGBS, and wollastonite found that 4% TiO_2 yielded optimal strength improvements of up to 20% [24]. Adebanjo et al. (2024) demonstrated the potential for sustainable, self-cleaning concrete systems using TiO_2 and ZnO nanoparticles [25], with TiO_2 showing superior photocatalytic performance under UV exposure [26].

Combining steel and PVA fibres in hybrid fiber-reinforced concrete improves durability and strain capacity, so balancing stiffness with flexibility [27]. Complementary to this, thermomechanical analysis of laminated composites using micromechanical models shows the vital part of accurate CTE predictions in structural stability [28]. Non-destructive methods allow one to reasonably evaluate the structural integrity of current RCC buildings, so stressing the need of in-situ evaluation [29]. Post-fire performance of UHPC shows recycled fibres perform comparably to industrial ones, so connecting ultrasonic velocity with residual strength [30]. Moreover, the chosen homogenisation models greatly influence the dependability of stress and dynamic analyses in functionally graded materials (FGMs), so influencing results in several engineering applications [31-35].

This study evaluates the performance and behaviour of M40 and M50 grade concrete incorporating 1% Nano-TiO_2 and 30% GGBS, with a focus on freeze-thaw durability, impact resistance, and surface wear resistance. The freeze-thaw resistance test (ASTM C666) exposed concrete specimens to 50 freeze-thaw cycles, assessing weight loss, dynamic modulus of elasticity, and durability factor. The impact resistance test (ACI 544) assessed the ability of the concrete to withstand dynamic loading conditions, while the Cantabro abrasion test evaluated surface wear resistance.

2. Materials Used

2.1. General

The experimental study utilized Ordinary Portland Cement (OPC) of 53 grade conforming to IS 12269 standards. This cement, sourced from Ultratech, was selected for its high early strength development and reliable performance in structural applications. The cement was fresh, dry, and free from lumps, ensuring consistency in all batches. Standard laboratory tests were conducted to verify its physical properties, such as specific gravity, initial and final setting times, and fineness, confirming its suitability for high-strength concrete mixes.

The fine aggregate used was clean, well-graded natural river sand passing through 4.75 mm IS sieve, complying with Zone II grading requirements as per IS 383. It was free from deleterious materials like silt, clay, or organic impurities. Coarse aggregate of nominal size 20 mm, sourced locally from Hyderabad, was used in a saturated surface dry (SSD) condition. The coarse aggregate conformed to IS 383 and fell under Zone II, providing good strength and bonding characteristics. The physical properties such as specific gravity, water absorption, and impact value were tested to ensure consistent quality across the mixes.

To improve durability characteristics and resistance to aggressive environments, mineral admixtures were incorporated. Titanium dioxide (TiO_2), obtained from NCI Hyderabad, was used in nano-powder form at a dosage of 1% by weight of cement. TiO_2 is known to enhance concrete's resistance to acidic conditions and reduce permeability due to its pozzolanic and photocatalytic activity. Additionally, Ground Granulated Blast Furnace Slag (GGBS) from JINDAL was used to replace 30% of the cement content. GGBS, a by-product of the steel industry, improves long-term strength and durability due to its latent hydraulic properties. A high-range water-reducing admixture, SP430 manufactured by FOSROC, was used to maintain desired workability while keeping the water-cement ratio low. This admixture conforms to IS 9103 and enhances flowability without segregation or bleeding. Potable water from the JNTUH bore well was used for both mixing and curing, ensuring it met the specifications outlined in IS 456 for use in concrete. **Table 1** gives the details about materials used in the experimental investigation.

Table 1. Materials Used.

Material	Description	Source
Cement	OPC 53 grade	Ultratech
Coarse Aggregate Fine Aggregate	ZONE II	Hyderabad
TiO_2 GGBS	Mineral Admixtures	NCI Hyderabad JINDAL
SP430	Chemical Admixture	FOSROC
Water	JNTUH Bore Well	Hyderabad

2.2. Nano Titanium Dioxide (Nano-TiO_2)

Nano-TiO_2 is a highly effective additive that improves concrete performance by refining its microstructure and reducing porosity. It also serves as a catalyst in pozzolanic reactions, accelerating early strength development. In this study, the Rutile form of Nano-TiO_2, with an average particle size of 19.6 nm, was used. Dosages ranging from 0.5% to 2.0% by cement weight were evaluated, with 1% identified as the optimal proportion for enhancing mechanical properties, durability, and resistance to environmental degradation.

2.3. Ground Granulated Blast Furnace Slag (GGBS)

A widely utilized cement-based material, GGBS is derived from the iron and steel industry and contributes to improved concrete performance while promoting sustainability. It improves workability, reduces the heat of hydration, and increases durability by minimizing chloride penetration and water permeability. In this study, GGBS was used as a partial cement replacement at levels of 30% and 40%, with 30% providing the most favourable results. The combined use of GGBS and Nano-TiO_2 exhibited a synergistic effect, significantly enhancing concrete performance while supporting environmental sustainability.

3. Theoretical Framework

3.1. Mix Proportions

In this experimental investigation, concrete mixes of M40 and M50 grades were developed in accordance with IS 10262:2019 guidelines to evaluate the influence of nano-titania (TiO_2) and ground granulated blast-furnace slag (GGBS) on concrete performance. The study involves systematic variations in mix compositions by incorporating nano-TiO_2 in proportions ranging from 0.5% to 2%, and partially replacing cement with GGBS at 30% and 40% levels. Tables 2 and 3 present the detailed mix proportions for M40 and M50 grades, respectively, highlighting changes in cementitious content while maintaining a constant water-to-cement ratio. These tailored mix designs were aimed at enhancing durability and sustainability, offering insight into how nano- and supplementary materials can effectively optimize concrete characteristics without compromising workability or aggregate consistency.

Table 2 presents a detailed comparison of various M50 concrete mix designs incorporating different dosages of nano-TiO_2 and GGBS. While the water-to-cement ratio (W/C) remains constant at 0.38 across all mixes, notable variations are seen in the cementitious components. As TiO_2 dosage increases (up to 2%) in the NT-series mixes, a corresponding reduction in cement content is observed. Similarly, in mixes NT_1G_{30} and NT_1G_{40}, GGBS partially replaces cement at 30% and 40%, respectively. The table highlights how nano- and supplementary materials are systematically introduced to enhance concrete performance while maintaining the overall mix balance.

The mix design (**Table 3)** presents a comparative overview of three concrete mixes—NT_0G_0, NT_1G_{30}, and NT_1G_{40}—highlighting the variation in their constituent materials. All mixes maintain a constant water-to-cement (W/C) ratio of 0.35, while the inclusion of nano-TiO_2 and ground granulated blast-furnace slag (GGBS) increases progressively in NT_1G_{30} and NT_1G_{40}. This substitution results in a significant reduction in cement content, demonstrating a more sustainable mix approach. Despite these replacements, the coarse and fine aggregates, water, and admixture quantities remain unchanged, ensuring consistency in workability and aggregate structure. This comparison effectively illustrates how supplementary materials can enhance concrete performance while reducing cement usage.

Table 2. M40 Grade Concrete Mix Proportions.

