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Treated Wastewater on Properties on Hardened Concrete

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Abstract

The global scarcity of fresh water has prompted increased interest in alternative water sources, such as treated wastewater (TWW), for concrete production. This study evaluates the effects of TWW on the properties of fresh and hardened concrete, focusing on its feasibility as a sustainable substitute for potable water. A comprehensive experimental design was employed to compare concrete mixes using fresh water (FW) and TWW, with and without the incorporation of SG and Silica Fume (SF) as admixtures. Compressive strength testing at 7, 28, and 56 days revealed that TWW alone reduced concrete strength due to its high biochemical and chemical oxygen demand. However, the use of Sodium Gluconate (SG) and SF significantly mitigated these negative effects, enhancing both workability and strength. TWW mixes with SG and SF achieved compressive strengths that met or exceeded the 90% threshold of FW controls, demonstrating their potential compliance with BS EN 1008 (2002) standards. These findings emphasize the promise of integrating TWW in concrete production, provided appropriate admixtures are utilized. Further research is recommended to investigate long-term durability and optimize admixture combinations to ensure consistency across varied TWW sources.

Keywords

Treated Wastewater, Concrete Properties, Sodium Gluconate, Silica Fume

1. Introduction

Water plays a critical role in concrete production, serving as an essential ingredient for cement hydration, enhancing workability, and enabling effective curing. Concrete, the most widely used construction material after water, is integral to modern infrastructure, with an average annual consumption of three tons per person globally [1]. Typically, concrete is made by combining cement, sand, crushed aggregates, water, and sometimes admixtures to improve performance. Annually, the concrete industry consumes approximately one billion tons of water worldwide, including significant quantities of fresh water for mixing and curing [2].

Potable water is commonly recommended for concrete production due to its regulated chemical composition and minimal impurities compared to alternative water sources like borehole water, untreated wastewater (WW), and treated wastewater (TWW). Standards stipulate that concrete made with alternative water must achieve at least 90% of the compressive strength of concrete produced with potable water [3]. However, impurities such as chlorides, sulfates, alkalis, organic matter, and solids in non-potable water can adversely affect concrete properties, including strength, setting time, and durability [4].

Despite these risks, untreated water is frequently used in construction without proper evaluation of its impact, even as the global water crisis intensifies due to growing demands from agriculture, industry, and construction [5]. TWW sourced from wastewater treatment plants has emerged as a potential alternative for concrete production. However, its chemical composition—marked by higher levels of BOD, COD, and TDS compared to fresh water—may negatively influence concrete properties. Standards such as ASTM C1602 and BS EN 1008:2002 recommend thresholds for these parameters, including pH (>4), TDS (2000 mg/L), and chloride content (1000 mg/L for reinforced concrete and 5000 mg/L for plain concrete). Evaluating TWW's compliance with these standards is crucial before its adoption in construction.

Research highlights the adverse effects of wastewater impurities on concrete properties. For instance, a study by [1] found that wastewater from industries such as food processing and ceramics caused compressive strengths below 90% of potable water controls due to organic impurities like oils. However, the long-term effects of using TWW on concrete durability remain insufficiently explored, necessitating further investigation.

To mitigate the impact of impurities, admixtures such as Fly Ash (FA), Calcium Nitrate (CN), and Ground Granulated Blast Furnace Slag (GGBS) have been successfully used with non-potable water [6] [7]. Similarly, SG and SF have improved the strength and durability of concrete made with potable water [8] [9]. These admixtures hold promise for enhancing the performance of TWW-based concrete.

This study focuses on evaluating the potential of TWW in concrete production, with particular emphasis on its effects on the properties of fresh and hardened concrete. By examining TWW's impact on strength, workability, and durability, and the mitigating effects of SG and SF, this research aims to establish the feasibility of using TWW in construction, while addressing its long-term implications for structural integrity.

1.1. Contribution

Concrete is among the most extensively used construction materials globally, requiring approximately 1 billion tons of water annually. While FW is the preferred choice for concrete production due to its regulated quality, there is a growing trend of using any readily available water, including TWW from wastewater treatment plants. TWW is often discharged into downstream water sources and subsequently utilized in construction without thoroughly assessing its quality.

