Quality Assessment of Concrete Utilizing Harvested Rainwater, Stormwater and Conventional Water

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Abstract: Preserving and conserving freshwater resources has become increasingly crucial with the growing global population. In the present study, the viability of replacing freshwater in the manufacturing of concrete with other sources, such as potable water (PW), harvested rainwater (HRW), stormwater (SW), and borehole well water (BW), was investigated. The investigation adhered to applicable standards, analyzing the physical and chemical properties of these water sources. The fresh concrete properties, including setting time and workability, were scrutinized, and the mechanical properties were evaluated through compressive, split tensile, and flexural strength tests at 7, 28, and 90 days. Durability was evaluated through examinations such as the Volhard assay to measure chloride content at 90 and 150 days and the rapid chloride permeability test (RCPT) for 90 days. The results indicated that the water quality from all sources met the recommended standards for concrete. There were no notable variations in the mechanical characteristics when compared to those of standard concrete. RCPT exhibited high durability concerning chloride ion penetration, with all the tested mixes exhibiting low chloride content (below 0.2%). This emphasizes how crucial it is to use a variety of durability tests. Saving resources and protecting the environment may be aided by using non potable water sources such as harvested rainwater and stormwater in place of freshwater.

Key words: Different types of water, setting time, mechanical properties, durability, statistical analysis.

1. Introduction

Concrete production is a major consumer of freshwater, with approximately one billion tons of water used annually. Each cubic meter of concrete requires between 150 and 210 liters of water. By 1997, the demand for freshwater in concrete production had already exceeded 800 billion liters, increasing to 825 billion liters by 2010. This highlights the concrete industry's significant environmental impact [1] and [2]. This issue is compounded by the escalating depletion of freshwater resources due to expanding urbanization and population growth. The high consumption of water in concrete production puts significant stress on freshwater resources, necessitating the exploration of alternative water sources. By addressing these gaps, this study seeks to clarify the practical feasibility and advantages of using alternative water sources in concrete production, thereby contributing to broader sustainability goals within the construction industry. Water quality plays a critical role in the preparation of concrete, impacting its performance in both the fresh and hardened stages. Previous literature surveys on the use of treated domestic wastewater, industrial wastewater, and seawater in concrete production have indicated that these alternative water sources contain various organic and inorganic substances. These impurities can interfere with the hydration process of cement, crucial for the hardening and strength development of concrete. Specifically, the presence of such substances can delay the setting time of cement, potentially affecting the overall performance and structural integrity of the concrete. These studies highlight the importance of carefully assessing the quality and treatment level of wastewater to ensure it meets the standards required for safe and effective use in concrete mixing [3] and [4]. This situation calls for the exploration of alternative water sources to alleviate the pressure. By addressing existing gaps, this study seeks to clarify the practical feasibility and advantages of using alternative water sources in concrete production, thereby contributing to the broader goals of sustainability within the construction industry. Additionally, using local alternative water sources like harvested rainwater and stormwater can lead to significant economic benefits by reducing the costs associated with transporting and procuring freshwater. This research aims to establish guidelines for the effective use of non-conventional water sources in concrete, including mixing harvested rainwater and stormwater with conventional sources like borewell water and potable water, ensuring the resulting concrete meets industry standards and performs reliably in various construction applications. Governmental initiatives, such as the Bangalore Water Supply and Sewerage Board (BWSSB) mandate in 2011, require rainwater harvesting in Bengaluru, India. This study aims to assess the suitability of harvested rainwater and stormwater for mixing concrete. The assessment focuses on their effects on setting time, workability, durability, and mechanical properties, providing insights into the potential of these alternative water sources in concrete production and their impact on the quality of the final product.

