ISSN 2393-8471

International Journal of Recent Research in Civil and Mechanical Engineering (IJRRCME)
Vol. 12, Issue 1, pp: (63-74), Month: April 2025 – September 2025, Available at: www.paperpublications.org

Evaluation of Effects of Treated Wastewater on Durability of Concrete

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DOI: https://doi.org/10.5281/zenodo.16838355

Published Date: 13-August-2025

Abstract: **Concrete production heavily relies on fresh water, a challenge given growing global water scarcity. Treated wastewater (TWW) is a sustainable alternative but raises concerns regarding its impact on long-term durability. Despite numerous studies, inconsistencies exist in evaluating TWW's effects on concrete durability, particularly under aggressive environmental conditions. This study investigates how TWW and chemical admixtures (Sodium Gluconate [SG] and Silica Fume [SF]) affect concrete's durability parameters such as electrical resistivity, water absorption, and ultrasonic pulse velocity (UPV). Six concrete mix designs, using FW and TWW with/without SG and SF, were assessed. Durability tests included electrical resistivity (AASHTO TP 95), water absorption (ASTM C642), and UPV (BS 1881:203). Each parameter was tested at 7, 28, and 56 days of curing. Concrete made with TWW exhibited lower durability compared to that with FW, evident in higher water absorption and lower UPV and resistivity. However, the combined use of SG and SF significantly improved durability indicators in TWW mixes. Statistical analysis confirmed that differences among mix designs were highly significant ($p < 0.001$). TWW negatively impacts concrete durability, but SG and SF effectively mitigate these effects, making TWW a feasible alternative when properly treated and supplemented with admixtures.**

Keywords: **Treated Wastewater (TWW); Concrete Durability; Sodium Gluconate (SG); Silica Fume (SF); Electrical Resistivity; Water Absorption; Ultrasonic Pulse Velocity (UPV); Sustainable Concrete.**

I. INTRODUCTION

Concrete is the second most consumed material on Earth after water, and its production heavily depends on the availability of fresh water, nearly 500 liters are used to produce one cubic meter of concrete [1, 2]. As global water scarcity intensifies, driven by population growth [3], rapid urbanization, and industrial development, especially in arid and semi-arid regions, the construction industry's heavy reliance on potable water has raised concerns about sustainability.

Treated wastewater (TWW), typically originating from sewage treatment plants or industrial sources, has emerged as a viable alternative water source in concrete production [4]. Studies have shown that, under certain conditions, TWW can replace potable water without significantly compromising the mechanical properties of concrete. For instance, partial replacement of mixing and curing water with TWW has sometimes resulted in comparable or even improved compressive strength and workability [5, 6]. However, durability, a critical aspect of long-term concrete performance, presents a more complex picture. Research shows varying impacts of TWW on durability indicators such as chloride ion penetration, sulfate resistance, water absorption, freeze-thaw performance, and carbonation resistance [7, 8, 9].

High chloride or sulfate contents in TWW can elevate the risk of reinforcement corrosion and decrease freeze-thaw resistance [10]. The variability in chemical composition and solid content of TWW, especially when sourced from different treatment plants or industrial processes, further complicates its evaluation for consistent use in structural applications [11].

Despite increasing research into using treated wastewater in concrete, a significant knowledge gap remains concerning its long-term effects on concrete durability. While many studies confirm acceptable mechanical performance, durability assessments are either limited in scope or yield contradictory findings, especially under aggressive environmental conditions such as chloride ingress, sulfate attack, and freeze-thaw cycles [4, 9, 8]. The variability in TWW composition, depending on treatment level and origin, raises reliability concerns. Thus, there is a pressing need to systematically evaluate the influence of TWW on durability parameters such as water permeability, porosity, chloride diffusivity, acid resistance, and microstructural stability to establish clear guidelines for its safe and sustainable use. This study aims to bridge this gap by comprehensively evaluating the effects of treated wastewater on the durability characteristics of concrete, contributing to both resource conservation and environmentally responsible construction practices.

