BILINGUAL PUBLISHING GROUP

Journal of Building Material Science

https://journals.bilpubgroup.com/index.php/jbms

ARTICLE

Utilizing Nano-TiO_2 and GGBS to Improve Concrete's Acid Resistance and Durability

Mamidi Srinivasan* *, P. Sravana

Department of Civil Engineering, College of Engineering, Science & Technology, Jawaharlal Nehru Technological University, Hyderabad 500085, India

ABSTRACT

Although concrete is a commonly used building material, it suffers deterioration in acidic surroundings. Significant structural damage and expensive repairs can follow from this. This work examined the strength and durability of M40 and M50 grade concrete incorporating 30% ground granulated blast furnace slag (GGBS) and 1% titanium dioxide (TiO_2). Several tests, including an acid resistance and fast chloride penetration test (RCPT), evaluated this altered concrete's performance. Over 28, 90, and 180 days, the acid resistance test assessed the effects of 5% sulphuric acid (H_2SO_4), hydrochloric acid (HCl), and sodium sulfate (Na_2SO_4). The modified concrete showed less weight loss and more residual compressive strength than conventional concrete, according the findings. The calculations of the acid durability factor verified that the modified concrete mix showed better resistance against hostile chemical surroundings. Measuring the overall charge passed through concrete specimens, the Rapid Chloride Penetration Test (RCPT) evaluated chloride ion permeability. Classifying the modified concrete as "very low", it displayed a notable decrease in chloride penetration with roughly (50–60)% lower permeability for M40 and (40–50)% for M50 compared to the control mix.

Keywords: Concrete Pavement; Nano Titanium Dioxide (TiO_2); Ground Granulated Blast Furnace Slag (GGBS); Acid Attack Resistance; RCPT; Durability

*CORRESPONDING AUTHOR:

Mamidi Srinivasan, Department of Civil Engineering, College of Engineering, Science & Technology, Jawaharlal Nehru Technological University, Hyderabad 500085, India; Email: msn9865@yahoo.co.in

ARTICLE INFO

Received: 25 April 2025 | Revised: 23 May 2025 | Accepted: 26 May 2025 | Published Online: 12 June 2025

DOI: https://doi.org/10.30564/jbms.v7i2.9696

CITATION

Srinivasan, M., Sravana, P., 2025. Utilizing Nano-TiO_2 and GGBS to Improve Concrete's Acid Resistance and Durability. Journal of Building Material Science. 7(2): 175–192. DOI: https://doi.org/10.30564/jbms.v7i2.9696

1. Introduction

Because of its great compressive strength and durability concrete is the most often used building material [1]. On the other hand, exposure to hostile surroundings, such acidic solutions and conditions high in chloride, can cause degradation, so lowering its service life [2–5]. Further cementitious materials and nanomaterials have been investigated to improve the durability of concrete [6,7]. This work investigates how ground granulated blast furnace slag (GGBS) and titanium dioxide (TiO_2) inclusion in concrete might increase its resistance to chemical attack and chloride penetration [8-10].

A photocatalytic nanomaterial, titanium dioxide (TiO_2) has been looked at for possible use improving the mechanical and durability qualities of concrete [11]. Widely used as a partial replacement for cement to increase the long-term strength and durability of concrete [12], GGBS, a by-product of the steel sector, TiO_2 and GGBS taken together should improve concrete's performance in demanding surroundings [13-15].

Many studies have looked at how industrial by-products and nano-TiO_2 might be combined to improve concrete's durability and strength while so supporting sustainability. Reviewing the effects of partial replacement of cement with nano-TiO_2 and GGBS, it was noted improvements in concrete properties [16-18]. Emphasizing difficulties in nanoparticle dispersion and regulatory compliance [19-21], stressed need of more innovation in nano-modified concrete. Authors detailed how nano-TiO_2 influences fresh, mechanical, and durability properties of cementitious composites, suggesting an optimal dosage while noting lowered workability [22]. It was showed that geopolymer mortars' thermal resistance and strength improved by nano-TiO_2 and nano-Al_2O_3 [23].

Other noteworthy contributions include [24], who discovered that although limited durability gains in acidic environments, combining nano-TiO_2 and ZnO enhanced photocatalytic and self-cleaning properties. Reviewed the self-cleaning potential and environmental advantages of TiO_2 in concrete [25]. Reduced porosity and increased fiber-reinforced concrete strength were shown nano-TiO_2 and nano-SiO_2 [26]. Increasing NT and GGBS content, according to authors, raised fracture energy and toughness while simultaneously raising brittleness. While it was showed that combining waste glass powder with nano-TiO_2 offered synergistic improvements in strength and durability, workability dropped with increasing nano-TiO_2 content [27]. It was found that nano-TiO_2 improved the durability and mechanical performance of rubberized concrete.

Using nano-TiO_2, it was examined the mechanical and fracture behavior of fiber-reinforced geopolymer composites, revealing notable increases in compressive and tensile strength, particularly with 2% macro-steel fiber content exhibiting strain hardening under flexural stress [28]. Analyzed the effects of nano-TiO_2 and water-cement ratio on fracture properties, found that both lower w/c ratios and higher nano-TiO_2 content improve fracture energy and toughness [29]. 1% nano-TiO_2 maximally increases compressive and flexural strength while improving microstructure by void reduction and C-S-H crystal development, according to research 50.62% Rhodamine B removal at 28 days was obtained investigating GGBS-based geopolymer mortars and finding that nano-TiO_2 and basalt fiber addition improved strength and self-cleaning performance [30]. Emphasizing that nano-TiO_2 increased binding gel formation to improve thermal resistance in fly ash-based geopolymers [31]. By means of UV-driven RhB degradation presented the photocatalytic efficiency of manufactured geopolymer tiles with nano-ZnO, so benefiting the environment. After looking at the combined effects of nano TiO_2 or Al_2O_3 with polypropylene fibers, it was found that nano-Al_2O_3 produced better mechanical performance. Although overdosing may cause agglomeration and reduced benefits, showed that TiO_2-graphic composites densify alkali-activated slag mortars and increase durability.

The durability of M40 and M50 grade concrete changed with 1% TiO_2 and 30% GGBS is assessed in this work. The study comprises the fast chloride penetration test (RCPT) to ascertain chloride ion permeability and acid resistance testing against sulphuric acid (H_2SO_4), hydrochloric acid (HCl), and sodium sulfate (Na_2SO_4). The main goal is to evaluate how well this modified concrete mix reduces strength loss, minimizes weight degradation, and increases resistance to chloride ingress, so qualifying it for infrastructure subjected to demanding environmental conditions.

Reference [32] studied concrete with silica fume and ultra-fine TiO_2, finding improved strength with steel fiber addition. It was reported enhanced durability using magnetic water and micro-silica in acidic conditions. It showed that steel fibers improved compressive and flexural strength more than polypropylene or glass in UHPC. It was highlighted that high-range superplasticizers improved rheology and strength in low w/c mixes. It was found banana fiber reinforcement slightly improved the thermal stability of polymer composites for construction use.

Reference [33] investigated the use of superabsorbent polymers (SAPs) in cementitious materials and demonstrated through neutron radiography that SAPs can effectively reduce capillary absorption and water permeability in cracked specimens by swelling and sealing the cracks, thus improving the long-term durability and water-tightness of concrete. It was introduced a novel crack closure system using shrinkable polymers, which, upon activation, closed preformed cracks in mortar specimens and induced stress across the crack faces, showing potential to support autogenous healing and increase concrete durability. Reference [34] explored biochar-embedded and bacterial self-repairing techniques in concrete, revealing that bacterial cultures can trigger crack healing and strength recovery.

Despite promising outcomes from incorporating Nano-TiO_2 and GGBS into M40 and M50 grade concrete for improved acid resistance and chloride durability, several research gaps remain. Existing studies primarily focus on short- to medium-term performance (up to 180 days) under controlled acid and chloride exposure, leaving uncertainties about the long-term durability and microstructural evolution of such modified concretes in real-world, variable environmental conditions. Furthermore, while individual improvements in mechanical and durability parameters are documented, a comprehensive understanding of the synergistic effects of Nano-TiO_2 and GGBS on concrete's pore structure, crack propagation, and self-healing potential remains underexplored. Additionally, the scalability, economic viability, and environmental trade-offs associated with the widespread adoption of these additives in large-scale construction projects need deeper investigation.

2. Materials Used

2.1. General

Carefully chosen materials for this project help to improve concrete's mechanical and durability qualities as well as support sustainability. The main binder was ordinary Portland Cement (OPC), 53 grade; complementary coarse and fine aggregates came from local sources. Ground Granulated Blast Furnace Slag (GGBS) and Nano Titanium Dote (Nano-TiO_2) were added as mineral admixtures to raise performance. While GGBS helped to increase durability and lower permeability, Nano-TiO_2, in its Rutile form was used for its ability to refine concrete microstructure and boost early strength. Workability was improved also using a high-range water-reducing admixture called SP430. Every component was obtained from trustworthy local sources to guarantee consistency over the experimental program. **Table 1** details all the components used in the current study.

Table 1 lists the components of the experimental study. The main binder was 53 grade ordinary Portland cement (OPC) from Ultratech. Hyderabad provided locally both coarse and fine grade aggregates for Zone II. Ground granulated blast furnace slag (GGBS) came from Jindal; nano titanium dioxide (TiO_2), used as a mineral admixture, was sourced from NCI Hyderabad. To improve workability, a chemical admixture from FOSROC—SP430—was added. Drawn from the JNTUH bore well in Hyderabad, water for the mix came from.