Mix Designation	W/C	Cement (Kg/m^3)	TiO_2 (Kg/m^3)	TiO_2 (%)	GGBS (Kg/m^3)	GGBS (%)	Coarse Agg. (Kg/m^3)	Fine Agg. (Kg/m^3)	Water (lit)	Admixture (lit)
NT_0G_0	0.38	390	0	0	0	0	1316	596	148	2.73
$NT_{0.5}G_0$	0.38	388	1.95	0.5	0	0	1316	596	148	2.73
NT_1G_0	0.38	386	3.9	1	0	0	1316	596	148	2.73
$NT_{1.5}G_0$	0.38	382	5.85	1.5	0	0	1316	596	148	2.73
NT_2G_0	0.38	382	7.8	2	0	0	1316	596	148	2.73
NT_1G_{30}	0.38	270	2.7	1	117	30	1316	596	148	2.73
NT_1G_{40}	0.38	232	3.24	1	155	40	1316	596	148	2.73

Table 3. M50 Grade Concrete Mix Proportions.

Mix Designation	W/C	Cement (Kg/m^3)	TiO_2 (Kg/m^3)	TiO_2 (%)	GGBS (Kg/m^3)	GGBS (%)	Coarse Aggregate (Kg/m^3)	Fine Aggregate (Kg/m^3)	Water (lit)	Admixture (lit)
NT_0 G_0	0.35	423	0	0	0	0	1236	628	148	2.96
NT_1 G_{30}	0.35	292	2.96	1	126.9	30	1236	628	148	2.96
NT_1 G_{40}	0.35	251	2.58	1	169.2	40	1236	628	148	2.96

3.2. Freezing and Thawing Test

Particularly important for buildings in cold climates where freeze-thaw action can cause internal cracking and surface scaling, per ASTM C666 the freezing and thawing test was carried out to evaluate the resistance of concrete specimens to cyclic temperature variations. Standard geometry concrete specimens—100 mm cubes—were made and tested in line with the guidelines. A programmable environmental chamber (Model: ThermoLab FTC-300) able of maintaining exact temperature ranges and cycle timing was used for the cycles. Every one of the fifty cycles consisted in a three-hour freezing phase at -10°C then a three-hour thawing phase at 25°C. Specimen weight loss, density, dynamic modulus of elasticity, relative dynamic modulus, and durability factor were among the measurements taken five-cycle intervals. Every ten cycles, compressive strength was also measured with a calibrated compression testing machine (Model: AIMIL-CTM-2000KN) to track increasing mechanical degradation. This all-encompassing arrangement sought to accurately replicate environmental stress and evaluate over time the durability and freeze-thaw resistance of the several concrete mixes (**Figure 1**).

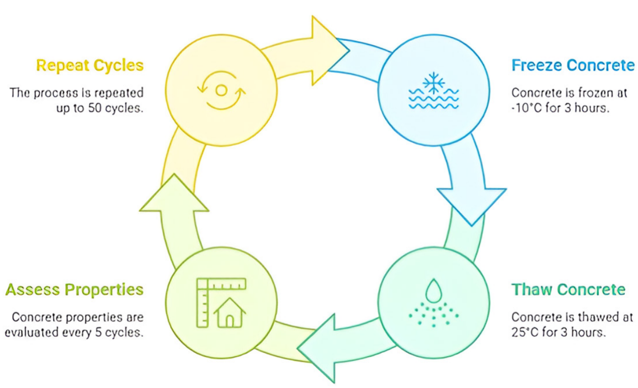

Figure 1. Freeze-Thaw Cycle in Concrete Testing.

Percentage weight loss = (*initial weight – weight of specimen after 'n' freeze thaw cycles*) */initial weight* × 100 (1)

Dynamic modulus of elasticity = $E = V^2\rho(1+\mu)(1-2\mu)/((1-\mu))$ (2)

E = Dynamic modulus of elasticity (N/m²)

V = Pulse velocity (m/sec)

ρ = mass density (Kg/m³)

μ = Poisson's ratio (assumed to be 0.2)

Relative dynamic modulus of elasticity $RDME(\%) = \frac{E_c}{E_o} \times 100$ (3)

Ec = Dynamic modulus of elasticity at cycle 'x'

Eo = Dynamic modulus of elasticity at zero cycles

Durability factor = $RDME_n/M$ (4)

(RDME)n = Relative dynamic modulus of elasticity at n cycles

n = Number of cycles

M = Specified number of cycles for testing completion

3.3. The Impact Resistance Test

Conforming with ACI 544 recommendations, the impact resistance of concrete was assessed using the drop weight technique (**Figure 2**). Custom-built vertical drop weight impact equipment—a guided steel frame, a release mechanism, and a hardened steel anvil base—was used for tests. Made per standard, cylindrical disc specimens with a 150 mm diameter and a 63.5 mm thickness were produced. To guarantee correct and repeatable drops, a 4.5 kg steel hammer (ISI-marked, cast iron drop weight with flat striking face) was repeatedly released from a fixed height of 450 mm through a vertical guide shaft. To evenly distribute the force, the hammer struck a 63.5 mm diameter hardened steel ball (EN31 grade) centred at the middle of every disc. The test setup kept constant impact energy, same to that of conventional testing setups. Reflecting the specimen's ability to absorb dynamic energy and delay crack development under sudden load conditions, the number of blows needed to start the first visible surface crack was recorded as the first-crack impact strength (N1).

The failure impact strength (N2) was measured by counting the number of blows required to achieve ultimate failure upon contact. The energy absorption capacity of each specimen in this test was determined using the following equation:

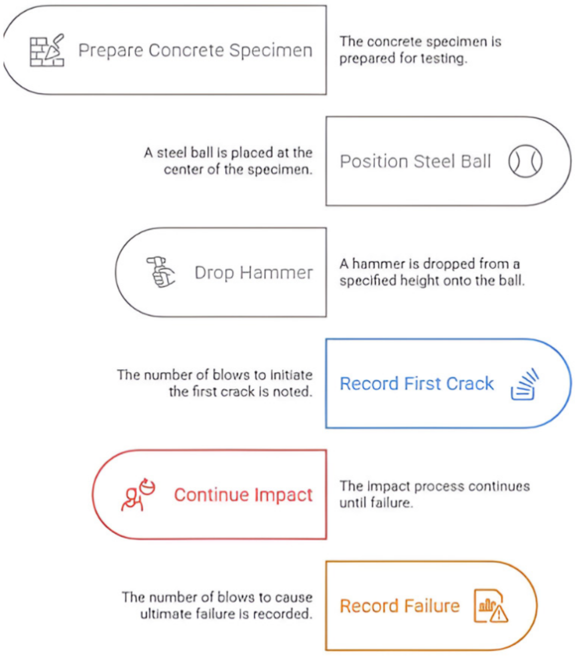

Figure 2. Impact Resistance Test Sequence.

$$Impact\ Energy\ (U) = NmgH \quad (5)$$

Where,

N = Number of blows

m = Weight of drop cylinder = 4.5 kg

g = Loading due to acceleration = 9.8 m/s^2

H = Height of free fall = 0.45 m

Hence,

$$Impact\ Energy\ (U) = N \times 19.45\ Nm \quad (6)$$

3.4. The Cantabro Abrasion Test

The Cantabro Abrasion Test was conducted in accordance with ASTM C1747 using a Los Angeles Abrasion Testing Machine (Model: AIM 456, Aimil Ltd., India), configured to operate without the inclusion of steel balls, as per the standard procedure (**Figure 3**). Three cylindrical concrete specimens, each measuring 150 mm in diameter and 150 mm in height, were used for the test. The initial weight (W_1) of each specimen was carefully recorded using a digital precision balance (accuracy ±0.1 g) before testing. The LAT machine was operated at incremental revolution counts of 50, 100, 150, 200, 250, and 300 revolutions under a rotational speed of 30–33 rpm. After each specified revolution count, the specimens were gently removed from the drum, cleaned of any loose particles or debris using a soft brush, and reweighed to determine the final weight (W_2). The weight loss percentage was then calculated to assess the abrasion resistance of each concrete mix. The percentage of weight loss, which serves as an indicator of the material's resistance to abrasion, was calculated using the following equation:

$$Cl\% = ((W_1 - W_2) / W_1) \times 100 \quad (7)$$

where Cl% = Cantabro weight loss (%); W_1 = Initial weight of the specimen (g); W_2 = Final weight of the specimen after abrasion (g).