Literature Review

Numerous studies have examined the impact of wastewater on concrete properties. Studies by [5],[6], and [7] thoroughly evaluated how wastewater's solid content affects concrete. These studies revealed that when wastewater replaced tap water in concrete mixtures and the combined water content was kept below 6%, the slump of the concrete changed by less than 30 mm. They found that the solid content influenced workability, but the type of mixing water did not significantly affect the slump, aligning with A.M. Neville's observations. The use of grey water and resin waste in concrete mixing led to a reduction in a slump, while an increase in the electrical conductivity of water corresponded to an increase in a concrete slump, as noted by [8] and [9]. Despite the insights into slump and workability, relatively few studies have addressed the resilience of wastewater concrete to sulfate attacks and freezing. Studies [10] and [11] noted that wastewater delayed concrete setting times, especially with high total solid or heavy metal contents, such as Zn, Cu, or Pb. This delay in setting time was accompanied by significant reductions in tensile and compressive strength when untreated wastewater with high organic content was used. Additionally, water containing fluorides and bicarbonates were found to react with alumina, forming calcium fluoraluminates, which enhance concrete strength, as observed by [12]. Various chemical interactions within the concrete matrix can significantly impact its properties. Elevated levels of salts, heavy solids, bicarbonates, fluorides, and acidic water influence concrete's setting time and durability. The presence of dissolved salts like Ca^{2+}, K^{+}, Na^{+}, SO_4^{2-}, and OH^{-} affects the solubility of gypsum, alite, and C_3A phases through the common ion effect. Calcium ions enhance supersaturation, leading to faster portlandite precipitation and accelerated alite dissolution [13]. As discussed by [14], elevated levels of calcium and sulfate ions contribute to delays in concrete settings, though this effect is mitigated. Specifically, sulfate ions slow the hydration and dissolution of aluminates while accelerating the hydration rate of alite. Sulfates, present in surface water, groundwater, and soil, pose significant risks to concrete. As highlighted by [15], sulfates like $CaSO_4$, $MgSO_4$, Na_2SO_4, $(NH_4)_2SO_4$, and $FeSO_4$ can cause volume expansion and cracking due to the formation of ettringite (CSA) during cement hydration. This reaction leads to structural damage and strength loss. High levels of lead in water, which do not react with calcium oxide in cement, can extend the setting time. Additionally, magnesium hydroxide, calcium sulfate, inorganic solids, and phosphorus in mixing water accelerate setting times due to gyrolite formation [16], while sulfuric and hydrochloric acids also hasten setting times. The presence of sodium chloride can have both beneficial and detrimental impacts on concrete. According to [17], chloride activators can enhance early-age strength. However, chloride penetration accelerates the corrosion of reinforcement, as highlighted by [18]. In developing communities, seawater is often used for concrete mixing due to its availability, as discussed by [19],[20] and [21]. Seawater, which is significantly more saline than river water, contains high levels of sodium chloride, accounting for approximately 88% of its composition. With a pH range of 7.4 to 8.4, seawater's main elements calcium, chloride, magnesium, potassium, and sodium ions can adversely affect the lifespan of concrete by promoting corrosion. The literature also explores the use of harvested rainfall and stormwater in concrete manufacturing. Studies suggest that separating less contaminated wastewater from heavily polluted streams can mitigate treatment issues, especially during economic downturns. This approach is particularly significant in reducing dependency on potable water for concrete production, as emphasized by [22],[23],[24],[25] and [26]. This study aims to utilize collected harvested rainfall, stormwater, and conventional water in fresh and hardened concrete, assessing their impact on concrete properties. This literature review highlights the diverse effects of various water sources on concrete properties. While wastewater and non-traditional water sources can alter workability, setting times, and strength, careful assessment and management of water quality are crucial for maintaining concrete durability and performance. The insights gained from these studies underscore the importance of evaluating alternative water sources to reduce potable water usage in concrete production, thus promoting sustainability in construction practices.