The use of TWW in concrete works raises concerns about its potential impact on strength and durability, as its impurities, such as organic matter, chlorides, sulfates, and dissolved solids, can negatively influence concrete properties. These impurities may alter cement hydration, extend setting times, reduce compressive strength, and compromise durability. Consequently, it is essential to evaluate the chemical and physical properties of TWW before its application in concrete. Moreover, appropriate mitigation strategies, such as the incorporation of admixtures like SG and Silica Fume (SF), should be considered to counteract the adverse effects of these impurities.

1.2. Research Objective

This research explores the implications of using TWW in concrete production, with a focus on how it affects the properties of fresh and hardened concrete. By addressing both challenges and solutions, the study aims to establish a framework for the safe and effective utilization of TWW in construction projects.

2. Related Works

2.1. Concrete

Concrete is a heterogeneous material comprising cement, aggregates, water, and admixtures [10]. The mix typically includes 70% aggregates, 20% cement, and 10% water by mass. Water plays a crucial role in concrete for hydration, strength development, and workability, with approximately 1 billion tons of water consumed annually in its production and curing [2].

Aggregates form 60% - 75% of concrete's volume and are categorized into: Fine Aggregates: Particles passing through a 3/8-inch sieve (natural sand or crushed stone). Coarse Aggregates: Particles larger than 0.19 inches, up to 1.5 inches. Good-quality aggregates are clean, hard, and free from absorbed chemicals, clay, or coatings that might weaken concrete. Aggregates can be naturally sourced or crushed from quarry rocks.

Admixtures enhance properties of fresh and hardened concrete, affecting strength, water-to-cement ratio, workability, and setting time. Superplasticizers reduce water content by up to 30% without affecting workability [11].

Cement acts as the binding material, consisting of chemical constituents as shown in **Table 1**.

The hydration reactions in cement are key to strength and durability due to:

Formation of ettringite $C_3A + 3CSH_2 + 26H \rightarrow C_6AS_3H_{32}$; Hydration of tricalcium silicate: $C_3S + 6H \rightarrow C_3S_2H_3 + 3CH$; Hydration of dicalcium silicate: $C_2S + 4H \rightarrow C_3S_2H_3 + CH$ and reaction of ferrite with gypsum: $C_4AF + 3CSH_2 + 3H \rightarrow C_6\left(A,F\right)S_3H_{32} + \left(A,F\right)H_3 + CH$.

Table 1. Chemical components of cement.

Chemical Constituent	Wt%
Silica (SiO_2)	17% - 25%
Lime (CaO)	60% - 67%
Alumina (Al_2O_3)	3% - 8%
Iron Oxide (Fe_2O_3)	0.5% - 6%
Magnesia (MgO)	0.1% - 4%
Sulfur Trioxide (SO_3)	1% - 3%
Potash (K_2O) & Soda (Na_2O)	0.5% - 1.3%

Water is vital for concrete workability, hydration, and strength. Potable water is typically used in construction due to its well-regulated composition. Guidelines for potable water in Kenya, set by WASREB, are summarized in **Table 2**.

Table 2. WASREB guidelines for potable water quality.

Characteristic	Unit	Guide Value
Total Dissolved Solids (TDS)	mg/L	1500
pH	-	6.5 - 8.5
Ammonia (NH_4^+)	mg/L	0.5
Nitrate (NO_3^-)	mg/L	10
Sulphate (SO_4)	mg/L	400

TWW from wastewater treatment plants is increasingly considered for concrete production due to fresh water scarcity. However, its impurities, including BOD, COD, and TDS, can negatively impact concrete by prolonging setting times, reducing strength and durability and affecting hydration reactions. Mitigation measures include addition of admixtures such as SG and SF which can counteract these negative effects, enhancing strength and reducing porosity.

2.2. Empirical Review

The use of TWW in concrete production is gaining attention as a solution to fresh water scarcity in the construction industry. However, concerns arise about its potential impact on the properties of fresh and hardened concrete. TWW often contains impurities such as biochemical oxygen demand (BOD), chemical oxygen demand (COD), and total suspended solids (TSS), which can negatively affect workability, setting time, strength, and durability. While several studies have explored these impacts, they underscore the need for rigorous evaluation and mitigation strategies to optimize the use of TWW in concrete works.