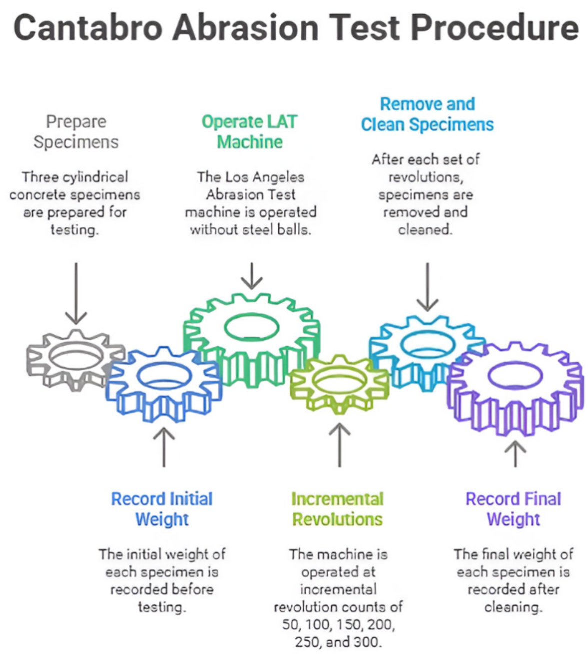

Figure 3. Cantabro Abrasion Test Procedure.

4. Results

Key new understanding of the effects of ground granulated blast-furnace slag (GGBS) and nano-titania (TiO_2) on mechanical durability and performance of M40 and M50 grade concretes came from the experimental research. Rigid testing including freeze-thaw resistance, impact strength, and abrasion resistance tested a range of mix designs, systematically varied with TiO_2 (0.5–2%) and GGBS (30–40%). Standardised methods guaranteed test conditions and specimen geometry consistency. The results shown here highlight their behaviour under cyclic thermal stress, dynamic impact loads, and surface wear conditions, so capturing the relative performance trends among many mixes.

4.1. Freezing and Thawing Test

It's crucial to assess the frost resistance of concrete to prevent unfavorable effects on its functionality in low temperatures. The freeze–thaw test data is evaluated to determine the degree of influence of nanosized titania and glass powder on the behavior of M40 concrete. The study compares the weight reduction of original concrete (M40-NT_0G_0) and a modified mix (M40-NT_1G_{30}) that includes1% nano-TiO_2 and 30% glass powder, after being subjected to 50 freeze–thaw cycles. The aim is to determine whether incorporating nanosized titania and glass powder improves concrete's resistance to damage through fragmentation and internal fracturing over a series of freeze–thaw cycles.

Figure 4 illustrates the impact of freeze–thaw cycles on the weight loss percentage of two M40 concrete mixes: M40-NT_0G_0 and M40-NT_1G_{30}. Initially, both mixes show no weight loss up to 25 freeze–thaw cycles, indicating strong resistance to early cyclic deterioration. From the 30th cycle onwards, a progressive increase in weight loss is observed in both mixes. However, M40-NT_0G_0 exhibits a steeper rise in weight loss compared to M40-NT_1G_{30}, suggesting it is more vulnerable to degradation. For example, at 40 cycles, M40-NT_0G_0 reaches a weight loss of 0.11%, whereas M40-NT_1G_{30} records a lower value of 0.07%. This trend continues, and by the 50th cycle, M40-NT_0G_0 reaches a maximum weight loss of 0.28%, in contrast to 0.20% for M40-NT_1G_{30}. These findings clearly indicate that the inclusion of NT_1 and G_{30} in the mix enhances the concrete's resistance to freeze–thaw-induced damage, making M40-NT_1G_{30} the more durable option under cyclic environmental stress.

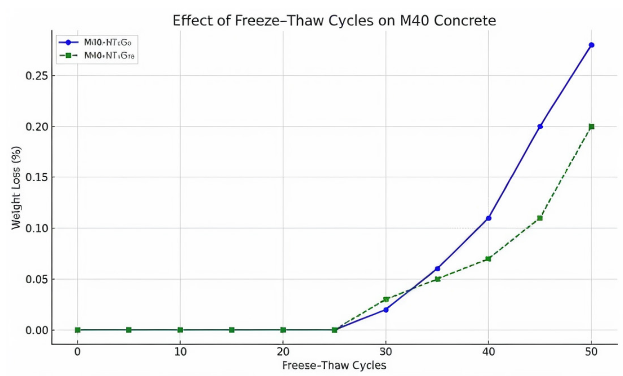

Figure 4. Weight Loss Percentage After 50 Freeze-Thaw Cycles for M40 Grade Concrete.

Measured in 10-cycle intervals, **Figure 5** shows the variation in residual compressive strength of two M40 grade concrete mixes—M40-NT_0G_0 (control) and M40-NT_1G_{30} (containing 1% nano-silica and 30% glass powder)—over the course of 0 to 50 freeze–thaw cycles. Reflecting the beneficial effects of nano-silica and glass powder on early-age strength development, M40-NT_1G_{30} already shows a significantly higher compressive strength of 56.21 MPa at 0 cycles than for the control mix. Micro-cracking and internal damage resulting from ice formation and hydraulic pressure within pores causes both mixes to progressively lose compressive strength as freeze–thaw cycles advance. M40-NT_1G_{30} shows a far slower rate of decay, though. The control mix drops to 44.95 MPa by the 50th cycle; the modified mix keeps a strength of 53.65 MPa.

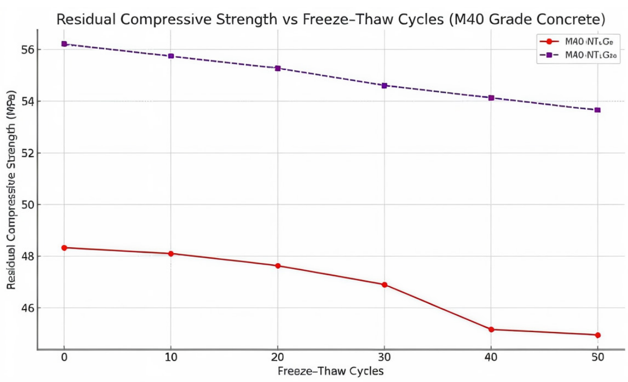

Figure 5. Residual Compressive Strength Degradation of M40 Concrete under Freeze–Thaw Cycles.