II. RELATED WORKS

A. Theoretical Understandings

Growing water scarcity and stricter environmental regulations have encouraged the construction industry to reuse TWW from concrete plants or municipal facilities as mixing water [12]. The wastewater is generated when aggregates, mixers, vehicles and equipment are washed and that it contains fine particles of cement, unhydrated cement clinker, mineral admixtures and dissolved ions [13]. These particles (such as calcium hydroxide, ettringite, calcite and C-S-H gel) have sizes mostly under 10 µm and can fill capillary pores in cement paste, increasing density and potentially acting as nucleation sites for further hydration [14]. The alkaline environment created by dissolved lime and other ions promotes hydration and generates additional C-S-H gel, reducing porosity and enhancing compressive strength [14]. However, variability in TWW composition and the presence of aggressive species such as chlorides and sulfates create concerns about long-term durability [15]. The present study aims to address this contradiction by systematically evaluating the influence of TWW on durability parameters, water permeability, porosity, chloride diffusivity, acid resistance and microstructural stability, under aggressive environments. This research aligns with sustainable development goals by conserving potable water and reducing wastewater discharge.

Treated wastewater can be chemically comparable to potable water when properly treated, tertiary treated samples had neutral pH (~7.2), very low solids and chloride levels within WHO limits [13]. Ready-mix plant effluents mainly contain calcium hydroxide, silica, calcite, ettringite and unhydrated silicates; roughly 20 % of particles are under 10 µm, enabling a filler effect that improves gradation and reduces porosity. The alkaline environment accelerates hydration and lowers porosity, but high pH and ions may cause ettringite-induced durability issues [16].

B. Empirical Reviews

Several empirical studies have investigated the impact of treated wastewater on the durability of concrete, highlighting both its potential benefits and limitations. Yao [17] examined the environmental and economic implications of substituting potable water with wastewater in concrete production. Their study involved preparing C20 concrete samples with wastewater substitution levels ranging from 0% to 100%. Durability tests, including freeze–thaw cycles, carbonation resistance, and drying shrinkage, alongside microstructural analyses, revealed that replacing up to 75% of potable water improved compressive strength and frost resistance. Furthermore, a denser microstructure with reduced porosity was observed at this substitution level. However, carbonation resistance declined, suggesting that while wastewater presents a sustainable alternative, its optimal use must be carefully controlled to avoid long-term deterioration.

Hamada [18]conducted a critical literature review to explore the effects of various treated wastewater types on concrete properties. Their comparative analysis indicated that the use of treated effluents improved both setting time and compressive strength. Moreover, concrete samples incorporating wastewater exhibited a 7%–27% reduction in porosity compared to control mixes. Nonetheless, an increase in chloride penetration was also observed, attributed to the elevated chloride ion content in the treated water. The authors concluded that while treated wastewater holds promise for sustainable concrete production, mitigating its chloride-induced deterioration remains a key challenge.

Nasseralshariati [9] evaluated the use of industrial wastewater in concrete through an extensive experimental program involving 450 samples. Their investigation assessed a range of mechanical and durability parameters across varying concentrations of wastewater. The results demonstrated that moderate levels of industrial wastewater (up to 10%) caused only a slight reduction in compressive strength (less than 10%). However, higher concentrations adversely affected the pore structure and long-term durability of concrete. The study emphasized the importance of refining industrial wastewater and controlling impurity levels to ensure compatibility with concrete performance requirements.

Peighambarzadeh [19] addressed a gap in the literature regarding the fracture properties of concrete containing wastewater. Their experimental work involved single-edge notched beam (SENB) tests on concrete made with five different mixing ratios of drinking water and treated domestic wastewater. The results showed that fracture toughness remained within a 2%–6% variation compared to control specimens. SEM analysis revealed the formation of ettringite bridging crack surfaces, while treated wastewater slightly increased slump and setting time. These findings supported the feasibility of using treated wastewater in structural concrete without significant detriment to fracture performance.

Yao [20] provided a comprehensive review of previous research focused on the effects of solid content in wastewater from ready-mix concrete plants. Their analysis highlighted that low to moderate levels of solid content contributed to improved density and reduced permeability in concrete. However, higher solid concentrations were associated with increased risks of carbonation and chloride ingress. The review underscored the need for future studies to establish clearer correlations between wastewater composition, microstructural development, and long-term durability indicators.

C. Research Gap

The reviewed literature indicates that treated wastewater can replace potable water in concrete without severely compromising mechanical performance when substitution levels are moderate [18, 6, 11]. Benefits arise from fine particles acting as microfillers and alkaline ions enhancing hydration. Durability assessments remain inconsistent. Some studies report improved frost and shrinkage resistance [10], while others note increased chloride and carbonation susceptibility [6]. The composition of TWW varies widely; high pH and dissolved salts may accelerate ettringite formation or create porous microstructures, raising concerns about sulfate and chloride attack [6]. The research gap lies in the lack of systematic long-term durability evaluations under aggressive environments and insufficient understanding of how specific wastewater components affect pore structure and diffusivity.