Table 1. Materials used.

Material	Description	Source
Cement	OPC 53 grade	Ultratech
Course aggregate Fine aggregate	ZONE II	Hyderabad
TiO_2 GGBS	Mineral admixtures	NCI Hyderabad JINDAL
SP430	Chemical admixture	FOSROC
Water	JNTUH bore well	Hyderabad

OPC 53 grade cement primarily consists of lime (CaO) 60–67%, silica (SiO_2) 17–25%, alumina (Al_2O_3) 3–8%, and iron oxide (Fe_2O_3) 0.5–6%, with smaller amounts of magnesia (MgO), sulfur trioxide (SO_3), alkalis (Na_2O, K_2O), and loss on ignition. These oxides combine to form key compounds like tricalcium silicate (C_3S) and dicalcium silicate (C_2S) which provide early and long-term strength, along with tricalcium aluminate (C_3A) and tetracalcium aluminoferrite (C_4AF) influencing setting time and durability. The high C_3S content makes OPC 53 ideal for high-strength, fast-setting applications.

2.2. Nano Titanium Dioxide (Nano-TiO_2)

Highly efficient additive nano-TiO_2 improves concrete performance by microstructure refinement and porosity reduction. It accelerates early strength development by acting as a catalyst in pozzolanic reactions as well. This work focused on the Rutile form of Nano-TiO_2 using an average particle size of 19.6 nm. Doses ranging from 0.5% to 2.0% by weight of cement were investigated; 1% proved to be the ideal proportion for improving mechanical properties, durability, and resistance to environmental degradation.

2.3. Ground Granulated Blast Furnace Slag (GGBS)

A by-product of the iron and steel sector, GGBS is a commonly used sustainable cementitious material improving concrete performance. By lowering chloride penetration and water permeability, it increases durability by improving workability, lowers heat of hydration. This work included GGBS as a partial cement replacement at 30% and 40% levels; 30% produced the best results. GGBS and Nano-TiO_2 shown a synergistic effect that greatly enhanced concrete performance and supported environmental sustainability.

3. Experimental Investigation

In the current experimental investigation, the mix proportion for M40 and M50 grades of concrete has been determined per IS 10262: 2019. The tables below list the amounts of each component used in M40 and M50 concrete.

Table 2 provides the mix ratios for M40 grade concrete, which show a methodical fluctuation in the ground granulated blast furnace slag (GGBS) and titanium dioxide (TiO_2) inclusion to investigate their effects on concrete properties. All mixes have a fixed concentration of coarse and fine aggregates, water, and admixture and a constant water-to---cement (W/C) ratio of 0.38. With GGBS added at 30% and 40%, respectively, TiO_2 content ranges from 0% to 2% across mixes NT_0G_0 and NT_2G_{40} respectively. With NT_1G_{30} and NT_1G_{40} representing ternary blends combining both mineral additives, replacing cement with TiO_2 and GGBS seeks to improve durability and sustainability.

Table 3 shows the mix proportions for M50 grade concrete including several combinations of ground granulated blast furnace slag (GGBS) and titanium dioxide (TiO_2). Every combination keeps a constant water-to---cement (W/C) ratio of 0.35. The control mix (NT_0 G_0) consists just of cement without any TiO_2 or GGBS. Thirty percent and forty percent of the cement is replaced with GGBS respectively in the NT_1 G_{30} and NT_1 G_{40} mixes; 1% TiO_2 is added in both cases. Using consistent aggregate content and admixtures helps to maintain workability and strength while lowering cement content, so improving sustainability and durability. **Figure 1** shows Compressive strength testing of cube. The **figure 2** shows Testing of cube using RCPT apparatus

Table 2. Mix proportions of M40 grade concrete.

Mix Designation	NT_0 G_0	$NT_{0.5}$ G_0	NT_1 G_0	$NT_{1.5}$ G_0	NT_2 G_0	NT_1 G_{30}	NT_1 G_{40}
W/C	0.38	0.38	0.38	0.38	0.38	0.38	0.38
Cement (Kg/m³)	390	388	386	382	270	232	232
TiO_2 (Kg/m³)	0	1.95	3.9	5.85	3.9	2.7	3.4
TiO_2 (%)	0	0.5	1	1.5	1	1	1
GGBS (Kg/m³)	0	0	0	0	117	156	156
GGBS (%)	0	0	0	0	30	40	40
Coarse Aggregate (Kg/m³)	1316	1316	1316	1316	1316	1316	1316
Fine Aggregate (Kg/m³)	596	596	596	596	596	596	596
Water (lit)	148	148	148	148	148	148	148
Admixture (lit)	2.73	2.73	2.73	2.73	2.73	2.73	2.73

Table 3. Mix proportions of M50 grade concrete.

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

Figure 1. Compressive strength testing of cube.

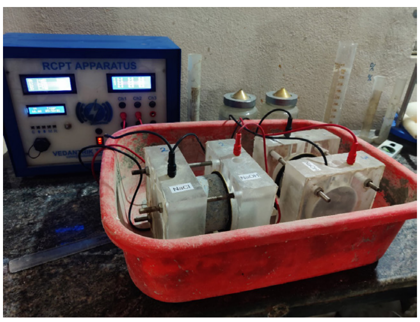

Figure 2. Testing of cube using RCPT apparatus.

4. Results

4.1. Acid Attack Resistance

Residual compressive strength, acid weight loss factor, and acid durability factor help one determine concrete's chemical resistance. For this experiment, concrete specimens measuring 100 mm × 100 mm × 100 mm are cast; water cures for 28 days afterwards. After 28 days of curing, the specimens were taken off the curing tank and let to dry for one day before their original weights were recorded. The specimens then were submerged in acids including H_2SO_4, HCl, and alkaline Na_2SO_4 all with 5% concentrations for 28, 90, and 180 days. Following 28 days, 90 days, and 180 days of immersion in chemical solutions, the specimens' weight loss and residual compressive strength are tested.

Given in Equation (1), the Acid Durability Factor (ADF) gauges concrete's capacity to maintain strength under acidic conditions. It is computed relative to the total planned exposure duration (M) using the relative strength (Sr) at a given number of days (N) during the exposed period. Better resistance to acid attack comes from a higher ADF. By means of comparison between the weight of the specimen before and after immersion, the Acid Weight Loss Factor—defined in Equation (2)—quantifies the percentage of material lost owing to acid contact. These parameters taken together assist to assess concrete's degradation behavior and durability in acidic surroundings.

$$\text{Acid Durability Factor} = S_r \times \frac{N}{M} \tag{1}$$

S_r = relative strength at N days (%);
N = number of days at which durability factor is required;
M = number of days at which the exposure is to be terminated.

$$\text{Acid weight loss factor (\%)} = \frac{\textit{loss of weight of specimen after immersion}}{\textit{original weight of specimen before immersion}} \times 100 \tag{2}$$

4.2. Compressive Strength

Table 4 shows M40 grade concrete's compressive strength under varying curing times—28, 90, and 180 days. Over time, the control mix (M40-NT0-G0) exhibits a slow rise in strength until it reaches 54 MPa 180 days. By contrast, the modified mix with nano and GGBS additions (M40-NT1-G30) shows noticeably more strength at all stages, reaching 67 MPa at 180 days. This suggests that addition of GGBS and nano-silica improves the long-term strength development of M40 concrete.

Table 4. Compressive strength of M40 grade concrete.

M40 Grade Concrete	Compressive Strength (MPa)		
	28 DAYS	90 DAYS	180 DAYS
M40-NT_0-G_0	48	52	54
M40-NT_1-G_{30}	56	63	67

After exposure to various aggressive chemical environments (H_2SO_4, HCl, and Na_2SO_4)—between 28, 90, and 180 days—the **Figure 3** compares the residual compressive strength of two concrete mixes—M40-NT0-G0 (control mix) and M40-NT1-G30 (modified mix). M40-NT1-G30 routinely shows much higher residual compressive strength than the control mix over all three chemical exposures and time intervals. Compared to 41 MPa for the control, the modified mix shows a strength of 53 MPa in all conditions at 28 days. The strength of the modified mix lowers somewhat to 49 MPa after 90 days, while the control falls to 33 MPa, suggesting a more marked degradation in the traditional mix. Degradation in both continues at 180 days; the modified mix preserves a strength of 39 MPa while the control mix drops to 20 MPa.

With much less degradation over time, this trend amply emphasizes that M40-NT1-G30 has better resistance to acid and sulfate attacks. The inclusion of particular additives or treatments (e.g., nanomaterials or geopolymer content, as advised by "NT1" and "G30") that improve durability and chemical resistance in hostile environments could help to explain this improved performance. The figure shows generally how well the modified concrete mix preserves structural integrity over extended chemical contact.

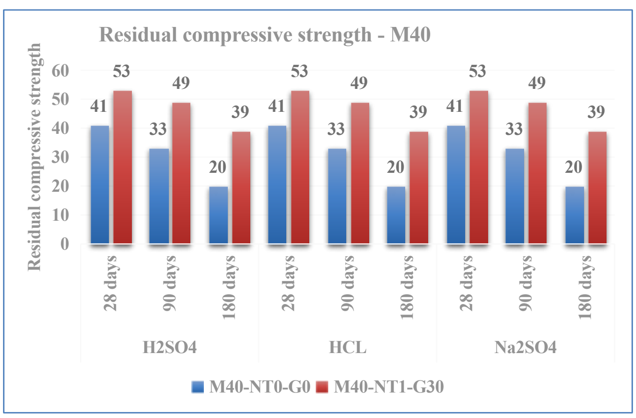

Figure 3. residual compressive strength (Mpa) of M40 grade concrete.