A study by [12] emphasized the importance of assessing the chemical properties of TWW before use, as parameters like BOD, COD, and TSS often exceed acceptable thresholds for environmental discharge. Similarly, [13] observed that high COD (150 mg/L) and BOD (114 mg/L) in TWW reduced concrete workability. The organic matter forms complex compounds, increasing viscosity and limiting water availability for cement hydration, thereby impairing both workability and strength.

[14] findings in India corroborated this, showing that concrete made with primary treated wastewater (PTWW) and secondary treated wastewater (STWW) had lower compressive strength compared to FW mixes. This reduction was attributed to elevated BOD and COD levels in TWW, further highlighting the need for comprehensive chemical evaluation before use.

[15] found that concrete mixes made with secondary and tertiary treated wastewater exhibited prolonged setting times due to high COD levels. They noted that impurities affected cement hydration, leading to reduced early-age strength. [6] further highlighted that chloride content in TWW accelerates corrosion, posing long-term durability risks.

To address these issues, research has focused on the use of admixtures. [16] demonstrated that SG effectively inhibits corrosion even in aggressive environments containing chlorides and sulfates. SG improves hydration and workability, mitigating some of the adverse effects of TWW impurities.

[17] emphasized the role of SG in enhancing the resistivity of concrete. For instance, concrete made with TWW had an electrical resistivity of 11 ohms at 28 days, indicating high corrosion risk as per AASHTO TP95. Adding SG improved resistivity to 21.3 ohms (moderate corrosion risk). When SF was also included, resistivity increased to 28.933 ohms, categorizing the concrete as low-risk for corrosion. This improvement was attributed to the pozzolanic activity of SF, which densifies the concrete matrix and reduces porosity.

[18] demonstrated the effectiveness of plasticizers and SF in reducing water absorption rates. Their findings showed that combining SG and SF with TWW lowered water absorption to 2.73%, meeting ASTM C642 standards for high-quality concrete. This aligns with [9], who found that SF enhances microstructural refinement, compensating for the limitations of suboptimal water sources.

While these studies highlight promising results, several challenges remain. Many investigations, including those by [6] and [15], did not fully explore the long-term effects of TWW on concrete properties. Furthermore, variations in TWW quality across different treatment plants complicate standardization. Mitigation strategies, such as the use of SG and SF, show potential but may not fully counteract the adverse effects of TWW impurities. Future research should focus on optimizing admixture combinations and exploring other supplementary cementitious materials to enhance TWW concrete performance. The use of treated wastewater in concrete production presents both challenges and opportunities. While impurities like BOD, COD, and chlorides negatively impact workability, strength, and durability, the incorporation of admixtures such as sodium gluconate and silica fume significantly mitigates these effects. However, more research is needed to establish long-term performance standards and ensure consistent results across varied TWW sources. By addressing these challenges, TWW can become a viable alternative to fresh water in sustainable construction practices.

3. Methodology

3.1. Materials

The materials used in this study included Ordinary Portland Cement (OPC), aggregates, water (both fresh and treated), and chemical admixtures. The OPC was obtained from Bamburi Cement and classified as 32.5 N in accordance with the KS EAS 18-1 specification. The coarse aggregates were sourced from Katani Quarries in Machakos County, with a maximum nominal size of 20 mm, while the fine aggregates comprised natural river sand, also obtained from Machakos County. Both aggregate types were cleaned and dried to remove organic impurities prior to use.

The water used for concrete production comprised two sources: FW, sourced from the potable water supply system at Jomo Kenyatta University of Agriculture and Technology (JKUAT), and TWW, collected from the Ruai Wastewater Treatment Plant (WWTP) located in Nairobi County. The Ruai WWTP employs a secondary treatment process, which includes primary sedimentation followed by biological oxidation. This clarification is essential, as the treatment method influences the residual chemical and organic content in TWW and thereby affects its interaction with cementitious materials. Recognizing the variability in wastewater treatment technologies across different regions, the secondary treatment context at Ruai WWTP provides a defined benchmark for interpreting the performance of the TWW used in this study.