Across these studies, research gaps centre on durability. Yao [12] did not test chloride or sulfate attack, limited work to a single concrete grade, and assessed only short-term effects. Hamada [13] synthesised prior work but offered no quantitative durability data and lacked meta-analysis. Nasseralshariati [9] did not investigate microstructural mechanisms and focused on industrial wastewater, leaving municipal effluent behaviour unclear. Peighambarzadeh [14] examined only fracture behaviour, omitting permeability, chloride diffusion and freeze–thaw resistance. Yao [15] suggested a need to link solid content with durability metrics but provided no quantitative comparisons.

III. METHODOLOGY

A. Materials

The study used OPC (32.5 N) from Bamburi Cement, coarse aggregates from Katani Quarries, and natural sand from Machakos. Water sources included potable water from JKUAT and treated wastewater from Ruai. Admixtures used were Sodium Gluconate (SG) from Almaris Chemicals and Silica Fume (SF) from Sika Kenya.

B. Methods

1) Characterization of Materials

a) Aggregates

Coarse aggregates (20 mm, washed and dried) from Katani Quarries and natural river sand from Machakos were used. Both were tested for specific gravity, water absorption (BS 812 Part 2), and grading (BS 812-103) to ensure quality.

b) Water

Water was sampled using the discrete method, three 5-litre labelled samples per source. Treated wastewater (TWW) was collected at discharge points post-treatment, as presented in Fig. 1, Fig. 2 and Fig. 3, following BS EN 1008 (2002), ensuring samples represented the specific time and location of collection

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Fig. 1: Photo showing sampled TWW from RUAI, WWTP and FW from JKUAT for Testing.

Water quality tests were conducted at NCWSC (for TWW) and JKUAT (for FW) labs. Parameters tested included TDS, pH, chlorides, COD, BOD, nitrates, dissolved oxygen, hardness ($CaCO_3$), and sulphates, with results presented in TABLE I.

Fig. 2: Photo showing Ongoing Laboratory test of the TWW at NCWSC laboratory.

Fig. 3: Ongoing Laboratory test of the FW at JKUAT laboratory

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TABLE I: WATER PARAMETERS TESTED AND METHODS USED

Sno.	Parameters	Test Method
1	PH	APHA Method
2	Total Dissolved Solids (TDS)	
3	Dissolved Oxygen	
4	Chlorides (Cl^-)	
5	Sulphate (SO_4^{2-})	
6	Nitrate (NO_3^{2-})	
7	Chemical Oxygen Demand (COD)	
8	Biochemical Oxygen Demand (BOD)	
9	Hardness ($CaCo_3$)	

c) Cement

Portland cement 32.5N from Bamburi Cement, compliant with KS EAS 18-1, was used. Its chemical composition was analyzed per BS EN 196-2 (2005), while specific gravity and fineness tests were conducted following BS EN 196-6 standards.

d) Admixtures Sodium Gluconate and Silica Fume

(1) Silica Fume

The material from Sika Kenya Ltd. was used to enhance concrete properties. Its chemical composition was analyzed per BS EN 196-2 at the Ministry of Roads laboratory. Specific gravity and fineness tests followed BS EN 196-6 procedures.

(2) Sodium Gluconate

The material used was sourced from Almaris Chemical limited and its characteristics had been defined by the manufacture, their key role is to enhance the properties of concrete.

2) Durability Testing of Hardened Concrete

The tests carried out were water absorption test, electrical resistivity, and Ultrasonic Pulse Velocity test.

a) Electrical Resistivity Test

Electrical resistivity was measured using a four-point Wenner probe (AASHTO TP 95). Three 100×200 mm cylindrical specimens per mix were tested at 7, 28, and 56 days. Higher resistivity indicates lower corrosion risk. A total of 54 cubes were tested as presented in TABLE II.