2. Materials and Experimental Program

2.1. Material

Water Sampling Program

The research study's sampling locations were chosen from the AIEMS campus at Bidadi, Ramanagaram, Karnataka, India. The rainwater harvesting system under evaluation was used to collect rain from June to October 2023 during the monsoon season, as shown in Figure 1. Rainwater collected from the RCC roof was passed through a PVC gutter pipe and stored in sanitized polyethylene cans. Two containers were stacked one above the other for the first and second flushes. The first flush samples had higher solid concentrations; thus, the second flush samples were collected and kept in larger containers for examination.

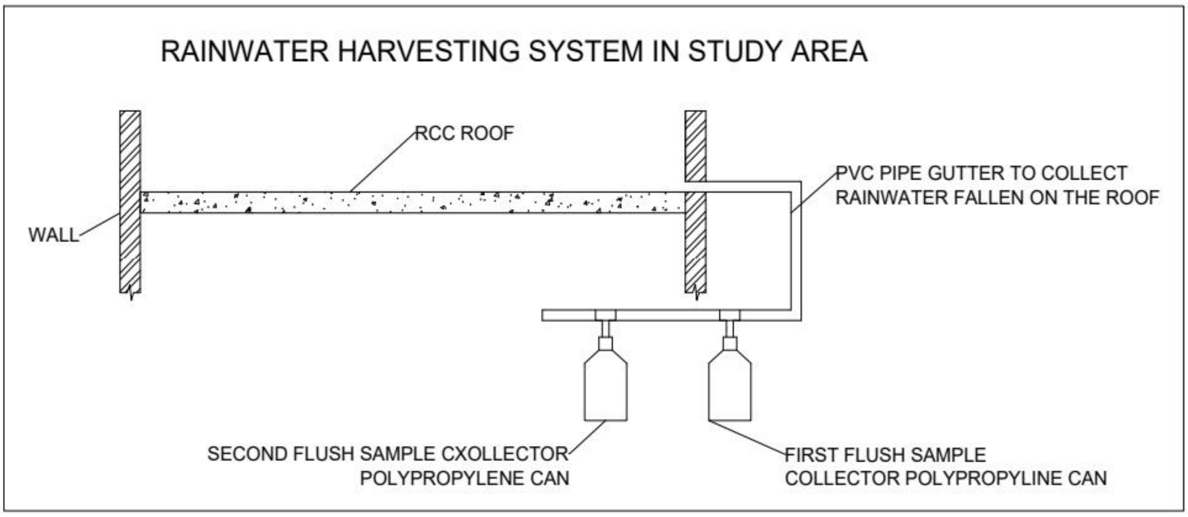

Fig. 1. Rainwater harvesting system at the sampling points.

Surface runoff samples were collected via stormwater drainage on days when there was precipitation at certain places in the research region. After being collected in polyethylene bottles, the stormwater was screened to remove any coarse particles or floating debris. After screening, the samples were placed in a large container for storage. Separate collections of purified potable water and bore well water were made, and the samples were stored in polypropylene containers. Throughout the course of the study, ten samples from various sources were consistently collected to guarantee sufficient amounts for mixing and curing. The implementation of a systematic sampling technique enabled a thorough comparison, which in turn promoted comprehension of quality variances and aided in the computation of average values.

Cement and Fine and Coarse Aggregates

Table 1 compares results to the BIS:12269-2013 standards for Ordinary Portland Cement (OPC) 53 Grade. Key components include Calcium Oxide (62%) and Silicon Dioxide (20.10%), critical for strength development, while others like Aluminum Oxide (5.73%) and Ferric Oxide (5.38%) contribute to early setting and long-term strength. Magnesium Oxide (0.95%) and Sulphur Trioxide (2.71%) levels are within safe limits to prevent expansion and cracking. The alumina-to-iron oxide ratio (1.05) and Lime Saturation Factor (0.94) ensure proper clinker formation. Chloride content (0.008%), Loss on Ignition (2.42%), and Insoluble Residue (0.70%) are all within permissible limits, ensuring the cement's quality and durability.