Several microstructural elements help to explain this performance variation. Including nano-silica helps to produce extra calcium silicate hydrate (C-S-H), so improving the pore structure and lowering the concrete's permeability. Concurrent with this, the fine glass powder particles fill voids and provide pozzolanic reactivity, so densifying the matrix. This denser microstructure lowers the volume of freezable water and minimises water ingress, so lowering internal stresses during freeze–thaw cycles. Furthermore, better interfacial bonding between aggregates and cement paste increases resistance to the beginning and spread of cracks. Based on their increased retained strength over the testing period, these physical changes together explain the better freeze-thaw durability of M40-NT_1G_{30}.

Figure 6 illustrates the variation in density of two M40 grade concrete specimens—M40-NT0G0 (control) and M40-NT1G30 (with 1% nano-TiO_2 and 30% GGBS)—

subjected to up to 50 freeze–thaw cycles. The control mix (M40-NT0G0) exhibited a steady decline in density from 2370 kg/m³ to 2342 kg/m³, indicating material degradation due to microcracking and internal damage. In contrast, M40-NT1G30 maintained a relatively stable density, decreasing marginally from 2451 kg/m³ to 2449 kg/m³. While this trend suggests improved freeze–thaw resistance for the modified mix, the inference of enhanced durability and matrix densification remains speculative, as no supporting microstructural or permeability data (e.g., SEM imaging or water absorption tests) are provided. Therefore, the physical observations, although promising, lack direct micro-level justification for the claimed improvements in material integrity.

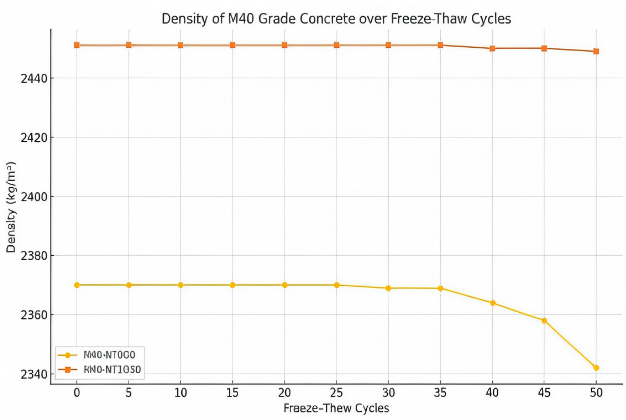

Figure 6. Variation in Density of M40 Grade Concrete Under Freeze–Thaw Cycles.

Figure 7 illustrates the variation in pulse velocity (in m/s) for M40 grade concrete subjected to 0 to 50 freeze–thaw cycles, comparing two mixes: M40-NT_0G_0 (control) and M40-NT_1G_{30} (modified with 1% nano-titania and 30% glass powder). Pulse velocity declines with increasing cycles for both mixes, reflecting internal microcracking and progressive degradation of the concrete matrix under repeated freezing and thawing. Initially, both mixes show high pulse velocity values—3940 m/s for the control and 3963 m/s for the modified mix—indicating good structural integrity.

However, as the cycles progress, the control mix experiences a steeper drop in pulse velocity, reaching 3665 m/s at 50 cycles, while the modified mix retains a slightly higher value of 3676 m/s. This relatively better retention in the modified mix can be attributed to the synergistic effects of nano-titania and glass powder. Nano-titania, due to its ultrafine particle size and high surface area, promotes pore refinement and densification of the cement matrix, limiting water ingress and subsequent freeze-induced expansion. Simultaneously, the pozzolanic reaction of glass powder contributes to secondary C-S-H formation, which enhances matrix cohesion and reduces porosity. Together, these mechanisms help mitigate crack propagation and internal damage during freeze–thaw cycling, resulting in improved pulse velocity retention. This highlights the physical basis for the modified mix's superior durability and validates the role of nano- and supplementary cementitious materials in enhancing freeze–thaw resistance in concrete.

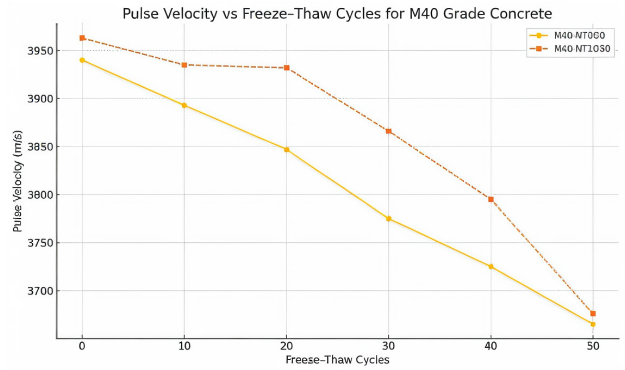

Figure 7. Effect of Freeze–Thaw Cycles on Pulse Velocity for M40 Grade Concrete.

Comparing the control mix (M40-NT_0G_0) with the modified mix (M40-NT_1G_{30}), which incorporates nano titanium and glass fibres, **Figure 8** shows the variation in dynamic modulus of elasticity (in GPa) for M40 grade concrete subjected to 0–50 freeze–thaw cycles. Reflecting cumulative internal damage resulting from freeze-thaw stresses, both mixes show a declining trend in dynamic modulus with an increasing number of cycles. Still, the adjusted mix always keeps better modulus values over all cycles. The roles of glass fibres and nano titanium in improving the microstructural integrity of the concrete help one to physically understand this development. Critical in freeze-thaw conditions, nano titanium particles serve as fillers that improve pore structure and raise matrix density, so lowering permeability and minimising water ingress. Under thermal and mechanical pressure, the glass fibres function as crack-bridging elements that help control microcrack development and propagation. These additives together reduce internal damage mechanisms including matrix disruption and ice-induced expansion, so enabling the modified mix to retain more of its elastic qualities over the freeze–thaw exposure. This shows how well fibre reinforcement and nanomaterial help to increase concrete's long-term durability under cyclic freezing conditions.

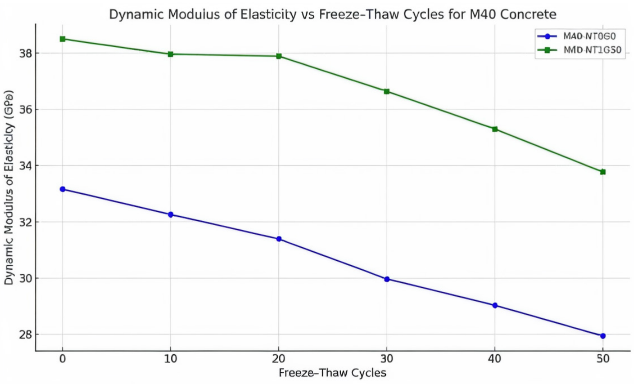

Figure 8. Effect of Freeze–Thaw Cycles on the Dynamic Modulus of Elasticity for M40 Grade Concrete.

Comparing two mixes—M40-NT$_0$G$_0$ (control) and M40-NT$_1$G$_{30}$ (modified with 1% nano-titania and 30% glass powder), **Figure 9** shows the variation in relative dynamic modulus of elasticity (%) for M40 grade concrete subjected to up to 50 freeze–thaw cycles. Although both mixes start at 100%, the modulus falls with increasing cycles; the control mix shows a more acute drop. The control mix drops to 84.25% by the 50th cycle, while the modified mix keeps a higher modulus of 87.72%, so indicating improved freeze-thaw durability (**Table 4**).