TABLE II: CONCRETE CUBES FOR ELECTRICAL RESISTIVITY TEST

Sno.	Casting	Number of Cubes for ERT Test		
		7 Days	28 Days	56 Days
1	FW	3	3	3
2	FW+ SG	3	3	3
3	FW + SG + SF	3	3	3
4	TWW	3	3	3
5	TWW + SG	3	3	3
6	TWW + SG + SF	3	3	3
	Total	**54 Cubes**		

b) Water Absorption Test

Water absorption was tested per ASTM C 642 (1994) using 100×100×100 mm specimens (Table 14). After 28 days of water curing, specimens were oven-dried for 24 hours to determine dry weight (W1). They were then re-immersed in water for 24 hours, surface-dried, and wet weights (W2) recorded. Three specimens per series were tested, and average values used. Water absorption was calculated using the difference between wet and dry weights, following the specified equation

$$\text{water absorption} = \frac{W_2 - W_1}{W_1} \times 100 \qquad (1)$$

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The lower the absorption rate, the better the concrete, in terms of permeability and subsequent durability, the total number of cylindrical cubes made were 18 as presented in TABLE III.

TABLE III: CONCRETE CUBES FOR WATER ABSORPTION TEST

Sno.	Casting	No. of Cubes for Absorption Test 28 Days Curing
1	FW	3
2	FW+ SG	3
3	FW + SG + SF	3
4	TWW	3
5	TWW + SG	3
6	TWW + SG + SF	3
	Total	18 Cubes

c) Ultrasonic Pulse Velocity test.

Ultrasonic Pulse Velocity (UPV) tests were conducted per BS 1881: Part 203 (1986) to assess concrete quality. Three 100×200 mm cylindrical specimens per mix were tested at 7, 28, and 56 days. A longitudinal ultrasonic pulse was transmitted through the concrete using an electroacoustical transducer. The pulse, after traversing a known path, was received by a second transducer and converted into an electrical signal. The time and velocity of the pulse were displayed, and three readings were averaged to obtain the representative UPV result. The total number of cubes made were 54, similar to those in TABLE II of ERT test.

IV. RESULTS AND DISCUSSION

A. Electrical Resistivity

A summary of the electrical Resistivity for the 7, 28- and 56-days curing were tested with concrete made with TWW and FW, incorporating the SG and SF as admixtures, the results are presented in Fig. 4.

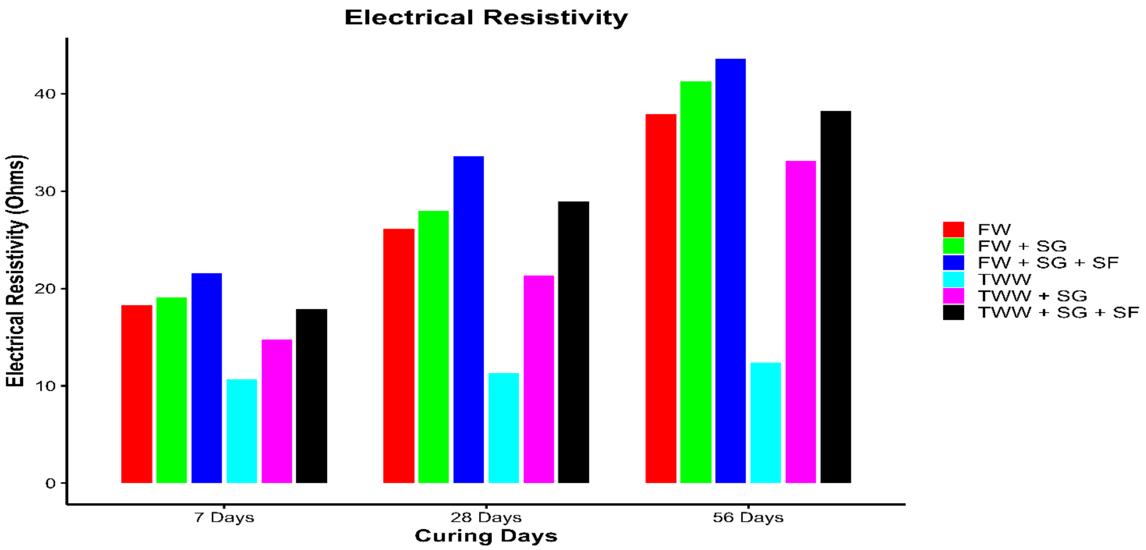

Fig. 4. Electrical Resistivity Results

Fig. 4. Shows concrete made with freshwater (FW) was used as the control to evaluate the influence of admixtures and water quality on electrical resistivity. At 7 days of curing, the mean resistivity for the FW mix was 18.3 Ω, which, according to AASHTO TP 95, corresponds to a moderate risk of corrosion. The incorporation of sodium gluconate (SG) into the FW mix increased the resistivity slightly to 19.1 Ω. SG functions as a set-retarding admixture, prolonging setting time and improving workability. This delay promotes better hydration and compaction, ultimately leading to a denser and more uniform microstructure. These findings are supported by [21], who demonstrated that SG enhances hydration efficiency and improves the final properties of concrete.