With a specific gravity of 3.15, a surface area of 2960 cm^2/g, and conformity with the IS: 12269 requirements, the OPC parameters were within the permissible range. For the concrete blend, the first setting time was 30 minutes, and the last setting time was 600 minutes. Provided the coarse and fine natural aggregates studied. The specific gravities of the coarse and fine aggregates were found to be 2.72 and 2.61, respectively. Furthermore, the bulk densities of the coarse aggregates were 2650 kg/m^3 and 2890 kg/m^3 for the fine aggregates, corresponding to 0.89% and 0.65%, respectively, of the water absorption rates. The table represents the chemical analysis of cement constituents, measured using methods like X-ray fluorescence (XRF), gravimetric analysis, and titration.

Table 1. Chemical Properties of OPC 53 Grade Cement.

Sl.No	Constituents	Test Results	Required as per BIS:12269-2013
1	Calcium Oxide (CaO)	62%	-
2	Silicon Dioxide (SiO_2)	20.10%	-
3	Aluminum Oxide (Al_2O_3)	5.73%	-
4	Ferric Oxide (Fe_2O_3)	5.38%	-
5	Magnesium Oxide (MgO)	0.95%	Not more than 6%
6	Sulphur Trioxide (SO_3)	2.71%	Max.3.0%when$C_3A>5.0$ Max.2.5%when$C_3A<5.0$
7	Ratio of alumina/iron Oxide	1.05	Min 0.66
8	Lime Saturation Factor	0.94	0.80 to 1.02
9	Chloride Content	0.008%	Max 0.1%
10	Loss on Ignition (LOI):	2.42%	Max 4%
11	Insoluble Residue	0.70%	Max 5%

2.2 Experimental Procedure for Determination of Water Quality

Samples of water from several sources, including borehole water, stormwater, harvested rainwater, and potable water, were brought to the laboratory and examined immediately for total dissolved solids (TDS), pH, and conductivity. These samples were kept cold until they were analyzed. To test different water quality parameters, the laboratory used standard procedures, as described in the "Standard Methods for the Examination of Water and Wastewater of the American Public Health and American Water Work Association and Water Environment Federation pollution" (APHA) 2012. These included total alkalinity, calcium, magnesium, potassium, sodium, bicarbonate, sulphate, chloride, phosphate, nitrate, zinc, lead, copper, and manganese. The total suspended solids, inorganic solids, and organic solids were also included. The samples were acidified with 2% concentrated nitric acid for metal evaluation. This article provides an extensive examination of both national and international standards to compare the permissible limits for water used in concrete mixing.

2.3 Experimental Procedure for Concrete and Mortar

Table 2 provides the design specifications for the different types of concrete samples. Specifically, PW427, PW384, and PW350 denote concrete samples prepared using potable water, with 427, 384, and 350 representing the respective kg/m^3 of cement in one cubic meter of concrete. Similarly, HRW427, HRW384, and HRW350 refer to concrete samples prepared using harvested rainwater. The SW427, SW384, and SW350 designations pertain to concrete samples prepared using Stormwater, while BW427, BW384, and BW350 designate concrete samples prepared using Borewell water.

Table 2: Design Specifications for Concrete Samples. (Kg/m^3 cube of concrete)

Types of mixing water	% Replacement of water	Types of composites	W/C Ratio	Cement (Kg/m^3)	Fine aggregate (Kg/m^3)	Coarse aggregate (Kg/m^3)	Water (lit/m^3)
PW, HRW, SW, BW.	100%	Concrete	0.45	427	590	1143	192
PW, HRW, SW, BW.	100%		0.5	384	650	1096	192
PW, HRW, SW, BW.	100%		0.55	350	582	1206	197
PW, HRW, SW, BW.	100%	Mortar	0.5	568	1704	-	280

The design specifications for the different types of concrete samples are provided in Table 2. These samples are designated based on the type of water used and the amount of cement in kg per cubic meter of concrete.