Two chemical admixtures were incorporated to mitigate the negative effects of impurities in TWW and enhance concrete performance: Sodium Gluconate (SG), sourced from Almaris Chemicals, and SF, obtained from Sika Kenya Limited. Both admixtures were selected for their established roles in improving hydration kinetics, microstructural densification, and resistance to the adverse effects of organic and inorganic impurities.

3.1.1. Aggregates

Both coarse and fine aggregates were utilized in this study. The coarse aggregates were sourced from Katani Quarries in Machakos County and conformed to a maximum nominal size of 20 mm. They were washed and air-dried to eliminate any organic or deleterious substances before testing. The fine aggregates consisted of natural river sand obtained from the same region. Aggregate characterization was conducted in accordance with BS 812 Part 2 for specific gravity and water absorption, and BS 812-103 for particle size distribution (grading). These procedures ensured the aggregates met the required specifications for use in structural concrete.

3.1.2. Water

The discrete sampling method was used for sampling of water; three samples were collected in an individual container, being representative at the time and place at which the samples were taken. The samples were collected in separate 5-litre sampling cans and clearly labelled. For the TWW, this was collected at the discharge points where it is expected to be fully treated; this is in line with (BS EN 1008 (2002)). **Figure 1** shows samples of TWW from RUAI, WWTP and FW from JKUAT for Testing, and **Figure 2** shows ongoing laboratory tests of the TWW at NCWSC laboratory.

Figure 1. Samples of TWW from RUAI, WWTP and FW from JKUAT for testing.

Figure 2. Ongoing laboratory test of the TWW at NCWSC laboratory.

General water quality parameters were tested for water to examine their qualities. This was carried out at the Nairobi City Water and Sewerage Company (NCWSC) laboratory for TWW and FW at JKUAT laboratory, as indicated in **Figure 3**. The tests carried out were "Total Dissolved Solids (TDS), pH, Chlorides, Chemical Oxygen Demand (COD), Biochemical Oxygen Demand (BOD), Nitrates, Dissolved Oxygen, Hardness ($CaCO_3$), and Sulphates".

3.1.3. Silica Fume

SF was sourced from Sika Kenya Limited. The material was selected for its pozzolanic properties, which contribute to pore structure refinement and improved durability of concrete. The chemical composition of the SF was verified through laboratory testing in accordance with BS EN 196-2, and the results aligned with manufacturer specifications. SF was introduced in powdered form and added to the concrete mixes at a controlled dosage to enhance microstructural development and reduce porosity, particularly in mixes using TWW.

3.1.4. Sodium Gluconate

Sodium Gluconate (SG) was obtained from Almaris Chemicals Ltd., and its product specifications were confirmed through manufacturer documentation. SG is known for its effectiveness as a set retarder and corrosion inhibitor. In this study, SG was used to stabilize organic impurities in TWW, reduce microbial interference, and improve hydration efficiency. Its inclusion aimed to mitigate the adverse effects of elevated BOD and COD levels and support uniform strength development across all curing ages.

3.2. Strength Assessment

The initial setting time test was carried out in line with BS EN 196-3 (2008). Cement specimens were prepared using fresh water (FW), TWW, and those made with SG and SF admixtures. The set of cement paste with water mixes is as shown in **Table 1**. The initial setting pin was attached to the Vicat apparatus for the determination of the initial setting time of the cement paste and it is calculated as the total duration from when water was initially added to the sample and the time the initial setting needle ceases to penetrate the Vicat mould of 5 mm.

The types of mixes evaluated in the study included Fresh Water, Fresh Water + SG, Fresh Water + SG + SF, TWW, TWW + SG, and Treated Wastewater + SG + SF. All these mixes were tested using the BS EN 196-3 (2008) method. A Vicat apparatus, indicated in **Figure 3**, with appropriate penetrating needles was used, and the data was recorded for determining the initial setting time.

Figure 3. Ongoing setting time test at JKUAT materials laboratory.

The cube crushing test, as indicated in **Figure 4**, was carried out to determine the compressive strength of the concrete made of FW and TWW. The grease oil was applied to the mould, and concrete was then poured into the formworks in three layers and each layer was compacted 35 times with a rod. The formworks were left for 24 hours before being disassembled, and the hardened concrete was then removed from the mould and soaked in water (wet curing). The cubes were left to cure for 7, 28 and 56 days, with at least 3 number of cubes being made for every concrete mix, the curing was done using the FW and with every casting being done in its own curing tank, for this case 6 curing tanks were set in line with the type of casting mix water.