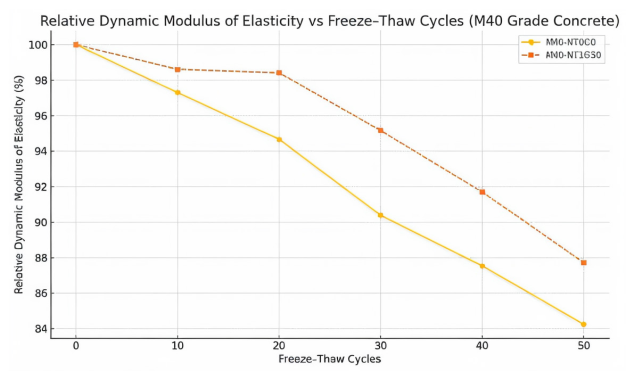

Figure 9. Effect of Freeze–Thaw Cycles on Relative Dynamic Modulus of Elasticity for M40 Grade Concrete.

Table 4. Durability Factor (DF) for 50 Freeze Thaw Cycles (%) for M40 Grade Concrete.

M40-NT0G0	M40-NT1G30
84.25	87.72

The combined physical and chemical advantages of glass powder and nano-titania help to explain this better performance. Because of its ultrafine particle size and high surface area, nano-titania fills voids and speeds hydration, so promoting a denser microstructure. Concurrently, the pozzolanic activity of glass powder combines with calcium hydroxide to generate extra calcium silicate hydrate (C-S-H), so improving the pore structure and lowering the permeability. The resultant denser and less porous matrix minimises internal water movement and ice formation, so lowering internal tensile stresses in freeze-thaw cycles. These microstructural improvements explain the better retention of dynamic modulus in the modified mix since they help maintain the integrity of the internal bonding and elastic characteristics of the concrete under repeated environmental stresses.

Figure 10 illustrates the effect of repeated freeze–thaw cycles on the weight loss percentage of M50 grade concrete for two mixes: M50-NT$_0$G$_0$ (control, without nano silica and glass fibers) and M50-NT$_1$G$_{30}$ (modified with 1% nano silica and 30% glass fibers). Both mixes show minimal weight loss up to 20 cycles, reflecting strong initial resistance to freeze–thaw damage. Beyond 25 cycles, the differences become more pronounced. The control mix experiences a steady increase in weight loss, reaching 0.25% after 50 cycles, indicative of progressive surface degradation due to microcracking and aggregate-paste interface weakening. In contrast, the modified mix shows significantly lower weight loss at 0.16%, demonstrating enhanced durability.

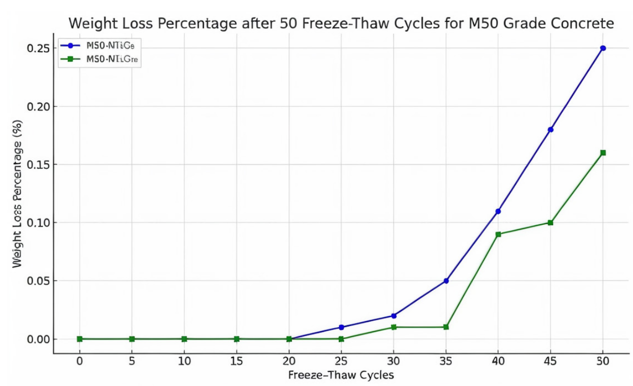

Figure 10. Effect of Freeze–Thaw Cycles on Weight Loss Percentage of M50 Grade Concrete with and without Glass.

This improved performance can be physically explained by the role of nano silica and glass fibers. Nano silica acts as a pozzolanic material that refines the pore structure, reducing capillary porosity and limiting water ingress that causes internal ice formation and expansion. Glass fibers contribute to mechanical reinforcement by bridging microcracks and delaying crack propagation during freeze–thaw cycling. Together, these effects strengthen the cement matrix and improve the interfacial transition zone, reducing microcrack formation and material spalling under cyclic freezing and thawing. As a result, the modified concrete better resists surface deterioration, showing lower weight loss and improved freeze–thaw durability.

Comparatively to the control mix (M50-NT_0G_0), which includes nano-TiO_2 and 30% glass powder replacement, **Figure 11** shows the residual compressive strength of M50 grade concrete subjected to increasing freeze-thaw cycles. Reflecting the usual degradation resulting from repeated freezing and thawing, both mixes gradually lose strength as freeze-thaw cycles advance. Still, the altered mix constantly shows better resistance to freeze-thaw damage by retaining greater compressive strength over. Several physical processes help to explain this enhanced performance: the nano-TiO_2 particles fill microvoids and enhance the pore structure, so lowering permeability and limiting the ingress of water causing internal freezing damage. Glass powder densifies the cement matrix simultaneously by generating extra calcium silicate hydrate (C-S-H), so strengthening the interfacial transition zone and improving cohesion inside the concrete. These effects together lower microcracking and surface scaling, so preserving compressive strength under freeze-thaw pressure. This synergy emphasises how well combined nanomaterials and additional cementitious materials increase durability in demanding environmental conditions.

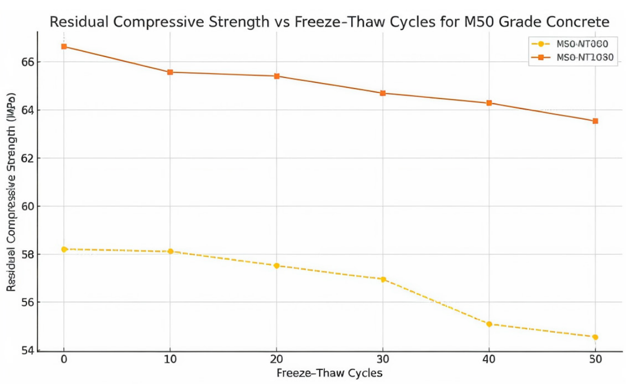

Figure 11. Residual Compressive Strength vs Freeze–Thaw Cycles for M50 Grade Concrete.

Figure 12 shows the range in density (kg/m^3) of M50 grade concrete specimens frozen and then thawed between 0 and 50. Two mix compositions—M50-NT0G0 (without nano titanium and glass powder) and M50-NT1G30 (containing 1% nano titanium and 30% glass powder) are compared here. Both mixes show consistent density values up to 25 cycles, suggesting little degradation initially. M50-NT0G0 shows a clear drop in density after 30 cycles, however, which reflects structural degradation most likely resulting from microcracking and water ingress caused by repeated freeze–thaw action, drops significantly by the 50th cycle. By contrast, M50-NT1G30 preserves rather constant density over the cycles, implying improved durability and resistance to environmental stress, probably related to the pozzolanic and pore-refining properties of nano titanium and glass powder. This trend underlines how well additional materials increase the freeze-thaw resistance of concrete.

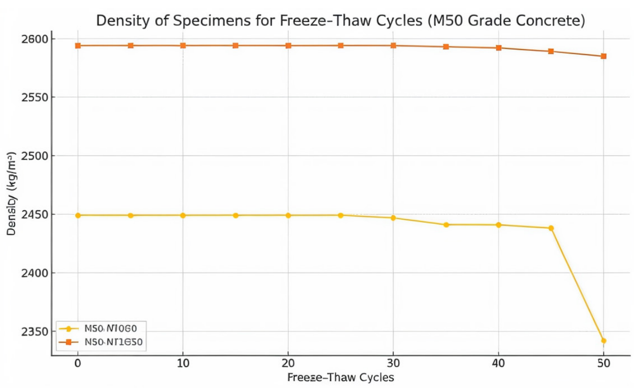

Figure 12. Variation in Density of M50 Grade Concrete Specimens under Freeze–Thaw Cycles.