Fresh and mechanical properties of the concrete

These tests include evaluating ordinary Portland cement (OPC) for setting time and mortar compressive strength at 7, 28, and 90 days. The OPC paste setting times were determined in accordance with ASTM C191-19. According to the standard, the OPC setting time is considered acceptable if it falls within a range of 1 hour earlier to 1.5 hours later than the setting time of the reference OPC paste. Moreover, the 7-day mortar compressive strength must be at least 90% of the average strength of the potable water mortar. The mortar combinations were prepared with a cement-to-fine aggregate ratio of 1:3, and the water-to-cement (W/C) ratio was set at 0.5.

The study centered on assessing the workability of concrete, which involves evaluating the ease of placing and finishing freshly mixed concrete while minimizing the loss of homogeneity. The slump cone test was used under the recommendations given in the BS EN 12350-2 (2009) standards. 150 X 150 mm Cubes tests were conducted at 7, 28, and 90-day intervals in compliance with the BS EN 12390-3 (2009) guidelines to determine the compressive strength of the concrete. A 100-ton compression machine was used to measure the concrete cubes, which were loaded at a pace of 4 tons per minute. The split tensile strength of concrete 150 x 300 mm cylinders was evaluated. Before the test started, a cylindrical specimen was properly placed and fastened to the testing apparatus. The split tensile strength could be measured since the specimen was loaded until it shattered. Using the two-point loading method and a flexural testing machine with a 100 kN capacity, the flexural strength of the concrete prism (150 x 500 mm) was evaluated. The load was applied over an effective span of 400 mm until the prism reached the point of failure.

Durability characteristics of concrete

The rapid chloride penetration test (RCPT) gauges the ability of chloride ions to permeate concrete and was executed according to the standards outlined in [29]. For each concrete mixture, permeability was further assessed through this test. Cylindrical concrete samples measuring 100 mm × 50 mm were prepared and cured for 90 days. The specimens were conditioned for three days at 50 °C in an oven. They were then coated with silicon epoxy around their periphery, vacuum-treated for three hours at a pressure of 50 mmHg in a desiccator, and immersed for eighteen hours in deaerated water. After conditioning, the specimens were placed inside two molds, one filled with a 0.3 N sodium hydroxide ($NaOH$) solution and the other with a 3% sodium chloride ($NaCl$) solution. The test molds were exposed to a 60 V potential difference for six hours, with current flows recorded every thirty minutes. The total charges transferred (Q) were computed using Equation (1):

$$Q = 900(I_0 + 2I_{30} + 2I_{60} + \cdots + 2I_{300} + 2I_{330} + I_{360}) \quad - \quad (1)$$

In the equation, the terms I0, I30, I60, etc., represent the applied current in amps at the beginning, after 30 minutes, after 60 minutes, and at each succeeding interval, respectively. Following the Nord test methodology described in NT BUILD 208 for evaluating chloride ions in hardened concrete, the Volhard method was used to determine the chloride ion content. This method releases chloride ions from a powdered concrete sample by digesting it with nitric acid, separating total and acid-soluble chloride ions. Using a rotary impact drill, holes were bored into prisms to a depth of 5 cm to extract powdered samples. The same prisms used at the 90-day stage were also employed at the 150-day stage. The filtration procedures determined the chloride ions in the concrete extracts.

Corrosion Potential Test

To measure corrosion potential using a half-cell potential meter (per ASTM C876/C876M-15), start by preparing the concrete surface, ensuring it's clean and free of contaminants. Calibrate the meter and mark measurement points near reinforcing bars. Place the reference electrode firmly on the surface, connect it to the meter, and take millivolt readings at each point. Higher millivolt readings generally indicate lower corrosion risk, while lower readings suggest potential corrosion activity. Document all measurements and conditions accurately for reporting according to ASTM standards.