ISSN 2393-8471

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When both SG and silica fume (SF) were incorporated into the FW mix, the resistivity rose significantly to 21.6 Ω. Silica fume, a highly reactive pozzolan, reacts with calcium hydroxide to form additional calcium silicate hydrate (C-S-H), which refines the pore structure and reduces porosity, further densifying the concrete matrix [21]. Concrete prepared using treated wastewater (TWW) exhibited a significantly lower resistivity of 10.7 Ω at 7 days, indicating a high risk of corrosion (AASHTO TP 95). This reduction in resistivity suggests that contaminants and residual organics in TWW impair the hydration process, leading to increased porosity. Elevated biochemical oxygen demand (BOD) and chemical oxygen demand (COD) interfere with cement hydration, resulting in a weaker, more porous matrix. These findings are consistent with studies by [22, 23] who reported that TWW increases porosity and facilitates faster electron movement due to higher permeability.

Adding SG to TWW mixes raised the mean resistivity to 14.8 Ω, indicating an improvement over plain TWW concrete but still lower than FW mixes. SG mitigates some of the negative effects of TWW by enhancing workability and hydration, contributing to a more compact matrix. When both SG and SF were added to TWW concrete, the resistivity increased further to 17.9 Ω, showing the combined effectiveness of both admixtures in enhancing concrete quality, even when using lower-quality water sources.

At 7 days, the F-statistic was 17.628 with a p-value < 0.001, indicating a statistically significant difference among the mix designs. This confirms that water type and admixture combinations significantly affect early-age electrical resistivity. The lower resistivity observed in TWW mixes can also be attributed to chemical reactions involving C_3A and gypsum. As noted by [24], the high BOD and COD in wastewater promote rapid transformation of C_3A and gypsum into ettringite ($C_6AS_3H_{32}$) and subsequently into monosulfate aluminates (C_4ASH_{18}):

$$C_3A + 3Ca\,SO_4.2H_2O + 26H_2O \rightarrow C_6AS_3H_{32}$$

$$2C_3A + 3C_6AS_3H_{32} + 22H_2O \rightarrow 3C_4A\,SH_{18}$$

These reactions increase porosity, thus reducing resistivity and compromising durability. Further support comes from Wu et al. (2023), who observed that in SG-containing mixes, slower hydration in the early-stage results in finer, more uniform AFt (ettringite) formation. These finer grains fill pore spaces more effectively, enhancing the concrete's internal structure. [25] also noted that SG forms stable complexes with Na^+ ions and organic compounds (BOD/COD), reducing microbial decomposition and limiting pore formation. This stabilization process helps reduce porosity even in TWW-mixed concrete, improving long-term durability.

At 28 days, electrical resistivity increased across all mixes, reflecting ongoing hydration and matrix densification. For FW concrete, resistivity rose to 26.1 Ω, indicating a well-hydrated and low-porosity matrix. Clean water ensures optimal hydration, contributing to long-term durability [26]. The addition of SG further improved resistivity to 28.0 Ω, due to enhanced workability and delayed setting, which improved matrix density. When both SG and SF were added to FW concrete, the resistivity significantly increased to 33.6 Ω. According to [21], this is attributed to SF's ability to refine the pore structure, substantially reducing permeability. Based on AASHTO TP 95, these resistivity values indicate a low risk of corrosion. Concrete mixed with TWW showed a resistivity of 11.3 Ω at 28 days, still within the high-risk category. With SG, resistivity improved to 21.3 Ω, now falling within the moderate risk range. While SG enhances hydration and matrix formation, it does not fully offset the effects of impurities in TWW. When both SG and SF were used with TWW, the resistivity increased to 28.9 Ω, indicating a low corrosion risk. SF’s pozzolanic action clearly enhances matrix density even when poor-quality water is used. Although the resistivity of TWW+SG+SF concrete remained slightly below that of FW+SG+SF, the improvement was substantial and demonstrates the effectiveness of using both admixtures with non-potable water. At 28 days, the F-statistic was 11.174 with a p-value < 0.001, confirming significant differences among the mixes. The impact of admixtures on resistivity became more distinct as the concrete matured, particularly in enhancing performance of TWW mixes.