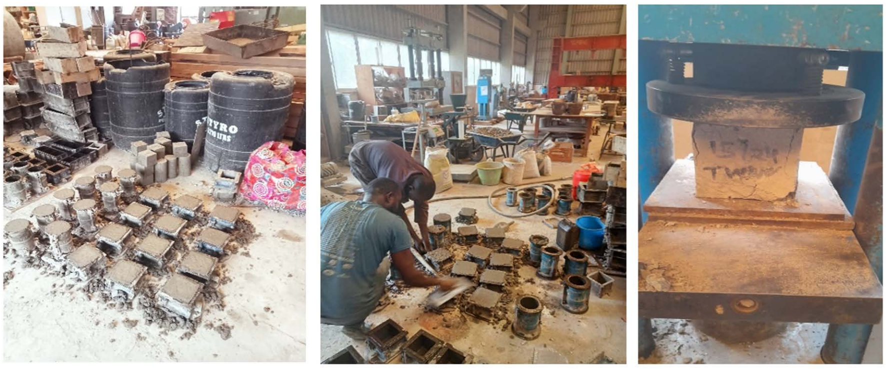

Figure 4. Cube making and curing at JKUAT materials laboratory.

For the compression test, cubes were cast for each mix type, with 3 cubes tested at 7 days, 28 days, and 56 days for each of the following mixes: FW, Fresh Water + SG, Fresh Water + SG + SF, TWW, Treated Wastewater + SG, and Treated Wastewater + SG + SF. In total, 54 cubes were cast and tested across all curing periods. After every maturity period, the concrete cubes were removed and weighed then the compression strength test was carried out by crushing using the compressive testing machine as per (BS 1881 part 116, 1983).

4. Results and Discussion

The Compressive strength for the 7, 28, and 56 days curing was tested with concrete made with TWW and FW, incorporating the SG and SF as admixtures; the results are shown in **Figure 5**.

Figure 5 indicates that the control mixes using FW achieved compressive strengths of 17.33 KN/mm^2, 21.31 KN/mm^2, and 22.8 KN/mm^2 at 7, 28, and 56 days, respectively. In contrast, TWW-based concrete cured with FW exhibited reduced strengths of 16.85 KN/mm^2, 18.98 KN/mm^2, and 19.91 KN/mm^2 over the same durations, achieving only 97% at 7 days and 87% at 28 and 56 days. These results fall short of the BS EN 1008 (2002) requirement, which stipulates at least 90% of control mix strength for questionable water. The strength reduction was attributed to high BOD and COD in TWW, which disrupts cement hydration. These impurities accelerate the transformation of C_3A and gypsum into ettringite and monosulfate aluminates, creating excessive porosity and reducing the bond between aggregates and cement paste. This aligns with findings by [19] and [20], who noted that organic matter impairs concrete strength and durability.