Sulphate Attack Test

Concrete specimens were prepared according to ASTM C192 for mixing. Cylinders measuring 150×300mm and prisms measuring 100x100x500mm were molded following ASTM C470 and cured in an ASTM C511 moist room until reaching 28 days of age. The specimens underwent Physical Sulfate Attack (PSA) testing under both laboratory and field conditions(Liu et al., 2018)(Zhutovsky & Douglas Hooton, 2017)(Jabbour et al., 2022). In the laboratory tests, specimens were partially submerged in 10% sodium sulfate solution and fully submerged in 30% sodium sulfate solution. The mass loss was monitored by vacuum filtering the solution every 20 days, and the scaled-off particles were weighed after oven drying. The test regimen lasted 100 days, with regular solution replenishment and changes every 30 days. Mass loss measurements were conducted every 20 days by determining the mass of samples after removing them from the exposure medium and surface drying. Expansion measurements were performed on concrete prisms, modified from ASTM C1012 to accommodate larger aggregates. Initial length readings were taken using a length change comparator, and the prisms were partially submerged in a 10% sodium sulfate solution and fully submerged in a 30% sodium sulfate solution after each reading. Expansion measurements were conducted every 100 days by checking the length of the samples after removing them from the exposure medium and surface drying.

Microstructural Analysis:

Microstructural analysis was conducted on fractured sections using a NOVA NANOSEM 450 scanning electron microscope as per ASTM C1723-16 provisions. The analysis included SEM to study the morphology of concrete and EDX to determine its chemical composition.

Statistical analysis

The primary purpose of the ANOVA test is to examine whether there is a correlation between multiple independent variables, encompassing cement content, water type, and curing age, and the dependent variable, specifically the compressive, spilt tensile, and flexural strength of concrete.

Results and discussion

3.1 Comparing the various water sources qualitative assessments to water quality requirements

Table 2 presents the results of the qualitative study, indicating that potable water (PW) and borewell water (BW) are considered conventional water sources, while harvested rainwater (HRW) and stormwater (SW) are alternative sources. The water properties were found to be within allowable limits as specified by ASTM C1602, IS 456-2000, and relevant literature references.

Table 2: Physical and chemical compositions of PW, BW, HRW, and SW in comparison to standards. (All the parameters are in mg/l except for pH, conductivity and turbidity).

Constituents	Various sources of water				Different concrete production standards			
	Conventional water		HRW	SW	IS 456:2000 Limits	ASTM C1602 Limits	As per for literature	In contrast to IS 456:2000 restrictions and ASTM C1602,
	PW	BW						
	Avg							
pH	7.23	7.32	6.51	7.05	>6	6 - 8	3 – 9	Within
Conductivity (µs/cm)	15.00	125.46	48.45	88.47	-	-	-	N/A
Turbidity (NTU)	0	0.66	12.01	23.03	-	-	2000	N/A
TSS	6.04	1.87	7.62	51.27	2000	50000	2000	Within
TDS	315.23	605.08	225.21	579.25	2000	-	2000 - 50000	Within
Inorganic solids	26.69	532.83	132.68	377.30	3000	-	-	-
Organic solids	5.55	107.71	11.45	92.57	200	-	-	-
Total alkalinity	93.95	406.57	41.59	118.71	250	600	500 - 1000	Exceed- IS 456
Ca2+	72.8	100.63	20.46	135.95	-	-	<2000	N/A
Mg2+	26.13	50.06	2.02	51.51	-	-	<2000	N/A
K+	16.93	31.57	1.69	23.57	-	-	<2000	N/A
Na+	19.81	94.34	2.38	32.17	-	-	2000	N/A
HCO3-	102.9	412.5	8.35	120.13	-	-	400	N/A
Cl-	147.27	216.24	22.16	225.4	500-2000	500 - 1000	500 – 2000	Within