B. Water Absorption

The Water Absorption for the 28-days curing were tested with concrete made with TWW and FW, incorporating the SG and SF as admixtures, the results are as shown in table 44 as shown below;

ISSN 2393-8471

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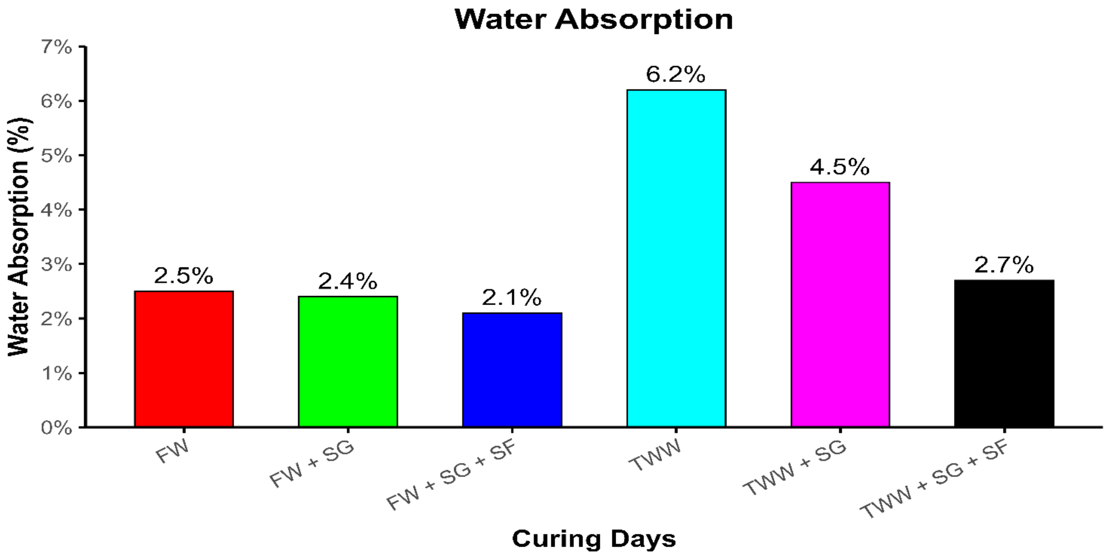

Fig. 5. Water Absorption percentage.

The results presented in Fig. 5 demonstrate clear differences in water absorption across the various concrete mixes evaluated at 28 days of curing. Concrete produced with freshwater (FW) exhibited a mean water absorption rate of 2.5%, indicating a relatively dense and impermeable microstructure. This performance aligns with previous findings by Kanwal et al. (2018), who emphasized that clean mixing water promotes effective hydration, producing compact concrete with reduced capillary porosity. When sodium gluconate (SG) was incorporated into the FW mix, the absorption rate slightly decreased to 2.4%. This improvement is attributed to SG's plasticizing effect, which enhances workability and reduces the water-to-cement ratio. Better compaction and reduced void content subsequently led to lower permeability. According to [21, 26], plasticizers such as SG contribute to the formation of a more uniform cement paste with decreased capillary pores, thereby lowering water absorption.

The addition of both SG and silica fume (SF) further reduced water absorption to 2.1%. Silica fume, a highly reactive pozzolanic material, reacts with calcium hydroxide to form additional calcium silicate hydrate (C-S-H), densifying the matrix and refining the pore structure. These findings are in agreement with [27], who reported that silica fume significantly improves concrete durability by decreasing permeability. According to ASTM C642, these values fall within the low absorption range, indicating durable concrete with good resistance to water ingress. Concrete produced with treated wastewater (TWW) exhibited a mean water absorption rate of 6.2%, which is considered high under ASTM C642, indicating poor-quality concrete. This elevated absorption is likely due to impurities such as biological oxygen demand (BOD) and chemical oxygen demand (COD), which interfere with hydration reactions. As described by [24], high concentrations of BOD and COD accelerate the transformation of C_3A and gypsum into ettringite and monosulfate aluminates. These reactions increase porosity by forming soluble phases that create additional voids in the hardened concrete. This interpretation is supported by [27], who concluded that wastewater leads to poor hydration and increased permeability due to unreacted compounds and weak bonding.