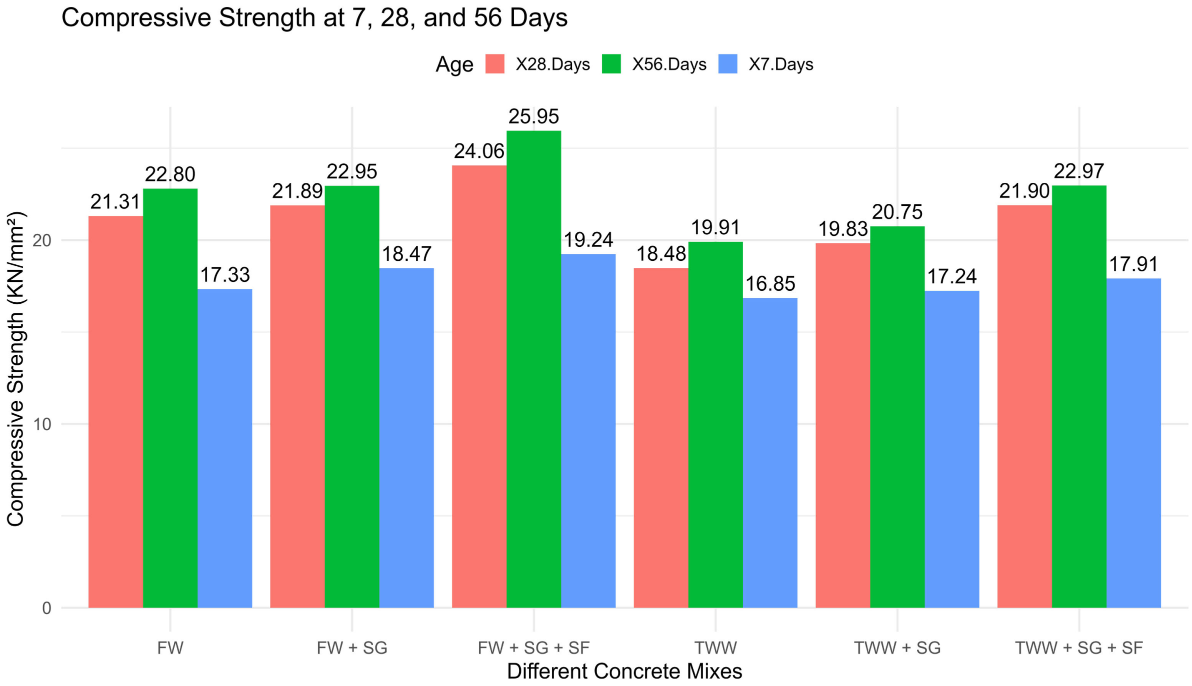

Figure 5. Concrete cubes compressive strength.

Incorporating SG significantly improved the performance of both FW and TWW mixes. FW + SG concrete achieved strengths of 18.47 KN/mm^2 (7 days), 20.36 KN/mm^2 (28 days), and 22.95 KN/mm^2 (56 days), representing improvements of 107%, 103%, and 101% over control. Similarly, TWW + SG concrete achieved 17.24 KN/mm^2 (7 days), 19.83 KN/mm^2 (28 days), and 20.75 KN/mm^2 (56 days), with the 28-day strength surpassing the 90% threshold required by BS EN 1008 (2002). The improvement is due to SG's ability to stabilize organic matter by forming stable complexes with BOD and COD, reducing microbial activity and enhancing hydration, as noted by Tour *et al.* (2021).

Adding SF alongside SG further enhanced strength properties. For FW + SG + SF mixes, compressive strengths reached 19.24 KN/mm^2 (7 days), 24.06 KN/mm^2 (28 days), and 25.95 KN/mm^2 (56 days), with increases of 111%, 113%, and 112% over control. TWW + SG + SF concrete demonstrated similar performance, achieving 17.91 KN/mm^2, 21.90 KN/mm^2, and 22.97 KN/mm^2 at 7, 28, and 56 days, respectively, fully meeting BS EN 1008 (2002) standards. These results confirm the synergistic effects of SG and SF, which refine pore structure, enhance pozzolanic reactions, and reduce porosity, as observed by [9].

Statistical analysis revealed significant differences among treatments across curing periods, with extended curing enhancing hydration and strength. [17] emphasized that superplasticizers like SG improve hydration, while SF enhances microstructural density, leading to durable concrete. The combination of SG and SF demonstrated superior performance, particularly with TWW, making it a viable strategy for optimizing concrete properties despite the presence of impurities. Table 3 presents descriptive statistics for effects of TWW on strength of concrete.

Table 3. Descriptive statistics for effects of TWW on strength of concrete.