SO42-	104.94	142.13	9.35	131.34	400	3000	400 – 3000	Within
Total N	21.78	32.11	4.48	38.52	-	-	500	N/A
Total P	0.08	0.24	0.05	0.34	-	-	100	N/A
Zinc	0.99	1.58	0.04	2.2	-	-	100 – 600	N/A
Lead	0	0.02	0.01	0.03	-	-	100 – 600	N/A
Manganese	0.17	0.01	0.01	0.02	-	-	500 – 600	N/A
Copper	0.05	1.03	0.01	1.5	-	-	500 – 600	N/A

The table presents a comprehensive comparison of water quality parameters across different sources used in concrete production, evaluated against ASTM C1602, IS 456:2000 standards, and relevant literature references. It categorizes water into conventional sources Potable Water (PW) and Borewell Water (BW) and alternative sources Harvested Rainwater (HRW) and Stormwater (SW). In terms of pH levels, all sources fall within the acceptable range of 6-8 outlined by ASTM C1602, with HRW and SW showing slightly lower values but still within safe limits. Furthermore, it was discovered that higher pH values made it easier for metals to precipitate, which decreased the amount of hydration cement[27]. Conductivity, although not directly governed by standards, indicates higher values for SW, suggesting greater mineral content. Turbidity, another quality measure not specified by standards but critical for clarity, reveals significantly higher levels in SW compared to other sources. Total Suspended Solids (TSS) and Total Dissolved Solids (TDS) adhere to the 2000 mg/L limit set by IS 456:2000 across all sources, ensuring minimal particulate matter and dissolved solids. Runoff obstructing grit particles may have contributed to the higher total solids content in SW (569.55 mg/l) since some components are difficult to dissolve in water. As a result, the concentration of total solids would increase. However, SW surpasses the inorganic solids threshold of 3000 mg/L, potentially affecting concrete composition and performance. Organic solids, within acceptable ranges as per literature, pose fewer concerns. Concentrations of inorganic components that are too high can prevent cement from hydrating, which can delay the setting of the new mixture and, in some cases, significantly reduce the strength of the concrete that has hardened[28]. Total Alkalinity levels exceed the IS 456:2000 limit of 250 mg/L in SW but fall within broader recommendations (500-1000 mg/L) cited in literature. Elements such as Calcium (Ca^{2+}), Magnesium (Mg^{2+}), Potassium (K^{+}), Sodium (Na^{+}), Bicarbonates (HCO^{3-}), Chlorides (Cl^{-}), Sulfates (SO_4^{2-}), Nitrogen (Total N), Phosphorus (Total P), Zinc, Lead, Manganese, and Copper generally comply with standards, underscoring their suitability for concrete production. A high chloride content in the mixing water may be the cause of the high early strength of cement concrete, according to [29]. In conclusion, while most parameters align with established guidelines, SW exhibits higher levels of certain constituents, necessitating careful consideration and potentially requiring treatment to mitigate adverse effects on concrete quality and performance. This comprehensive assessment ensures that water sources meet stringent criteria to maintain optimal conditions for concrete production, essential for sustainable and durable construction practices. The sulphate levels in each sample are barely below the maximum allowable limit for mixing concrete.[30] The sulphate concentration can lead to the formation of calcium sufflaminate, or ettringite, during cement hydration. This can cause issues, including uneven cracking, expansion of the concrete, and ensuing strength loss.

R version 4.3.1 software was used to construct box plots, which are visual representations of water quality data from various sources. Fig. 3 shows the concentrations of sulphates, chlorides, nitrates, and bicarbonate, and Fig. 2 shows the concentrations of significant water quality indices, such as pH, conductivity, total dissolved solids (TDS), and inorganic solids, for the different water sources. Fig. 3 displays the mean concentration of anions (sulfate, nitrate, bicarbonate, chloride) in PW, HRW, SW, and BW.