Table 5 presents the pulse velocity (measured in meters per second) of M50 grade concrete specimens subjected to freeze–thaw cycles ranging from 0 to 50, comparing two mixes: M50-NT0G0 (without nano titanium and glass powder) and M50-NT1G30 (with 1% nano titanium and 30% glass powder). Pulse velocity is a critical non-destructive indicator of concrete quality, integrity, and uniformity. As freeze–thaw cycles increase, both mixes show a gradual reduction in pulse velocity, indicating progressive internal damage due to microcracking and pore expansion caused by the freeze–thaw mechanism. However, the M50-NT1G30 mix consistently exhibits higher pulse velocity values across all cycles, with a notably slower rate of decline compared to M50-NT0G0. This suggests that the inclusion of nano titanium and glass powder enhances the concrete's internal cohesion and durability by refining the pore structure and improving resistance to thermal stresses. The improved performance of M50-NT1G30 under cyclic freezing and thawing emphasizes the beneficial role of these additives in maintaining the structural soundness of concrete in aggressive environments.

Table 5. Pulse Velocity(V) for (0-50) Freeze Thaw Cycles (m/s) for M50 Grade Concrete.

S. No.	Freeze–Thaw Cycles	M50-NT0G0	M50-NT1G30
1	0	4832	4861
2	10	4793	4832
3	20	4747	4825
4	30	4675	4763
5	40	4625	4696
6	50	4565	4588

Comparing two mixes—M50-NT_0G_0 (control) and M50-NT_1G_{30} (with 1% nano-silica and 30% glass powder), **Figure 13** shows the variation in dynamic modulus of elasticity (GPa) for M50 grade concrete subjected to 0 to 50 freeze–thaw cycles. Reflecting the progressive microstructural damage and loss of elasticity brought about by repeated freeze-thaw stresses, both mixes gradually lose dynamic modulus with increasing cycles. On the other hand, the M50-NT_1G_{30} mix constantly maintains better modulus values over the test, so indicating better durability.

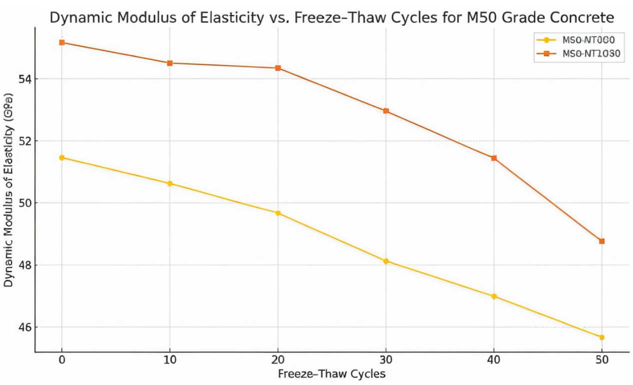

Figure 13. Effect of Freeze–Thaw Cycles on the Dynamic Modulus of Elasticity for M50 Grade Concrete.

The combined actions of glass powder and nano-silica on the microstructure of the concrete help to explain this improved performance. Ultra-fine particles of nano-silica function as nucleation sites, so encouraging the development of a denser and more polished calcium silicate hydrate (C-S-H) gel, so strengthening the matrix and lowering the permeability. Glass powder's pozzolanic activity meanwhile further consumes calcium hydroxide, densifying the interfacial transition zone and reducing microcracks. These effects together limit water ingress and lower internal ice formation and expansion pressure during freeze-thaw cycles, so controlling microcrack propagation and preserving more elastic stiffness. Therefore, the modified mix shows better resistance to freeze-thaw degradation, so supporting its suitability for demanding climatic conditions.

Table 6 shows the relative dynamic modulus of elasticity (%) for M50 grade concrete subjected to up to 50 freeze–thaw cycles, comparing the modified mix (M50-NT_1G_{30}) including 1% nano-silica and 30% glass powder with the control mix (M50-NT_0G_0). Beginning at 100%, both mixes reflect their undamaged state. The relative dynamic modulus falls in both mixes as increasing freeze-thaw cycles indicate damage progression from microcracking and internal stresses generated by freezing water expansion. Especially in the early phases, the modified mix notably preserves a higher relative modulus over most of the freeze-thaw cycles. The physical and chemical properties of the additives help to explain this better performance: nano-silica particles densify the cement matrix and lower permeability by filling nano-pores and encouraging the formation of extra calcium silicate hydrate (C-S-H), so improving the microstructure. Acting as a pozzolanic material, glass powder reacts with calcium hydroxide to improve the pore structure even more. These effects together lower internal freeze-thaw damage and water ingress, so slowing modulus degradation.

Table 6. Relative Dynamic Modulus of Elasticity (%) for M50 Grade Concrete Over 0–50 Freeze-Thaw Cycles.

S. No.	Freeze–Thaw Cycles	M50-NT0G0	M50-NT1G30
1	0	100	100
2	10	98.39	98.81
3	20	96.51	98.52
4	30	93.53	96.01
5	40	91.32	93.25
6	50	89	89

The M50 concrete matrix's natural high durability probably explains both mixes' similar relative modulus of 89% by the 50th cycle. But the slower modulus reduction rate in the modified mix emphasises how well glass powder and nano-silica improve freeze-thaw resilience, especially by reducing early-stage microstructural damage.

Table 7 shows after 50 freeze-thaw cycles the durability factor (DF) for M50 grade concrete mixes. With 1% nano-silica and 30% glass powder, both the control mix (M50-NT_0G_0) and the modified mix (M50-NT_1G_{30}) show an identical DF of 89%, so indicating that each retained 89% of its original dynamic modulus of elasticity post-exposure. This implies similar resistance to freeze-thaw degradation, but it would seem contradictory given other metrics including pulse velocity and absolute modulus values, which displayed better performance in the modified mix. Rounding rules in DF computation or the sensitivity limits of the test method most likely affect this flat DF result; these may not adequately reflect minor performance variations when both mixes lie inside a high durability range. Furthermore, it is likely that the improved performance of the modified mix helps to preserve initial stiffness rather than to raise the percentage retained after degradation. Still, the findings confirm that both mixes show great freeze-thaw durability and that the modified mix shows possible long-term performance that might not be entirely reflected by DF by itself.

Table 7. Durability Factor (DF) for 50 Freeze Thaw Cycles (%) for M50 Grade Concrete.

Mix	Durability Factor (%)
M50-NT0G0	89
M50-NT1G30	89

4.2. Impact Test

Tests were performed to assess the performance of M40 grade concrete in response to sudden impact while having two curing methods applied. An important goal of the study was to evaluate how a regular control mix (M40-NT_0G_0) performed relative to a modified mix (M40-NT_1G_{30}) with 1% nano-titania and 30% glass powder added. The behavior of impact resistance was studied at intervals of 28, 90 and 180 days of curing. The number of blows required to achieve failure was the main measure of concrete toughness and durability for this study and allowed evaluating how various nano- or supplementary materials affect the concrete's response to dynamic loading.