Type of treatment	N	Mean	Std. Error	Minimum	Maximum	F (p-value)
7 Days Curing						
FW (Control)	3	17.33	0.65831	16.41	18.61	3.210 (0.0045)
FW + SG	3	18.47	0.56881	17.48	19.45	
FW + SG + SF	3	19.24	0.36671	18.52	19.73	
TWW	3	16.85	0.18330	16.61	17.21	
TWW + SG	3	17.24	0.46758	16.34	17.91	
TWW + SG + SF	3	17.91	0.56928	17.10	19.01	
28 Days Curing						**F (p-value)**
FW	3	21.31	1.21327	19.98	23.84	3.937 (0.024)
FW + SG	3	21.89	1.23122	19.46	23.45	
FW + SG + SF	3	24.06	0.97521	22.60	25.91	
TWW	3	18.48	0.67715	17.14	19.32	
TWW + SG	3	19.83	0.74902	18.58	21.17	
TWW + SG + SF	3	21.9	0.81405	20.56	23.37	
56 Days Curing						
FW	3	22.8	0.68420	21.50	23.82	**F (p-value)** 4.737 (0.013)
FW + SG	3	22.95	1.35846	20.29	24.75	
FW + SG + SF	3	25.95	0.94904	24.83	27.84	
TWW	3	19.91	0.96191	18.13	21.43	
TWW + SG	3	20.75	0.97273	19.43	22.65	
TWW + SG + SF	3	22.97	0.72848	21.85	24.34	

Table 3 shows the compressive strength of concrete under different treatments and curing durations (7, 28, and 56 days). For each treatment, the mean strength (KN/mm^2), standard error, minimum, maximum values, and statistical significance (F-value and p-value) are reported. At 7 days, the control mix (FW) achieved a mean strength of 17.33 KN/mm^2, while the addition of SG increased it to 18.47 KN/mm^2. Incorporating SF along with SG (FW + SG + SF) further improved strength to 19.24 KN/mm^2. TWW without admixtures showed the lowest strength (16.85 KN/mm^2), but the addition of SG and SF increased it to 17.24 KN/mm^2 and 17.91 KN/mm^2, respectively. Differences were statistically significant ($F = 3.210$, $p = 0.0045$).

At 28 days, FW + SG + SF had the highest strength (24.06 KN/mm^2), surpassing TWW + SG + SF (21.9 KN/mm^2). TWW alone remained the weakest (18.48

KN/mm^2). Statistical differences were observed (F = 3.937, p = 0.024). By 56 days, FW + SG + SF showed the highest strength (25.95 KN/mm^2), while TWW + SG + SF outperformed TWW alone (22.97 KN/mm^2 vs. 19.91 KN/mm^2). Significant differences persisted (F = 4.737, p = 0.013). The results highlight the effectiveness of SG and SF in enhancing the strength of concrete, particularly when using TWW. The post hoc analysis of compressive strength for concrete made with TWW and admixtures SG and SF, cured with FW is presented in Table 4.

Table 4. Post hoc results of the effect on strength of concrete made with TWW.

(I) typeofmixture	(J) typeofmixture	Mean Difference (I - J)	Std. Error	Sig.	95% Confidence Interval	
					Lower Bound	Upper Bound
FW (control)	FW + SG	−0.46000	1.36885	0.743	−3.4425	2.5225
	FW + SG + SF	−2.63000	1.36885	0.079	−5.6125	0.3525
	TWW	2.95000	1.36885	0.052	−0.0325	5.9325
	TWW + SG	1.60000	1.36885	0.265	−1.3825	4.5825
	TWW + SG + SF	−0.46667	1.36885	0.739	−3.4491	2.5158
FW + SG	FW (control)	0.46000	1.36885	0.743	−2.5225	3.4425
	FW + SG + SF	−2.17000	1.36885	0.139	−5.1525	0.8125
	TWW	3.41000*	1.36885	0.028	0.4275	6.3925
	TWW + SG	2.06000	1.36885	0.158	−0.9225	5.0425
	TWW + SG + SF	−0.00667	1.36885	0.996	−2.9891	2.9758
FW + SG + SF	FW (control)	2.63000	1.36885	0.079	−0.3525	5.6125
	FW + SG	2.17000	1.36885	0.139	−0.8125	5.1525
	TWW	5.58000*	1.36885	0.002	2.5975	8.5625
	TWW + SG	4.23000*	1.36885	0.009	1.2475	7.2125
	TWW + SG + SF	2.16333	1.36885	0.140	−0.8191	5.1458
TWW	FW (control)	−2.95000	1.36885	0.052	−5.9325	0.0325
	FW + SG	−3.41000*	1.36885	0.028	−6.3925	−0.4275
	FW + SG + SF	−5.58000*	1.36885	0.002	−8.5625	−2.5975
	TWW + SG	−1.35000	1.36885	0.343	−4.3325	1.6325
	TWW + SG + SF	−3.41667*	1.36885	0.028	−6.3991	−0.4342
TWW + SG	FW (control)	−1.60000	1.36885	0.265	−4.5825	1.3825
	FW + SG	−2.06000	1.36885	0.158	−5.0425	0.9225
	FW + SG + SF	−4.23000*	1.36885	0.009	−7.2125	−1.2475
	TWW	1.35000	1.36885	0.343	−1.6325	4.3325
	TWW + SG + SF	−2.06667	1.36885	0.157	−5.0491	0.9158