When exposed to various chemical environments (H_2SO_4, HCl, and Na_2SO_4, over three time intervals: 28, 90, and 180 days), the **Figure 4** shows the percentage reduction in compressive strength of two concrete mixes—M40-NT0-G0 (control mix, shown in blue) and M40-NT1-G30 (modified mix, shown in orange). This chart quantifies the degree of deterioration each mix suffers, so complementing the previous one. The control mix shows the most loss under H_2SO_4 exposure: rising from 14% at 28 days to 36% at 90 days, then peaking at 63% at 180 days. With just 4%, 22%, and 42% loss at the respective time points, the altered mix shows noticeably less degradation as opposed. With HCl exposure, a similar trend is seen whereby the modified mix performs better with values of 1.5%, 17%, and 27%, respectively while the control mix shows a progressive increase in loss (4%, 21%, and 33%).

For Na_2SO_4, the degradation is rather minimal for both mixes. Still, the modified mix regularly beats the control. The modified mix stays just marginally better at 1%, 14%, and 22%; the control mix shows 2%, 17%, and 24% loss. Generally, especially in highly aggressive acidic environments like H_2SO_4, the figure unequivocally shows that M40-NT1-G30 is more resistant to chemical attack. Using additives or geopolymers in this modified mix probably helps to explain its lower porosity and better durability, which would translate into much less compressive strength loss over time than in the conventional concrete. This emphasizes the fit of the modified mix for long-term use in chemically hostile surroundings.

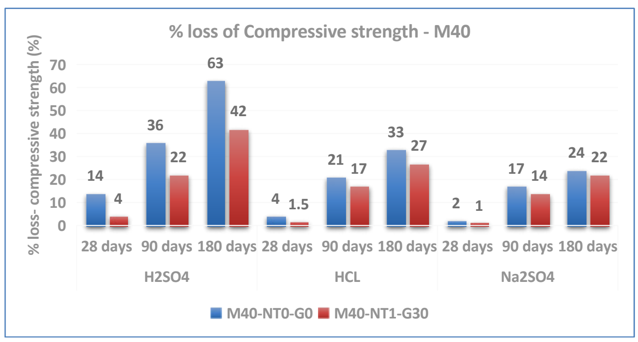

Figure 4. compressive strength loss of M40 grade concrete (%).

4.3. Acid Durability Factor

Particularly focusing on their performance in sulfuric acid (H_2SO_4) exposure, **Figure 5** offers a comparative analysis of two concrete mixes—M40-NT0-G0 (control mix, in blue) and M40-NT1-G30 (modified mix, in orange). For every mix, the chart shows three types of data: Acid Durability Factor (ADF) at 28, 90, and 180 days; relative strength retention over time (%; and 28-day compressive strength (in MPa). M40-NT1-G30's 28-day compressive strength, 56 MPa, first exceeds M40-NT0-G0's 48 MPa, suggesting a naturally stronger modified mix. Under protracted acid attack, the relative strength (%) to 28-day strength indicates how effectively the concrete maintains its strength. At 28 days, the modified mix keeps 96%; the control keeps 86%. M40-NT1-G30 retains 77% vs. 69% for the control at 90 days and only 42% at 180 days, so widening this disparity over time. This amply illustrates how much better the modified mix resists acid breakdown.

Following a similar trend is the Acid Durability Factor (ADF), which aggregates compressive strength and retention rate to reflect general durability under acidic conditions. ADF values for the modified mix are 15 at 28 days while for the control they are 13. ADF increases to 34 (control) and 37 (modified) at 90 days and shows a notable advantage with an ADF of 70, compared to just 42 for the control, 180 days. This figure shows generally that M40-NT1-G30 is far more suited for uses in chemically aggressive environments like sewer systems or industrial drainage infrastructure since it shows higher initial strength, better long-term strength retention, and much improved acid durability under H_2SO_4 exposure.

When exposed to hydrochloric acid (HCl), **Figure 6** contrasts the Acid Durability Factor (ADF) of two concrete mixes—M40-NT0-G0 (control mix, in blue) and M40-NT1-G30 (modified mix, in orange)—over time. The figure shows three measures: the ADF at 28, 90, and 180 days; relative strength (%) with regard to 28-day values; and 28-day compressive strength (MPa). Suggesting a stronger baseline, the first 28-day compressive strength for the modified mix (M40-NT1-G30) is 56 MPa, more than that of the control mix. The modified mix routinely beats the control in terms of relative strength retention. Both mixes hold over 95% of their starting strength—96% (control) and 98% (modified)—at 28 days. The difference becomes more noticeable over time: at 90 days M40-NT1-G30 retains 94% versus 85% for the control, and at 180 days 89% for the modified mix against 75% for the control. This suggests that the modified mix degrades in HCl more slowly.

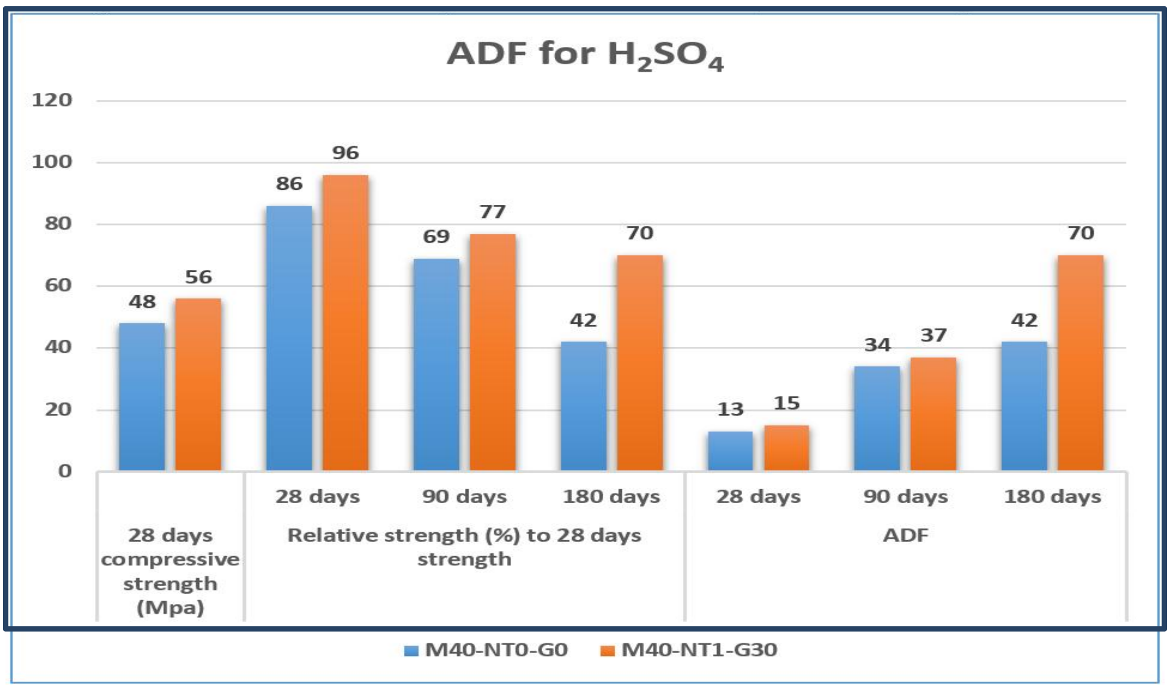

Figure 5. Acid Durability Factor for H_2SO_4.

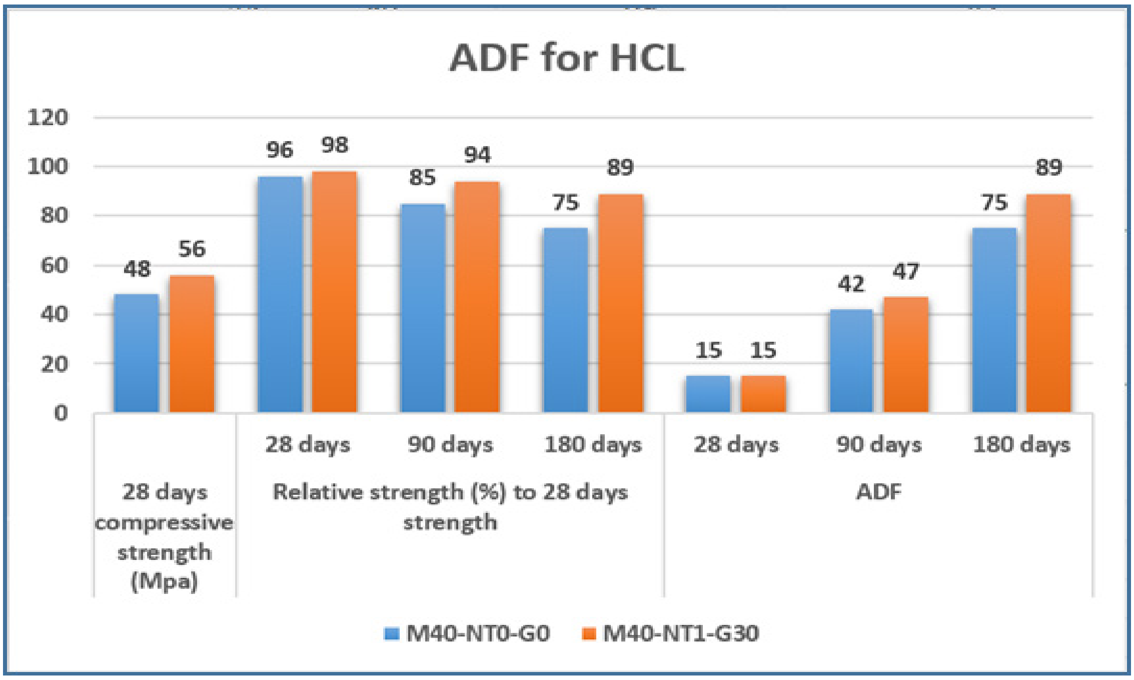

Figure 6. Acid Durability Factor for HCl.