Figure 14 shows, evaluated at curing ages of 28, 90, and 180 days, the impact value test results for M40 grade concrete specimens with and without the addition of glass powder and nano-titania. Two mixes—the modified mix M40-NT_1G_{30}, with 1% nano-titania and 30% glass powder, and the control mix M40-NT_0G_0—were tested. Two tests (N_1 and N_2) tracked the blow count needed to induce failure for every curing age. Reflecting continuous hydration and matrix strengthening, both mixes show a trend in increasing impact resistance over time. Comparing the modified mix to the control, it constantly shows much more impact resistance. The combined action of glass powder and nano-titania helps to explain this improvement in microstructure of the concrete. By means of nucleation sites accelerating cement hydration, nano-titania particles help to produce a denser and more cohesive matrix. The pozzolanic activity of the glass powder then improves interfacial bonding between aggregates and paste by refining pore structure. These systems taken together improve the concrete's capacity to absorb and dissipate energy under impact, so postponing the start and spread of cracking. Therefore, the improved impact resistance emphasises the efficiency of these additional components in prolonging the mechanical performance and durability of concrete over the lifetime.

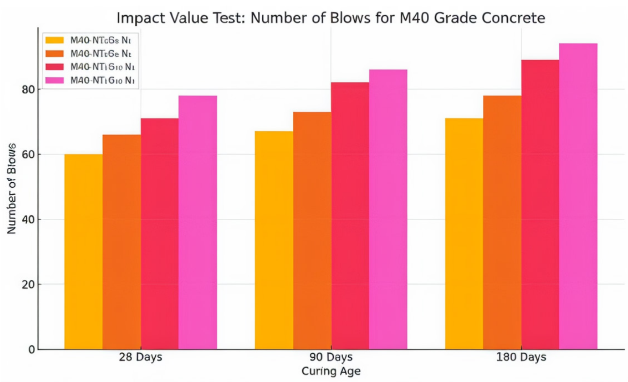

Figure 14. Variation in Impact Resistance of M40 Grade Concrete Over Time.

The impact resistance test results for M50-NT_0G_0 and M40-NT_1G_{30} concrete mixes at 28, 90, and 180 days of curing are shown in **Figure 15**. To guarantee consistency, two specimens (N_1 and N_2) were examined for every age. According to the findings, M40-NT_1G_{30} continuously demonstrates better impact resistance than M50-NT_0G_0 during every curing period. This improvement can be ascribed to improved energy absorption mechanisms brought about by the addition of 30% glass powder (G_{30}) and nano titanium (NT_1). While the glass powder adds to a denser matrix through pozzolanic activity, the nano-scale reinforcement probably improves the microstructure by boosting crack bridging and preventing crack propagation. These combined effects increase the material's ability to absorb and dissipate impact energy over time by improving fracture toughness and delaying the onset of cracks.

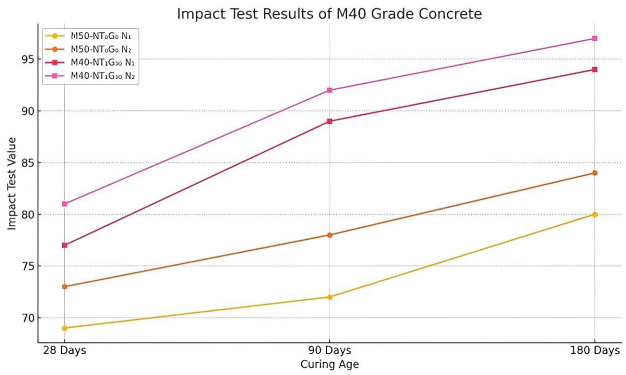

Figure 15. Impact Resistance Comparison of M50-NT_0G_0 and M40-NT_1G_{30} Concrete Mixes Over Time.

Figure 16 shows the number of blows sustained by M50 grade concrete specimens in impact value tests at curing intervals of 28, 90, and 180 days for two mixes: M40-NT_0G_0 (control) and M40-NT_1G_{30} (with nano or geopolymer additives). Both mixes demonstrate a clear increase in impact resistance as curing progresses, which is typical due to ongoing hydration and matrix strengthening. However, the M40-NT_1G_{30} mix consistently outperforms the control at all ages, suggesting that the additives significantly enhance the concrete's toughness and energy absorption capacity.

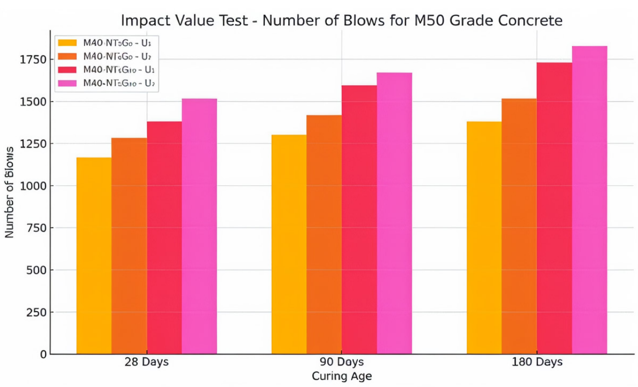

Figure 16. Impact Resistance of M50 Grade Concrete: Variation of Blow Count with Curing Age.

This improvement can be attributed to several physical mechanisms. The nano-additives likely refine the microstructure by filling nano-scale voids and promoting denser packing, which increases the matrix's stiffness and reduces microcrack formation under impact. Meanwhile, geopolymer components contribute to improved bonding between the aggregate and paste, enhancing the overall integrity and resistance to crack propagation. Together, these effects lead to higher energy dissipation during impact loading, allowing the modified concrete to sustain more blows before failure. This enhanced toughness is especially beneficial for applications requiring improved durability under dynamic loading conditions.

The results of the impact resistance test are shown in **Figure 17** under two mixes: M50-NT_0G_0 (control) and M50-NT_1G_{30} (with 30% G_{30} additive). M50 grade concrete specimens sustained a total number of blows. Both mixes show a progressive increase in impact strength with curing age; the G_{30}-enhanced mix always shows notably greater resistance, especially at later ages. Improved energy absorption mechanisms brought about by the G_{30} additive help to explain this increase. G_{30}'s fibrous and pozzolanic character most certainly helps to explain matrix densification and crack-bridging, which delays the start and spread of cracks under impact loading. Higher blow counts before failure follow from increased toughness and resistance to fracture. These results imply that adding G_{30} not only increases the mechanical integrity of the concrete over time but also helps it to dissipate impact energy by means of microstructural changes.

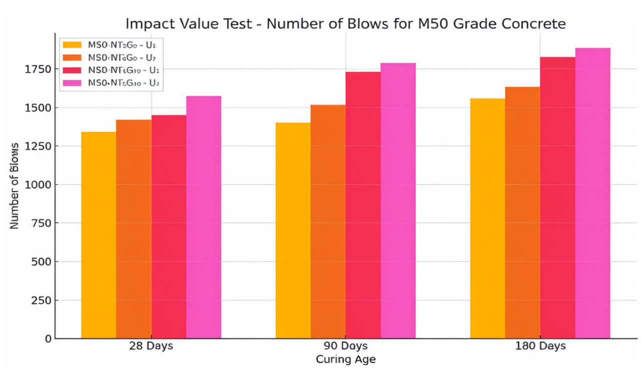

Figure 17. Effect of Curing Age on Impact Resistance of M50 Grade Concrete with and without G_{30} Additive.