Continued

TWW + SG + SF	FW (control)	0.46667	1.36885	0.739	−2.5158	3.4491
	FW + SG	0.00667	1.36885	0.996	−2.9758	2.9891
	FW + SG + SF	−2.16333	1.36885	0.140	−5.1458	0.8191
	TWW	3.41667*	1.36885	0.028	0.4342	6.3991
	TWW + SG	2.06667	1.36885	0.157	−0.9158	5.0491

*The mean difference is significant at the 0.05 level.

Table 4 indicates that the mean difference between FW and FW + SG was −0.460 MPa (p = 0.743), indicating no significant difference. Between FW and FW + SG + SF, the mean difference was −2.630 MPa (p = 0.079), suggesting a marginally significant increase in strength. TWW alone showed a mean difference of 2.950 MPa (p = 0.052), indicating a significant decrease in strength compared to FW.

Comparing FW + SG to TWW revealed a significant mean difference of 3.410 MPa (p = 0.028), showing higher strength in FW + SG. Further, FW + SG + SF exhibited significant strength improvements over TWW and TWW + SG, with mean differences of 5.580 MPa and 4.230 MPa (p < 0.01). TWW + SG + SF demonstrated a substantial 5.580 MPa increase over TWW (p = 0.002), emphasizing the effectiveness of combining SG and SF.

SG functions as a chelating agent that forms stable complexes with metal ions and organic matter [16]. This stabilization reduces microbial activity and interference with cement hydration, thereby improving early strength development. SF, being rich in amorphous SiO_2, undergoes pozzolanic reactions with calcium hydroxide [$Ca(OH)_2$] to form additional calcium silicate hydrate (C-S-H), refining the microstructure, reducing porosity, and increasing durability [9].

5. Conclusions

This study rigorously examined the feasibility of using treated wastewater as a partial or full replacement for FW in concrete production. Results confirmed that while untreated TWW led to reductions in compressive strength, up to 13% lower than FW controls at 7, 28, and 56 days, these shortcomings were substantially mitigated through the incorporation of SG and SF. When combined, SG and SF improved concrete strength by stabilizing BOD and COD and refining the microstructure via pozzolanic reactions. The resulting mixes not only met the BS EN 1008 (2002) requirement of attaining at least 90% of FW control strength but, in some cases, surpassed it, indicating that TWW, when properly modified, can be a viable component in sustainable concrete production.

Several limitations of the current study must be acknowledged. First, only compressive strength was evaluated, while other key indicators of long-term durability, such as permeability, shrinkage, sulfate and chloride resistance, freeze-thaw behavior, and reinforcement corrosion, were not assessed. This restricts the understanding of TWW's influence under real-world environmental exposures and long service life conditions. Second, the analysis of TWW composition, although inclusive of key chemical parameters, did not capture temporal variations in water quality, nor did it pinpoint the specific contaminants most detrimental to concrete performance. Third, the treatment process employed at the Ruai wastewater treatment plant was not detailed, limiting the transferability of results to other TWW sources with different treatment technologies and effluent profiles. While the study qualitatively described the roles of SG and SF in performance enhancement, further research is needed to quantitatively explore their chemical interactions and optimal dosages, especially in relation to varying TWW compositions. As such, future investigations should adopt a holistic durability testing framework, conduct seasonal TWW profiling, and explore additional admixture and SCM strategies to ensure consistency, safety, and structural integrity of TWW-based concrete across diverse conditions.

This research provides a foundational understanding of how TWW, when supplemented with suitable admixtures, can support more sustainable construction practices. Nevertheless, comprehensive studies addressing the highlighted limitations are necessary to fully validate and standardize its use in broader applications.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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