The incorporation of SG into the TWW mix reduced water absorption to 4.5%, which falls within the average absorption category under ASTM C642. This suggests that SG was partially effective in offsetting the adverse effects of TWW by improving mix workability and compaction. Kanwal et al. (2018) emphasized the effectiveness of plasticizers in improving the quality of concrete mixed with suboptimal water by minimizing voids and enhancing paste distribution.

When both SG and SF were used in TWW mixes, water absorption dropped substantially to 2.7%, returning to the low absorption range. This illustrates the synergistic effect of the two admixtures: while SG improves dispersion and reduces water demand, SF fills pores and enhances matrix density through pozzolanic activity. [21] reported similar results, demonstrating that silica fume can compensate for the negative effects of low-quality mixing water by significantly reducing porosity and enhancing durability. Concrete mixes made with TWW consistently showed higher water absorption than those made with FW, underscoring the importance of water purity in producing durable concrete. However, the use of SG and SF

ISSN 2393-8471

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proved effective in improving performance even when poor-quality water was used. The statistical analysis supports these findings: an F-value of 45.970 with a p-value < 0.001 indicates that the observed differences in water absorption across mixes are statistically significant. These variations are clearly attributable to the types of water and admixtures used, rather than random variation. The findings are consistent with observations by [9], who found that organic matter and impurities in wastewater lead to higher absorption due to the formation of additional voids and weak zones in the cement matrix. Nevertheless, the combined use of SG and SF significantly improved the performance of concrete made with TWW, bringing it close to the quality of concrete made with freshwater.

C. Ultrasonic Pulse Velocity

The Ultrasonic Pulse Velocity for the 7, 28- and 56-days curing were tested with concrete made with TWW and FW, incorporating the SG and SF as admixtures, the results are as presented in Fig. 6.

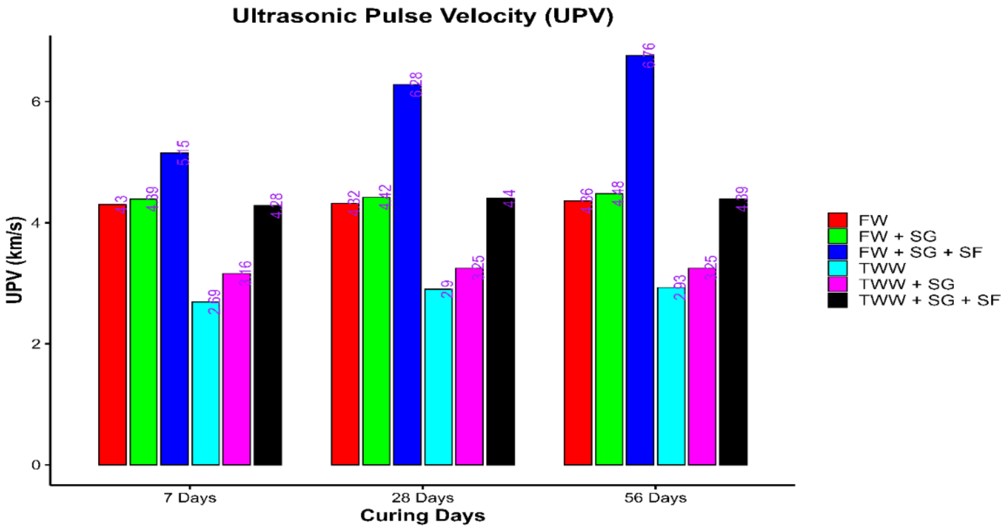

Fig. 6. Ultrasonic Pulse Velocity Results

As shown in Fig. 6, the UPV results reflect the influence of both water source and chemical admixtures on concrete's microstructure and long-term performance. At 7 days, concrete made with fresh water (FW) exhibited a mean UPV of 4.30 km/s, which, according to BS 1881 Part 203:1986, corresponds to good quality concrete. This suggests that the concrete had achieved sufficient hydration and compaction in the early curing stage. The inclusion of sodium gluconate (SG) further improved the UPV to 4.39 km/s. SG, acting as a plasticizer and set-retarder, enhances the dispersion of cement particles, promotes better workability, and contributes to a more homogenous cement paste structure, ultimately improving early durability [28]. When both SG and silica fume (SF) were incorporated, the UPV increased significantly to 5.15 km/s, indicating a denser matrix and improved early-age durability. The pozzolanic action of SF refines the pore structure and enhances the interfacial transition zone, which boosts resistance to chemical attack and permeability [21]. The concrete made with treated wastewater (TWW) showed a markedly lower UPV of 2.69 km/s, falling within the poor-quality range as per BS 1881 standards. This reduction in quality is attributed to residual contaminants such as BOD and COD, which disrupt cement hydration. According to [24], the presence of such impurities accelerates undesirable chemical reactions. These reactions result in increased porosity and reduced mechanical strength. This finding is consistent with the work of [29], who observed low UPV in concrete made with TWW containing elevated COD levels.