Further underlining this trend are the ADF values, which combine compressive strength and retention efficiency to reflect the lifetime of concrete under acidic conditions. After 28 days, both mixtures have the same ADF—15. The modified mix exhibits a higher ADF (47) at 90 days than the control (42), and by 180 days the ADF increases to 89 for the modified mix while the control reaches 75. Under HCl attack, M40-NT1-G30 shows better durability and acid resistance, according to the chart, so preserving greater strength and ADF values over time. This proves its adaptability for uses in settings like chemical plants or sewage systems where exposure to hydrochloric acid is anticipated.

Subjected to sodium sulfate (Na_2SO_4), **Figure 7** offers a comparative evaluation of two concrete mixes—M40-NT0-G0 (control mix, shown in blue) and M40-NT1-G30 (modified mix, shown in orange). Three main groups define the data: Acid Durability Factor (ADF) over 28, 90, and 180 days; relative strength (%) with regard to 28-day strength; and 28-day compressive strength (MPa). The 28-day compressive strength of the modified mix (M40-NT1-G30) is 56 MPa, higher than the 48 MPa of the control mix, so indicating a stronger initial performance. Under Na_2SO_4 exposure, both mixes show great relative strength retention. By 28 days, both still have 98% of their strength. M40-NT0-G0 retains 90% at 90 days; M40-NT1-G30 only marginally improves to 94%. The modified mix retains a superior 92%, indicating better long-term resistance to sulfate attack; the control mix retains 85% at 180 days.

The Acid Durability Factor (ADF) captures the combined effect of compressive strength and over time retention. Both mixes show equal ADF values of 15 at 28 days, so indicating comparable early-stage durability. But as time goes on, the altered mix starts to show better performance: ADF rises to 47 for M40-NT1-G30 at 90 days, from 45 for the control, and by 180 days the difference becomes more notable—92 for the modified mix against 85 for the control. Although both mixes show good performance under Na_2SO_4 exposure, M40-NT1-G30 regularly shows better sulfate resistance, shown in greater strength retention and ADF values at each stage overall. This supports its fit for infrastructure in sulfate-rich settings, including marine constructions and drainage systems.

After exposure to various chemical environments: H_2SO_4 (sulfuric acid), HCl (hydrochloric acid), and Na_2SO_4 (sodium sulfate), the **Figure 8** shows the degradation of two concrete mixes—M40-NT0-G0 (control mix, shown in blue) and M40-NT1-G30 (modified mix with nano-silica and glass powder, shown in orange): A data table displaying the exact percentage values of weight loss for both mixes over all time intervals supports the graph. 5%

at 28 days, rising to 9% at 90 days, and peaking at 16% by 180 days the control mix suffers notable weight loss. With only 2%, 3.5%, and 9.2% loss at the same intervals, the modified mix shows far better resistance. This significant variation shows that M40-NT1-G30 provides better resistance against mass degradation caused by acids.

M40-NT1-G30 performs once more above the control mix. While M40-NT1-G30 stays regularly lower at 1.5%, 2%, and 3.5%, the weight loss for M40-NT0-G0 increases from 2.5% (28 days) to 6.5% (180 days). The lower mass loss emphasizes the improved resistance of the modified mix against hydrochloric acid attack. Having very low weight loss values, both mixes show remarkable resistance to sodium sulfate exposure. While the modified mix shows even lower values—0.01%, 0.08%, and 0.14% over the same periods, the control mix records 0.01% at 28 days, then just 0.2% at 180 days. These small variations confirm that sulfate attack has a much less impact than in acidic environments, but M40-NT1-G30 still shows rather better performance.

This figure amply illustrates how consistently M40-NT1-G30 shows lower weight loss under all chemical exposures and time intervals than the control mix. Under strong acidic conditions like sulfuric and hydrochloric acid in particular, the addition of glass powder and nanomaterials seems to improve the chemical resistance and durability of concrete. These findings confirm the modified mix as a more long-lasting and environmentally friendly choice for buildings subjected to demanding surroundings.

Figure 9 shows clearly that while sodium sulfate has the least corrosive effect on concrete, sulfuric acid is the most aggressive chemical agent followed by hydrochloric acid. Reinforcing its great durability as also concluded from mechanical and weight loss tests, the modified concrete mix (M40-NT1-G30) shows better resistance and less visible damage across all three conditions. These visual signals offer concrete proof of how glass powder additions and nanosilica help to improve the chemical resistance of concrete.

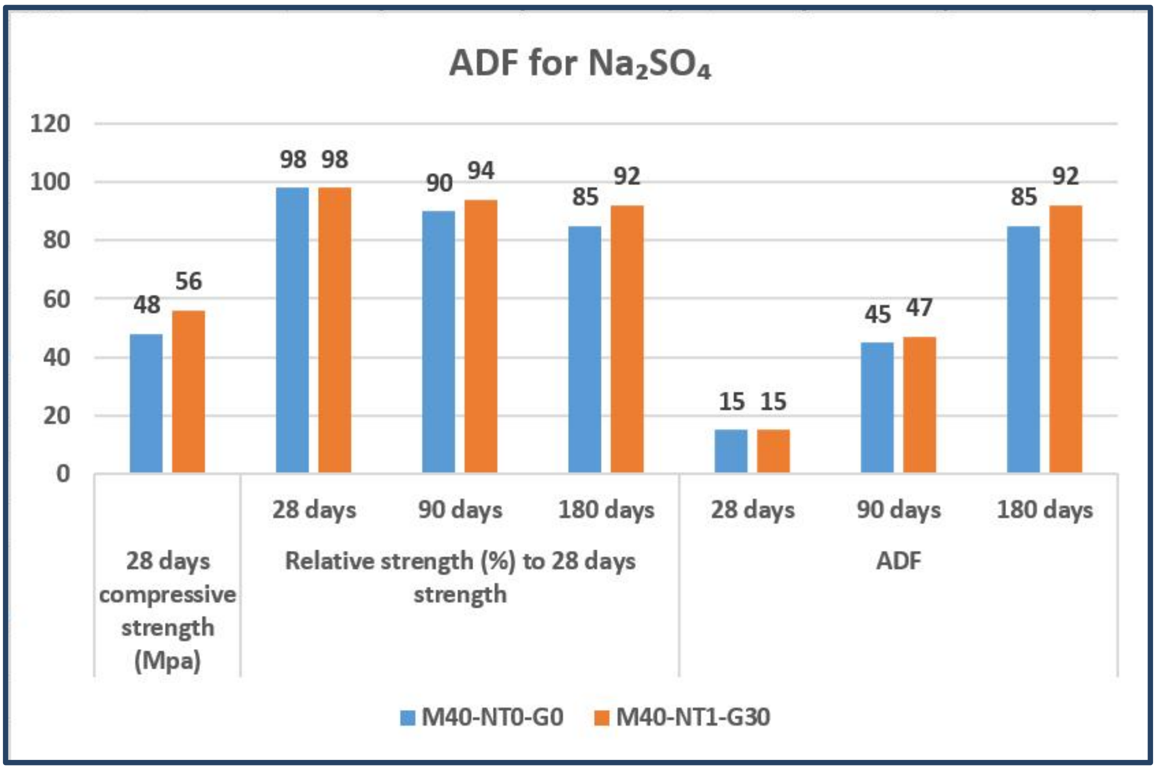

Figure 7. Acid Durability Factor for Na_2SO_4.