4.3. Cantabro Abrasion Test

The Cantabro abrasion test was carried out to evaluate the surface resistance of M40 grade concrete. It evaluates how well concrete holds up to frictional wear in service. GGBS addition to the concrete mix was studied for how it affected the concrete's resistance to abrasion over different time periods. Two concrete mixes were compared: M40-NT$_0$-G$_0$ (without GGBS) and M40-NT$_1$-G$_{30}$ (with 30% GGBS). The test was conducted at curing ages 28, 90 and 180 days. It allowed evaluation of the impact of GGBS on the lasting abrasion resistance of concrete

Comparing two mixes—M40-NT$_0$-G$_0$ (control) and M40-NT$_1$-G$_0$ (with 30% GGBS), **Figure 18** shows the Cantabro abrasion weight loss percentages for M40 grade concrete at curing ages of 28, 90, and 180 days. Improved abrasion resistance is indicated by the significant decrease in weight loss for the GGBS-modified mix over all curing intervals. Weight loss in the GGBS-enhanced mix specifically dropped from 5.34% at 28 days to 2.47% at 180 days. The physical and microstructural changes brought about by the GGBS inclusion help to explain this development. A denser and more cohesive matrix results from the pozzolanic reaction between GGBS and calcium hydroxide refining the pore structure and lowering general porosity. Furthermore, the development of extra C–S–H gel improves surface hardness, so increasing the concrete's resistance to abrasive pressures. These microstructural improvements confirm that GGBS not only strengthens the concrete but also greatly increases its resistance to surface wear over time, so helping to explain the observed decrease in material loss.

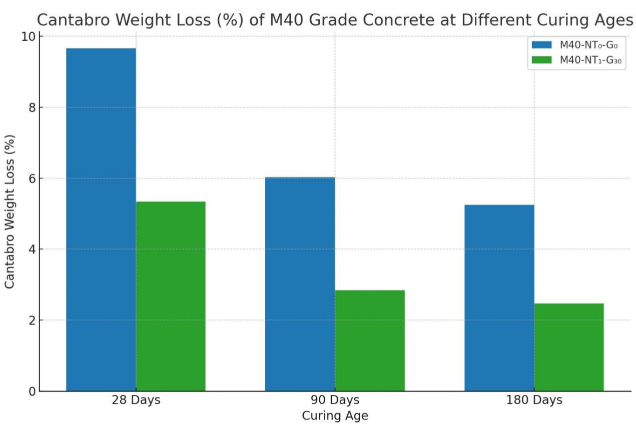

Figure 18. Effect of GGBS Incorporation on Cantabro Abrasion Resistance of M40 Grade Concrete.

For two mixes, M50-NT$_0$-G$_0$ (without GGBS) and M50-NT$_1$-G$_0$, **Figure 19** shows the weight loss percentages of M50 grade concrete at 28, 90, and 180 days of curing. Particularly at later ages, the inclusion of GGBS clearly increases abrasion resistance. For instance, the GGBS-modified mix shows a far smaller weight loss of 1.94% at 180 days than the control mix at 4.11%. Microstructural changes brought about by GGBS' pozzolanic action help to explain this improved resistance. GGBS combined with calcium hydroxide refines the pore structure, so lowering the total porosity and producing a denser concrete matrix. Furthermore, helping to provide enhanced surface hardness and better particle bonding is the evolution of secondary calcium silicate hydrate (C-S-H). Under abrasive forces, these physical improvements lower the concrete surface's sensitivity to aggregate detachment and material loss. Therefore, the lower Cantabro weight loss shows not only better durability but also quantifiable surface integrity enhancement of the GGBS-enhanced concrete.

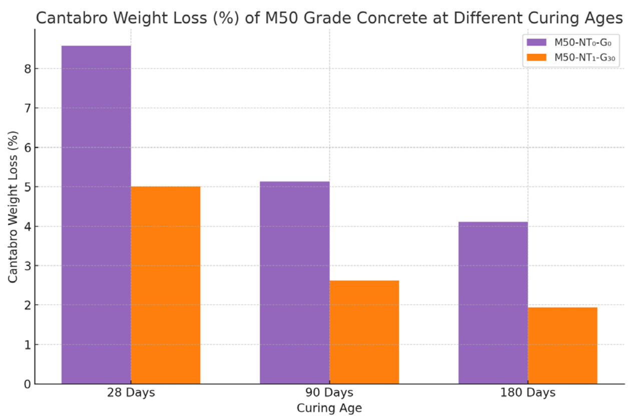

Figure 19. Influence of GGBS on Cantabro Abrasion Resistance of M50 Grade Concrete.

5. Conclusions

The experimental investigation clearly demonstrates that incorporating nano-scale additives such as nano-titania and supplementary cementitious materials like ground granulated blast-furnace slag (GGBS) and glass powder significantly enhances the mechanical strength and durability of M40 and M50 grade concretes. Mixes modified with 1% nano-titania and 30% GGBS or glass powder exhibited notable improvements in abrasion resistance and impact strength. The reduction in weight loss during abrasion tests and the increased number of blows sustained in impact tests indicate better surface integrity, improved toughness, and greater resistance to cracking. These enhancements are largely attributed to the synergistic effects of nano-materials and pozzolanic additives, which refine the pore structure and strengthen the concrete matrix.

Incorporating 1% nano-titania and 30% glass powder ($M40-NT_1G_{30}$) greatly increases durability, according to a thorough assessment of freeze-thaw performance in M40 grade concrete against the control mix ($M40-NT_0G_0$). After 50 freeze-thaw cycles, the modified mix shows reduced weight loss, increased residual compressive strength, more stable density, better pulse velocity retention, and improved dynamic and relative dynamic modulus values. These results are ascribed to the combined physical and chemical effects of the additives: glass powder's pozzolanic activity generates extra calcium silicate hydrate (C-S-H), densifying the matrix and lowering permeability; nano-titania refines the pore structure by filling voids and accelerating hydration. These microstructural improvements taken together reduce internal damage from ice formation and spread of cracks during cyclic freezing and thawing. Thus, under freeze-thaw stress, the modified mix preserves more structural integrity and elastic characteristics, so verifying the efficiency of nano and additional cementitious materials in extending the long-term durability of concrete in demanding conditions.

Additionally, freeze–thaw durability assessments further reinforce the effectiveness of these modifications. The concrete mixes with nano-titania and glass powder maintained higher dynamic modulus, density, and pulse velocity values over multiple freeze–thaw cycles compared to control mixes. This indicates better retention of stiffness, reduced internal damage, and improved resilience under cyclic environmental stress. The modified concrete's ability to preserve structural integrity over time highlights its potential for use in challenging environments.

Overall, the study underscores the advantages of integrating nano-materials and recycled glass powder into traditional concrete. These modifications not only contribute to enhanced mechanical performance and durability but also support sustainable construction practices by reducing cement usage and utilizing industrial waste. Such innovative concrete compositions are well-suited for modern infrastructure requiring long-lasting, high-performance materials.

Author Contributions

M.S. has contributed to this work under the guidance of P.S. All authors reviewed and approved the final version of the manuscript.

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Not applicable.

Informed Consent Statement

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Data Availability Statement

Data available on reasonable request.

Conflicts of Interest

The authors declare no conflict of interest.

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