However, the incorporation of SG with TWW increased the UPV to 3.17 km/s, placing it within the satisfactory quality range. This improvement demonstrates SG's capacity to enhance early-age workability and promote better hydration. The combination of SG and SF with TWW further elevated the UPV to 4.28 km/s, restoring concrete quality to the good range, comparable to FW mixes. The admixtures effectively mitigated the adverse effects of wastewater by refining the microstructure and enhancing durability. The F-statistic for the 7-day period was 18.317 (p < 0.001), indicating statistically significant differences in UPV between the various mix designs. After 28 days of curing, further improvement in UPV was observed across all mixes. The FW mix had a UPV of 4.32 km/s, while the FW+SG mix recorded a slightly higher value of 4.42 km/s, suggesting that SG continued to support workability and uniform hydration during curing.

ISSN 2393-8471

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The FW+SG+SF mix showed a substantial increase in UPV to 6.28 km/s, indicating a highly compact and durable matrix. The continued pozzolanic reaction of SF reduces porosity and refines the transition zone between aggregates and paste, significantly enhancing durability. All FW-based mixes at 28 days fall within the good to excellent quality range under BS 1881 Part 203:1986. TWW-based mixes also showed improvement at this stage. The plain TWW mix achieved a UPV of 2.90 km/s, which still qualifies as poor-quality concrete. However, the TWW+SG mix improved to 3.25 km/s, entering the satisfactory range. The TWW+SG+SF mix reached a UPV of 4.40 km/s, suggesting a good-quality concrete despite the initial limitations of the water source.

These trends underscore the effectiveness of admixtures in compensating for the quality reduction caused by TWW. The F-statistic at 28 days was 55.565 ($p < 0.001$), confirming that the variations in UPV between mixes were highly significant and not due to random chance. By 56 days, continued improvement in UPV was evident across all mixes. The FW mix reached 4.36 km/s, while the FW+SG mix increased to 4.48 km/s, highlighting the sustained benefits of SG in long-term hydration and matrix development. The FW+SG+SF mix recorded the highest UPV of 6.76 km/s, indicating exceptional concrete quality. This reflects the cumulative benefits of long-term pozzolanic activity and improved pore structure, leading to excellent durability [21].

TWW-based mixes also demonstrated significant progress. The plain TWW mix achieved a UPV of 2.93 km/s, still within the poor category. However, the TWW+SG mix maintained its value of 3.25 km/s, and the TWW+SG+SF mix further improved to 4.39 km/s, now well within the good-quality range. These results affirm the ability of SG and SF to enhance long-term performance, even when lower-quality water is used for mixing. The F-value for the 56-day period was 84.254 ($p < 0.001$), indicating that the differences in UPV among the mixes became even more pronounced over time. The statistical significance reinforces the role of admixtures and water quality as key variables influencing concrete durability.

V. CONCLUSION

This study evaluated the influence of TWW on the durability of concrete, focusing on electrical resistivity, water absorption, and UPV over 7, 28, and 56 days. The results revealed that while concrete made with TWW generally exhibited reduced durability, evidenced by lower resistivity, higher water absorption, and poor UPV, these effects were significantly mitigated by incorporating SG and SF. Particularly, the combined use of SG and SF in TWW-based mixes yielded performance comparable to or approaching that of fresh water (FW) mixes, indicating that TWW can be safely used in concrete production with proper admixture strategies.

While the study provides strong evidence of TWW's impact on concrete durability, it was limited to a single source of TWW and specific environmental conditions. Results may vary with different wastewater compositions or in harsher service environments such as marine or freeze-thaw exposures. Additionally, only three durability tests were conducted; future work should explore chloride ion penetration, carbonation resistance, and microstructural analysis using SEM for a more comprehensive understanding.

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