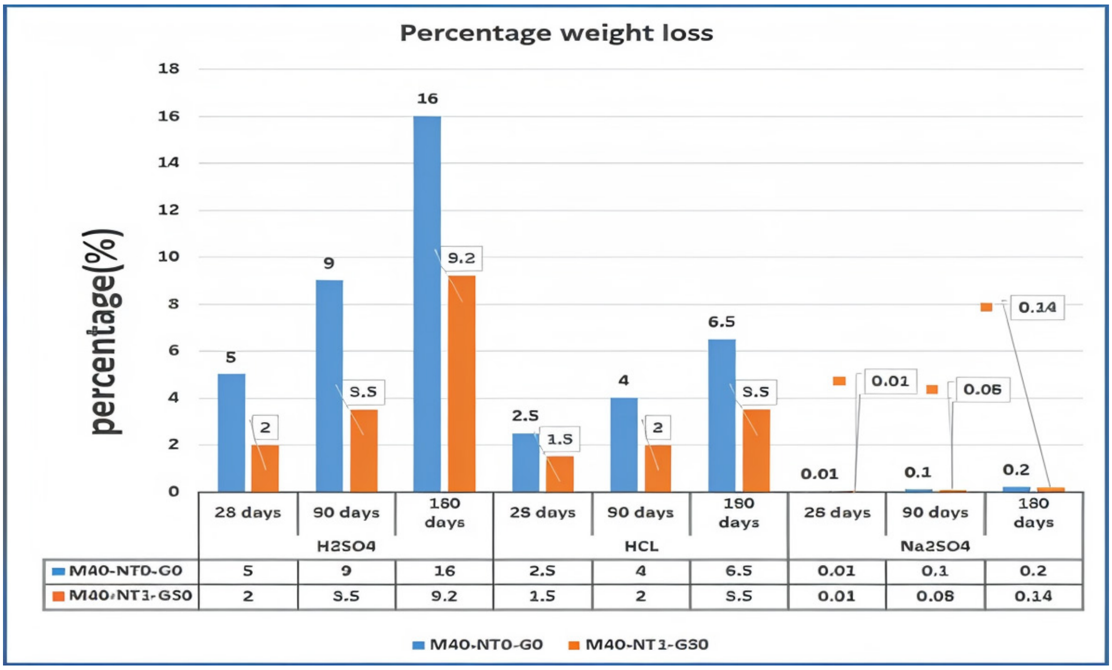

Figure 8. Percentage weight loss – M40.

(**a**) Effect of H_2SO_4 Solution

(**b**) Effect of HCl Solution

(**c**) Effect of Na2SO4

Figure 9. Effect of chemicals on concrete.

Tested at 28, 90, and 180 days, **Table 5** shows the compressive strength results of M50 grade concrete for two different mixes—M50-NT0-G0 (control mix) and M50-NT1-G30 (modified mix with nano-silica and 30% glass powder replacement.). Strength for the modified mix shows a consistent increase over all curing times. The strength rises from 58.2 MPa (control) to 66.64 MPa (modified) at 28 days; this trend carries forward at 90 and 180 days to produce 81.21 MPa for the modified mix. This implies that the long-term strength development of M50 concrete is much improved by including glass powder and nano-silica.

Table 5. Compressive strength of M50 grade concrete.

M50 Grade Concrete	Compresive Stength – M50		
	28 DAYS	90 DAYS	180 DAYS
M50-NT_0-G_0	58.2	65.02	69.1
M50-NT_1-G_{30}	66.64	76	81.21

Over periods of 28, 90, and 180 days, the residual compressive strength of M50 grade concrete exposed to three aggressive chemical environments—H_2SO_4 (sulfuric acid), HCl (hydrochloric acid), and Na_2SO_4 (sodium sulfate)—shown in **Figure 10**. Two mixes—M50-NT0-G0 (the control mix) and M50-NT1-G30 (including glass powder and nano-TiO_2) are evaluated. M50-NT1-G30 consistently shows greater residual strength across all three environments and exposure times, suggesting better durability and chemical resistance brought about by the nano material addition.

With the residual strength of M50-NT0-G0 declining dramatically from 51 MPa at 28 days to 31 MPa at 180 days, sulfuric acid among the three chemicals causes the most degradation. M50-NT1-G30 exhibits better resistance, though, and keeps 44 MPa at 180 days. With Na_2SO_4 showing the least change over time, both mixes keep more strength in HCl and Na_2SO_4. Especially, M50-NT1-G30 preserves a strength of 60 MPa even after 180 days in Na_2SO_4, so highlighting the improved long-term performance of the modified mix in environments rich in sulfates.

Figure 11 show over 28, 90, and 180 days the percentage loss of compressive strength in M50 concrete subjected to H_2SO_4, HCl, and Na_2SO_4. Two mixes—M50-NT0-G0 (control) and M50-NT1-G30 (modified with glass powder and nano-TiO_2)—are compared here. The M50-NT1-G30 mix shows consistently lower percentage strength loss across all environments and times, suggesting enhanced resistance to chemical attack by means of additional elements.

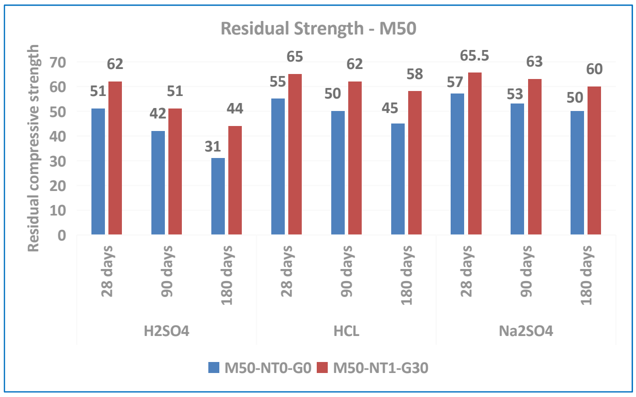

Figure 10. Residual compressive strength (Mpa) of M50 grade concrete.

With M50-NT0-G0 losing 55% strength at 180 days and M50-NT1-G30 showing a lowered loss of 46%, H_2SO_4 causes the most degradation. Less aggressive HCl and Na_2SO_4 have losses usually below 35%. At 28 days in all conditions, especially in HCl and Na_2SO_4 where M50-NT1-G30 shows only 2–2.5% decrease, the smallest percentage loss occurs. This information amply emphasizes the improved resistance of the modified concrete mix against sulfate and acidic environments.

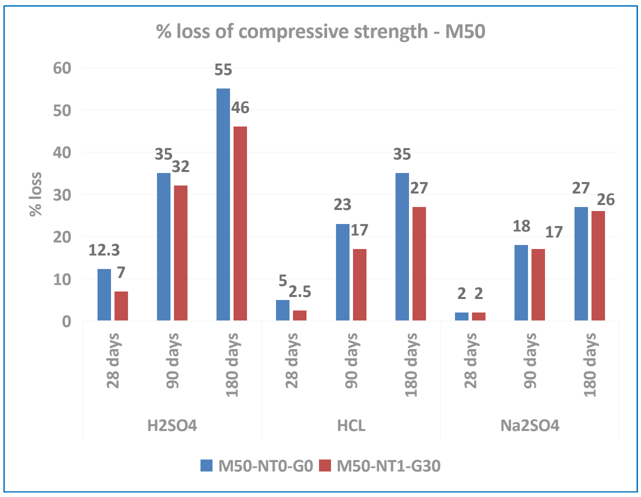

Figure 11. compressive strength loss of M50 grade concrete (%).

Comparatively a control mix (M50-NT0-G0) and a modified mix (M50-NT1-G30), **Figure 12** shows the Acid Durability Factor (ADF) and related compressive strength measurements for M50 concrete exposed to H_2SO_4. Incorporating nano-TiO_2 and glass powder clearly benefits the modified mix, which shows higher initial compressive strength (66.64 MPa) than the control (58.2 MPa). 28 days With 76% of the original strength retained at 90 days and 66% at 180 days, relative strength over time also shows better retention in M50-NT1-G30 than in the control, 72% and 53%.

The ADF values emphasize even more M50-NT1-G30's enhanced resistance to sulfuric acid. M50-NT0-G0 exhibits ADF values of 8, 26, and 53 at 28, 90, and 180 days respectively; the modified mix records better ADFs of 10, 33, and 66. M50-NT1-G30's increased acid resistance and longer-term durability reflect this consistent improvement across all phases, which makes it a better fit for aggressive environments including sulfuric acid.

Comparatively the performance of the control mix (M50-NT0-G0) and a modified mix (M50-NT1-G30) shows the Acid Durability Factor (ADF) and relative compressive strength of M50 concrete exposed to hydrochloric acid (HCl) (**Figure 13**). M50-NT1-G30 exhibits a 66.64 MPa compressive strength at 28 days over 58.2 MPa in the control mix. With 97%, 93%, and 87% strength retention at 28, 90, and 180 days respectively, the modified mix consistently shows relative strength retained over time higher than the control mix at 94%, 86%, and 77%.

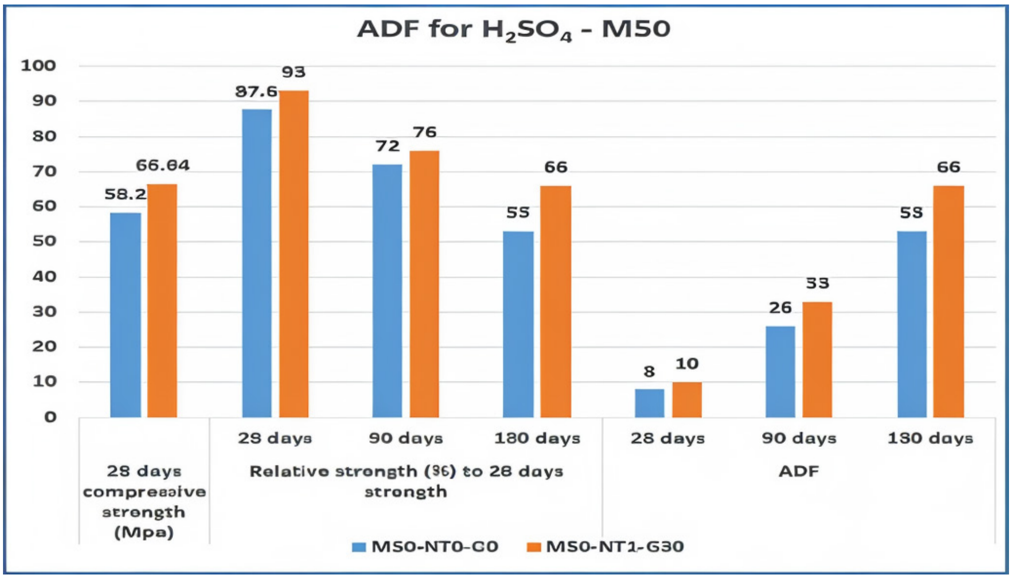

Figure 12. Acid Durability Factor for H_2SO_4.

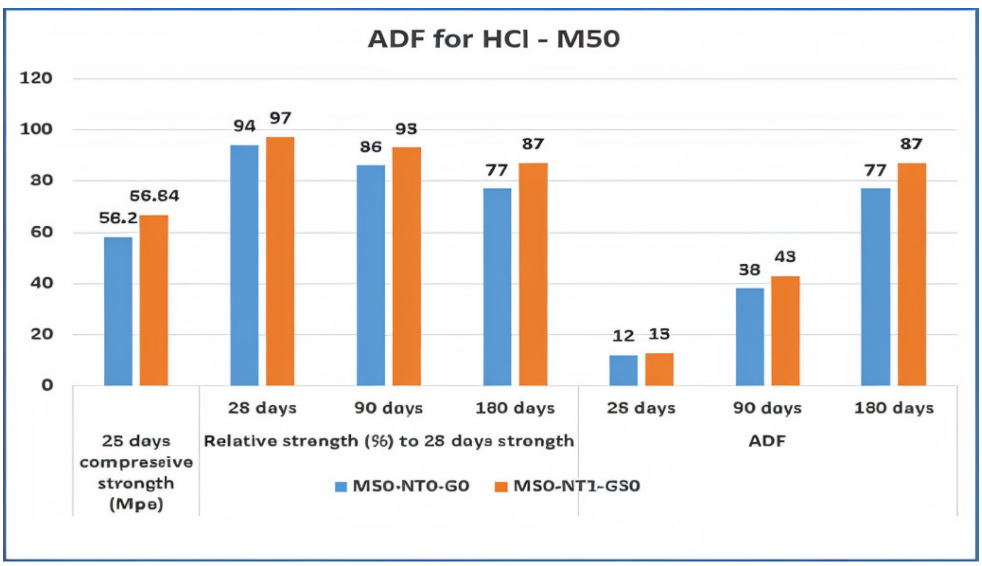

Figure 13. Acid Durability Factor for HCl.

Regarding ADF values, M50-NT1-G30 once more shows better performance under acidic environments. The control mix records somewhat lower values of 12, 38, and 77 for the same periods; the ADF values for the modified mix rise steadily from 13 at 28 days to 87 at 180 days. These findings confirm that adding glass powder and nano-TiO_2 improves the acid resistance of M50 concrete, so improving durability and extending the service life when subjected to HCl surroundings.

Comparing a control mix (M50-NT0-G0) and a modified mix (M50-NT1-G30), **Figure 14** shows the Acid Durability Factor (ADF) and relative compressive strength for M50 concrete exposed to sodium sulfate (Na_2SO_4). Reflecting the advantages of including nano-TiO_2 and glass powder, at 28 days the modified mix achieves a higher compressive strength (66.64 MPa) than the control (58.2 MPa). Though M50-NT1-G30 maintains 98%, 95%, and 90% of their 28-day strength at 28, 90, and 180 days respectively, slightly outperforming the control mix both mixes retain a high percentage of their original strength over time.

ADF values confirm even more the enhanced sulfate resistance of the modified mix. M50-NT1-G30 shows a somewhat higher ADF (14) at 28 days than the control (13), and this trend is evident at 90 and 180 days when it records ADF values of 45 and 90 respectively against 43 and 86 for the control. These results show that although both combinations work well in sodium sulfate environments, M50-NT1-G30 regularly shows somewhat better durability, thus it is a more dependable option for sulfate-rich environments.

Comparing a control mix (M50-NT0-G0) and a modified mix (M50-NT1-G30), **Figure 15** shows the percentage weight loss of M50 concrete samples exposed to various chemical environments (H_2SO_4, HCl, and Na_2SO_4) over 28, 900, and 180 days. The modified mix shows much reduced weight loss under all exposure conditions, suggesting better resistance to chemical degradation. Under H_2SO_4 exposure at 180 days, for example, M50-NT0-G0 loses 16%; M50-NT1-G30 shows only a 10% loss. With HCl exposure, a similar trend is seen whereby the modified mix records just 5% while the control mix reaches 7% loss.

Although both mixes experience minimum weight loss overall in the case of Na_2SO_4 exposure, the modified mix still shows better performance with somewhat smaller values at all intervals. M50-NT1-G30 records just 0.13% weight loss at 180 days, while the control records 0.21%. These results show how well glass powder and nano-TiO_2 improve M50 concrete's durability by reducing mass degradation in hostile conditions.

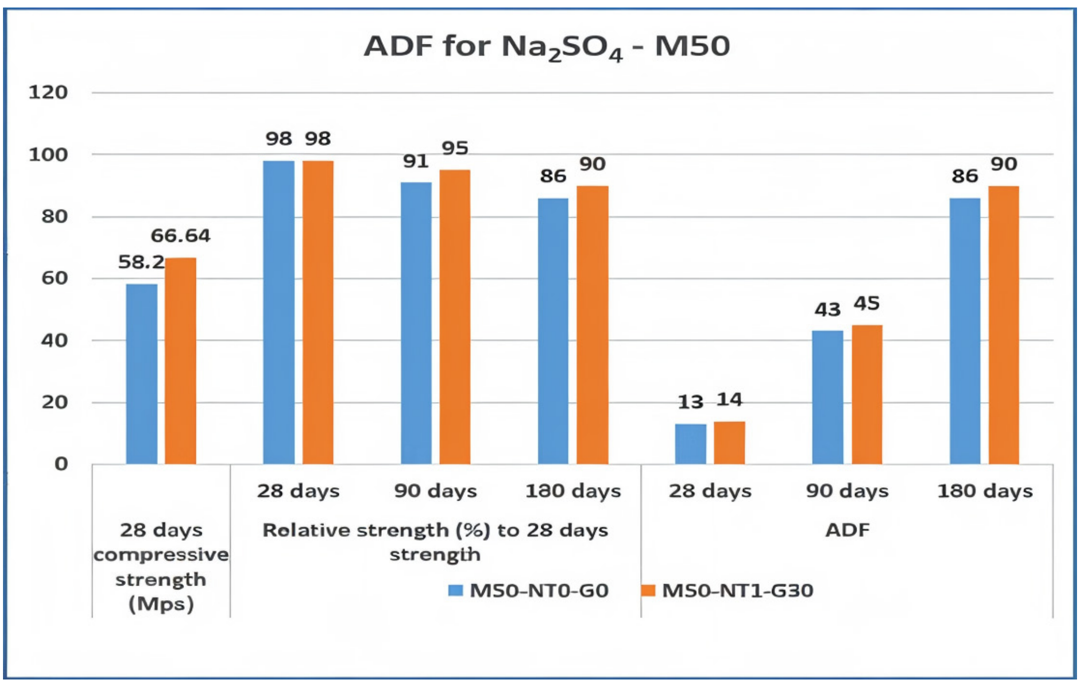

Figure 14. Acid Durability Factor for Na_2SO_4.

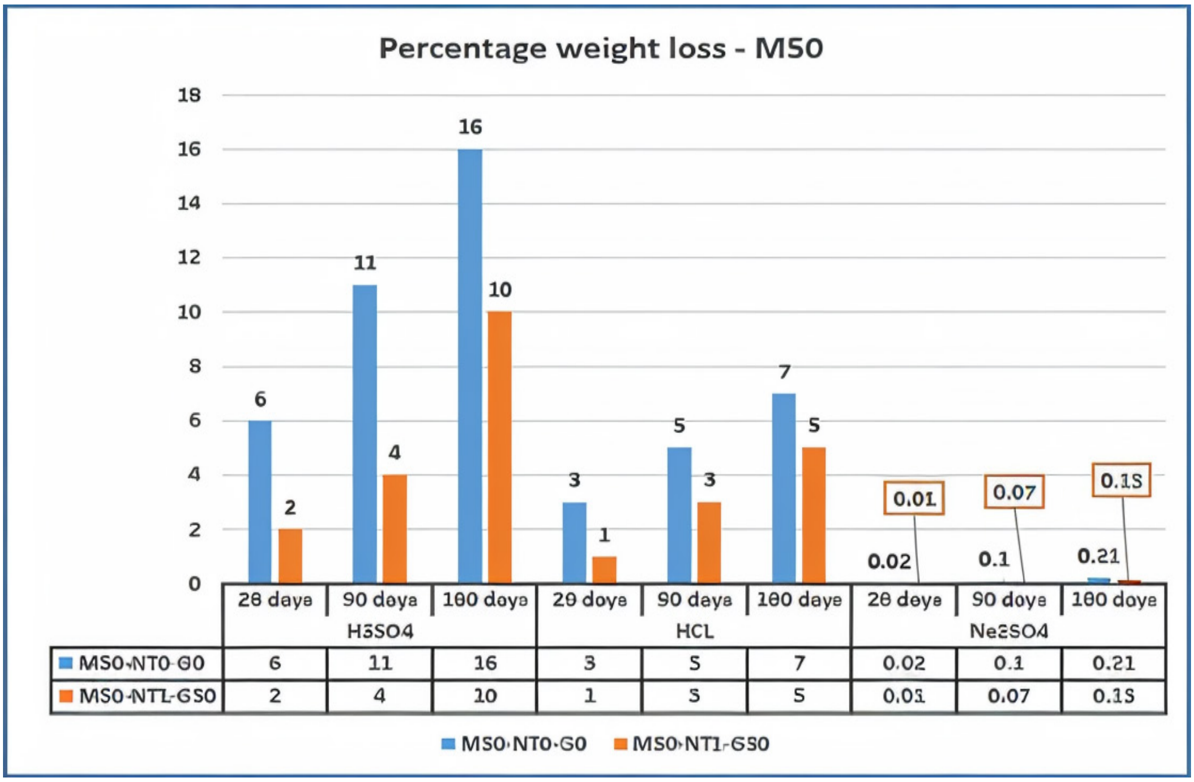

Figure 15. Percentage weight loss – M50.

ASTM C 1202's Rapid Chloride Penetration Test evaluates concrete's resistance to chloride ion penetration. Under an applied voltage, the test gauges the total charge passed across a concrete specimen (in coulombs) over 6 hours; the results show the permeability degree of the concrete.

To find the total charge passed—a gauge of chloride ion penetrability—concrete specimens shaped like 100 mm × 50 mm cylindrical discs were tested. Equation (3) helps one to determine the total charge, expressed in coulombs:

$$Q = 900\,(I_0 + I_{360} + 2I_{30} + 2I_{60} + \ldots\ldots\ 2I_{300} + 2I_{330}) \quad (3)$$

Here, I_0 represents the initial current (in amperes) immediately after voltage is applied, and It denotes the current at specific time intervals t in minutes. This equation is a numerical integration method (specifically, the trapezoidal rule) used to approximate the area under the current vs. time curve over a 6-hour period, which reflects the extent of chloride ion penetration in concrete.

Table 6 shows, using ASTM C1202 criteria, the classification of chloride ion penetrability in concrete depending on the total charge passed. Particularly in corrosive environments, durability depends on the concrete's resistance to chloride ion ingress, thus this classification aids in evaluation of that resistance. The table shows that while values between 2000 and 4000 indicate moderate levels, a charge passed more than 4000 indicates high penetrability. Low penetrability falls between 1000 and 2000 coulombs; values between 100 and 1000 indicate rather low penetration. A charge passed below 100 coulombs indicates great durability since it reflects very poor chloride ion penetration.

Table 6. Classification of Chloride Ion Penetrability Based on Charge Passed (ASTM C1202 Guidelines).

Charge Passed (in Coulombs)	Chloride Ion Penetrability
>4000	High
2000–4000	Moderate
1000–2000	Low
100–1000	Very Low
<100	Negligible

Table 7 shows the Rapid Chloride Penetration Test (RCPT) results for two different mixes—a modified mix with 1% nano-TiO_2 and 30% GGBS (M40-NT1G30) and a control mix (M40-NT0G0). M40 grade concrete The results reveal a notable decrease in charge passed over time, suggesting increasing resistance to chloride ion penetration

with aging. With a much lower charge passed (202.71 coulombs at 90 days) than the control mix (658.93 coulombs), the modified mix shows notably better durability falling into the "Very Low" penetrability category, so confirming the positive impact of nano and GGBS additions on the durability of the concrete.

Table 8 presents Incorporation of nano-TiO_2 and glass powder (M50-NT1G30) shows a notable increase in durability of M50 grade concrete Rapid Chloride Penetration Test (RCPT) results. Reflecting lower chloride ion penetrability, the modified mix consistently shows lower charge passed values at all ages tested: 28, 56, and 90 days compared to the control mix (M50-NT0G0). Especially at 28 days, the control mix shows low penetrability (1154 Coulombs), whereas the modified mix shows very low penetrability (684.1 Coulombs), which further lowers over time. M50-NT1G30 records only 138.5 Coulombs by 90 days, indicating its increased resistance to chloride ingress and possibility for great long-term durability in demanding surroundings.

The studied concrete samples exhibited distinct failure modes based on their resistance to chloride ion penetration. Control mixes (M40-NT0G0 and M50-NT0G0) showed higher charge passed values, placing them in the moderate to low penetrability range, indicating higher vulnerability to chloride-induced deterioration over time. In contrast, the modified mixes (M40-NT1G30 and M50-NT1G30), incorporating nano-TiO_2 and GGBS or glass powder, demonstrated significantly lower chloride ion penetrability, falling into the "very low" category per ASTM C1202, with M50-NT1G30 achieving as low as 138.5 Coulombs at 90 days. These results suggest that failure in control mixes may occur earlier due to chloride-induced corrosion, while modified mixes are more durable and resistant to such deterioration, highlighting enhanced long-term performance and reduced risk of failure in aggressive environments.

Recommendations: Based on the findings, it is recommended to use a combination of 1% Nano-TiO_2 and 30% GGBS in M40 and M50 grade concrete for structures exposed to acidic and chloride-rich environments, such as sewage treatment plants, coastal structures, and industrial foundations. This blend significantly improves acid resistance, compressive strength retention, and chloride ion impermeability, contributing to increased structural durability and service life. Long-term applications should prioritize this modified mix design to reduce maintenance costs and enhance sustainability in aggressive conditions.

Limitations: The study was limited to laboratory-scale conditions with specific acid concentrations (5% H_2SO_4, HCl, and Na_2SO_4) and controlled curing durations (28, 90, and 180 days). Real-world variability, such as fluctuating environmental exposures, mechanical loading, and thermal changes, were not considered. Additionally, only one percentage of Nano-TiO_2 (1%) and GGBS (30%) was tested; hence, the influence of other mix proportions or the potential synergistic effects with different admixtures remain unexplored. Further research is required to assess long-term field performance, cost-effectiveness, and workability impacts of this modified mix in diverse construction scenarios.

Table 7. RCPT for M40 grade concrete.

Age of Concrete Specimens	Charge Passed in Coulombs (M40-NT0G0)	Chloride ion Penetrability (M40-NT0G0)	Charge Passed in Coulombs (M40-NT1G30)	Chloride ion Penetrability (M40-NT1G30)
28 days	1685.28	Low	1075	Low
56 days	1086.56	Low	372.65	Very Low
90 days	658.93	Very Low	202.71	Very Low

Table 8. RCPT for M50 grade concrete.

Age of Concrete Specimens	Charge Passed in Coulombs (M50-NT0G0)	Chloride Ion Penetrability (M50-NT0G0)	Charge Passed in Coulombs (M50-NT1G30)	Chloride Ion Penetrability (M50-NT1G30)
28 days	1154	Low	684.1	Very Low
56 days	468.2	Very Low	228.3	Very Low
90 days	275.3	Very Low	138.5	Very Low

5. Conclusions

This work fully assessed M40 and M50 grade concrete with 1% Nano-TiO_2 and 30% GGBS in mechanical characteristics, acid resistance, and chloride permeability. Compressive strength tests, acid resistance tests (H_2SO_4, HCl, Na_2SO_4 exposure), and the Rapid Chloride Penetration Test (RCPT) spanning several curing periods (28, 90, and 180 days) evaluated the performance of the modified concrete.

The results showed that concrete durability was much improved by adding nano-TiO_2 and GGBS. With 40% improved Acid Durability Factor (ADF) under H_2SO_4, 15% under HCl, and 7% under Na_2SO_4, modified concrete showed lower weight loss and higher residual compressive strength compared to conventional concrete, according the acid resistance tests; M50 concrete showed 20%, 11%, and 4% improvements respectively. Particularly in H_2SO_4 and HCl exposure, the percentage weight loss in acidic conditions was also much lowered. Moreover, the RCPT findings confirmed that concrete with GGBS and Nano-TiO_2 displayed much reduced chloride ion permeability. Classifying it as per ASTM C1202, the charge passed in modified M40 concrete was lowered by (50–60%), while in M50 concrete it dropped by (40–50%), compared to conventional concrete.

Nano-TiO_2 and GGBS taken together enhanced mechanical strength, resistance to chemical attack, and durability against chloride ingress, so providing a workable solution for concrete buildings subjected to demanding conditions. The results highlight how these ingredients might improve the sustainability and lifetime of high-performance concrete.

Author Contributions

M.S. contributed to the conceptualization of the study, data collection, formal analysis, and drafting of the manuscript. P.S. supervised the research work, validated the results, and provided critical revisions and final approval of the manuscript. Both authors reviewed and approved the final version of the manuscript.

Funding

This work received no external funding.

Institutional Review Board Statement

Not applicable.

Informed Consent Statement

Not applicable.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Acknowledgments

The authors declare no acknowledgement.

Conflicts of Interest

The authors declare no conflict of interest.

References

[1] Adebanjo, A.U., Abbas, Y.M., Shafiq, N., et al., 2024. Optimizing nano-TiO_2 and ZnO integration in silica-based high-performance concrete: Mechanical, durability, and photocatalysis insights for sustainable self-cleaning systems. Construction and Building Materials. 446, 138038. DOI: https://doi.org/10.1016/j.conbuildmat.2024.138038

[2] Baikerikar, A.V., Ganachari, V., Khed, V.C., et al., 2024. Synergistic effects of nano titanium dioxide and waste glass powder on the mechanical and durability properties of concrete. Scientific Reports. 14(1), 27573. DOI: https://doi.org/10.1038/s41598-024-79263-9

[3] Dhanapal, J., Saravanan, S., Jayaprakash, S., et al., 2024. Eco-Friendly Concrete Solutions: The Role of Titanium Dioxide Nanoparticles in Enhancing Durability and Reducing Environmental Pollutants-A Review. Journal of Environmental Nanotechnology. 13(3), 332–344. DOI: https://doi.org/10.13074/jent.2024.09.243894

[4] Döndüren, M.S., Al-Hagri, M.G., 2022. A review of the effect and optimization of use of nano-TiO_2 in cementitious composites. Research on Engineering Structures and Materials. 8(2), 283–305. DOI: http://dx.doi.org/10.17515/resm2022.348st1005

[5] Maniseresht, A., 2024. Exploring the Impact of TiO_2 and Ggbs on Rcc Pavements Via Rsm. Available from: https://papers.ssrn.com/sol3/papers.

cfm?abstract_id=4855621 (cited 15 April 2025).

[6] Maraş, M.M., 2021. Mechanical and fracture behavior of geopolymer composites reinforced with fibers by using nano-TiO_2. Journal of the Brazilian Society of Mechanical Sciences and Engineering. 43(9), 412. DOI: https://doi.org/10.1007/s40430-021-03135-w

[7] Mustafa Mohamed, A., Tayeh, B.A., Ahmed, T.I., et al., 2025. Influence of nano-silica and nano-ferrite particles on mechanical and durability of sustainable concrete: A review. Nanotechnology Reviews. 14(1), 20250151. DOI: https://doi.org/10.1515/ntrev-2025-0151

[8] Pathak, S.S., Vesmawala, G.R., 2023. Influence of Nano-TiO_2 and water to cement ratio on fracture parameters of concrete. Asian Journal of Civil Engineering. 24(7), 1969–1979. DOI: https://doi.org/10.1007/s42107-023-00616-2

[9] Pathak, S., Vesmawala, G., 2025. Evaluation of fracture parameters of concrete notched beams containing Nano TiO2 and ground granulated blast furnace slag. Journal of Building Pathology and Rehabilitation. 10(1), 49. DOI: https://doi.org/10.1007/s41024-024-00560-x

[10] Rao, M.S.C., Packialakshmi, S., Rath, B., et al., 2023. Utilization of agricultural, industrial waste and nanosilica as replacement for cementitious material and natural aggregates–Mechanical, microstructural and durability characteristics assessment. Environmental Research. 231, 116010. DOI: https://doi.org/10.1016/j.envres.2023.116010

[11] Raza, A., Azab, M., Baki, Z.A., et al., 2023. Experimental study on mechanical, toughness and microstructural characteristics of micro-carbon fibre-reinforced geopolymer having nano TiO_2. Alexandria Engineering Journal. 64, 451–463. DOI: https://doi.org/10.1016/j.aej.2022.09.001

[12] Salama, A.H.E.-S., Assolie, A.A., Alsafasfeh, A., 2024. Mechanical Performance and Microstructure Evolution of Nano-Titanium dioxide Enhanced Cement–A Comprehensive Experimental Analysis. Advances in Science and Technology. Research Journal. 18(7). DOI: https://doi.org/10.12913/22998624/193524

[13] Sharma, J., Chaturvedi, G.K., Pandey, U.K., 2024. Impact of Nano Titanium Dioxide on Rubberized Concrete: Evaluating Physical, Mechanical, and Durability Characteristics. Mechanical, and Durability Characteristics. Available from: https://papers.ssrn.com/sol3/papers.cfm?abstract_id=5072487 (cited 15 April 2025).

[14] Shumuye, E.D., Liu, C., Fang, G., et al., 2024. Utilization of photocatalytic degradation and efficiency of engineered geopolymer composite tile doped with nano-particles under ultraviolet light. Cement and Concrete Composites. 153, 105729. DOI: https://doi.org/10.1016/j.cemconcomp.2024.105729

[15] Sivasakthi, M., Jeyalakshmi, R., Rajamane, N.P., 2021. Investigation of Microstructure and Thermo-mechanical Properties of Nano-TiO_2 Admixed Geopolymer for Thermal Resistance Applications. Journal of Materials Engineering and Performance. 30(5), 3642–3653. DOI: https://doi.org/10.1007/s11665-021-05708-1

[16] Srivastava, A., Mishra, A., Singh, S.K., 2025. An effect of nano alumina and nano titanium di oxide with polypropylene fiber on the concrete: Mechanical and durability study. Discover Civil Engineering. 2(1), 6. DOI: https://doi.org/10.1007/s44290-025-00161-8

[17] Srivastava, A., Mishra, A., Singh, S.K., 2025b. Mechanical and durability study of nano-SiO2 and nano-TiO2 on fiber reinforced concrete. Challenge. 16(1), 33–39. DOI: https://doi.org/10.20528/cjcrl.2025.01.004

[18] Tanimola, J.O., Efe, S., 2024. Recent Advances in Nano-Modified Concrete: Enhancing Durability, Strength, and Sustainability Through Nano Silica (nS) and Nano Titanium (nT) Incorporation. Applications in Engineering Science. 19, 100189. DOI: https://doi.org/10.1016/j.apples.2024.100189

[19] Tanyildizi, H., Yilmaz, A., Açik, V., et al., 2024. Self-Cleaning Performance of Basalt Fiber–Reinforced GGBS-Based Geopolymer Mortar Containing Nano TiO_2. Journal of Materials in Civil Engineering. 36(8), 04024205. DOI: https://doi.org/10.1061/JMCEE7.MTENG-17155

[20] Vaid, U., Lallotra, B., 2024. Effect on concrete strength and durability with partial replacement of cement by Nano-titanium dioxide (nano-TiO_2) and ground granulated blast furnace slag (GGBS): A Review Summary. IOP Conference Series: Earth and Environmental Science. 1326(1), 012046. DOI: https://doi.org/10.1088/1755-1315/1326/1/012046

[21] Yu, X., Xu, X., Yang, X., et al., 2023. High fire stability cement composite cementitious material based on semi-dry gas desulfurized ash/blast furnace slag system: The synergistic effect of nano-TiO_2 and nano-SiO_2. Asia-Pacific Journal of Chemical Engineering. 18(3), e2883. DOI: https://doi.org/10.1002/apj.2883

[22] Zhang, S.-L., Qi, X.-Q., Guo, S.-Y., et al., 2021. Effect of a novel hybrid TiO_2-graphene composite on enhancing mechanical and durability characteristics of alkali-activated slag mortar. Construction and Building Materials. 275, 122154. DOI: https://doi.org/10.1016/j.conbuildmat.2020.122154

[23] Ziada, M., 2024. The Effect of Nano-TiO_2 and Nano-Al_2O_3 on Mechanical, Microstructure Properties and High-Temperature Resistance of Geopolymer Mortars. Arabian Journal for Science and Engineering. DOI: https://doi.org/10.1007/s13369-024-09570-w

[24] Harle, S.M., 2014. Review on the performance of glass fiber reinforced concrete. International Journal of Civil Engineering Research. 5(3), 281–284.

[25] Chitkeshwar, A.K., Naktode, P.L., 2022. Concrete with rock quarry dust with partial replacement of fine aggregate. Materials Today: Proceedings. 62, 6455–6459. DOI: https://doi.org/10.1016/j.matpr.2022.04.195

[26] Wankhade, R.L., Landage, A.B., 2013. Non-destructive testing of concrete structures in Karad region. Procedia Engineering. 51, 8–18.

[27] Nadi, S., Beheshti Nezhad, H., Sadeghi, A., 2022. Experimental study on the durability and mechanical properties of concrete with crumb rubber. Journal of Building Pathology and Rehabilitation. 7, 1–12.

[28] Karthikeyan, B., Dhinakaran, G., 2018. Influence of ultrafine TiO_2 and silica fume on performance of unreinforced and fiber reinforced concrete. Construction and Building Materials. 161, 570–576.

[29] Nejati, M.Y., Behruyan, M., Sadeghi, A., et al., 2025. Experimental Study on the Compressive and Flexural Properties of the Ultrahigh-Performance Concrete Containing Fibers. Journal of Building Material Science. 7(1), 83–96. DOI: https://doi.org/10.30564/jbms.v7i1.8269

[30] Torres, A., Ellis, F.A.S.A.M., 2020. The Effect of Various Polynaphthalene Sulfonate Based Superplasti-cizers on the Workability of Reactive Powder Concrete. Journal of Building Material Science. 2(1), 2–29. DOI: https://doi.org/10.30564/jbms.v2i1.2731

[31] Islam, N., A Gafur, M., 2023. Matrix-Material Fabrication Technique and Thermogravimetric Analysis of Banana Fiber Reinforced Polypropylene Composites. Journal of Building Material Science. 5(2), 15–24. DOI: https://doi.org/10.30564/jbms.v5i2.5700

[32] Snoeck, D., Steuperaert, S., Van Tittelboom, K., et al., 2012. Visualization of water penetration in cementitious materials with superabsorbent polymers by means of neutron radiography. Cement and Concrete Research. 42(8), 1113–1121.

[33] Jefferson, A., Joseph, C., Lark, R., et al., 2010. A new system for crack closure of cementitious materials using shrinkable polymers. Cement and Concrete Research. 40(5), 795–801.

[34] Galano, S., Calabrese, A., Asvapathanagul, P., et al., 2025. Innovative Approaches to Enhancing Concrete Compressive Strength: An Extensive Investigation of Biochar-Embedded and Self-Repairing Techniques. Journal of Materials in Civil Engineering. 37(5), 04025112.