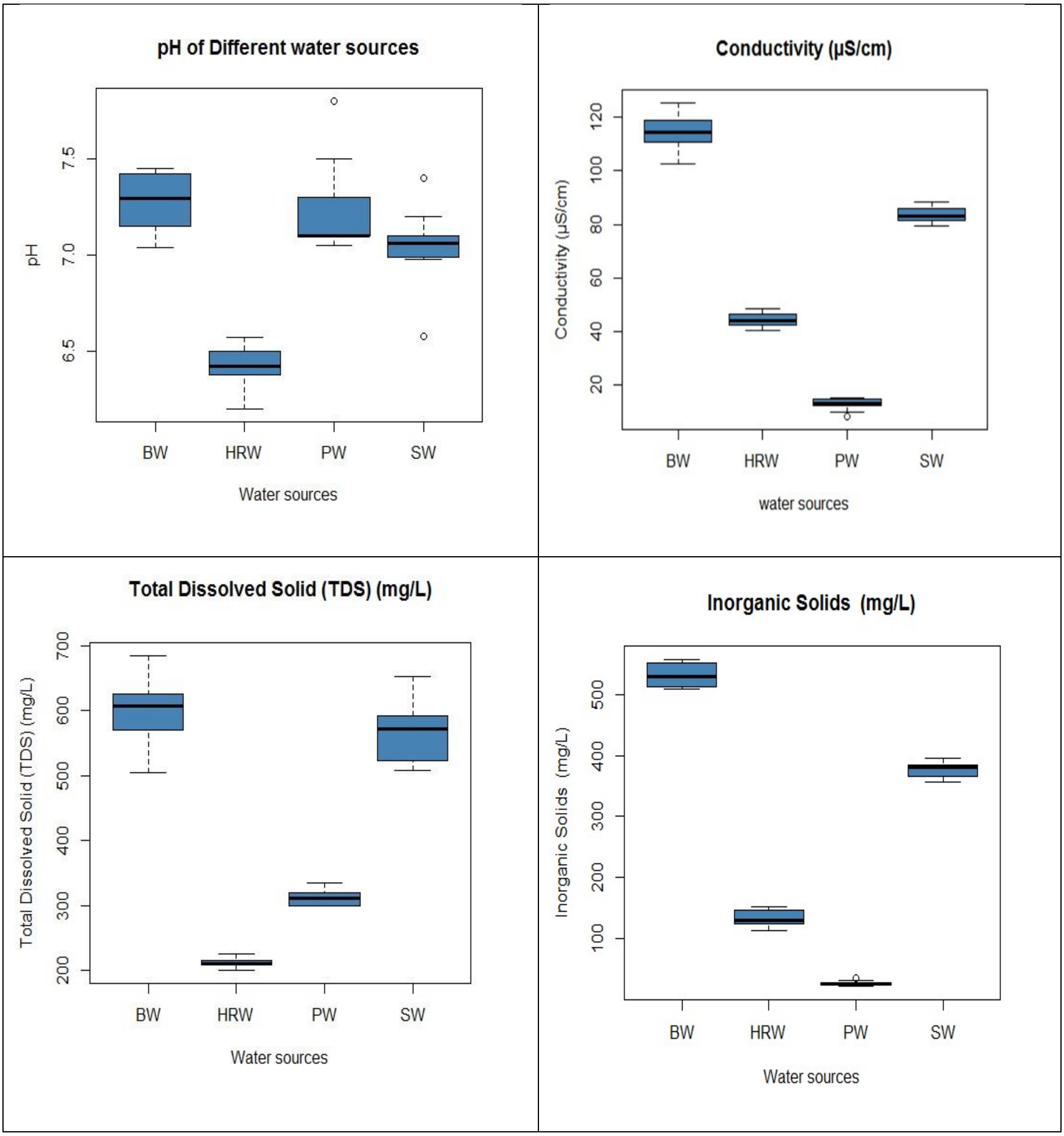

Fig. 2 pH, conductivity, TDS, and inorganic solids concentrations for various water sources.

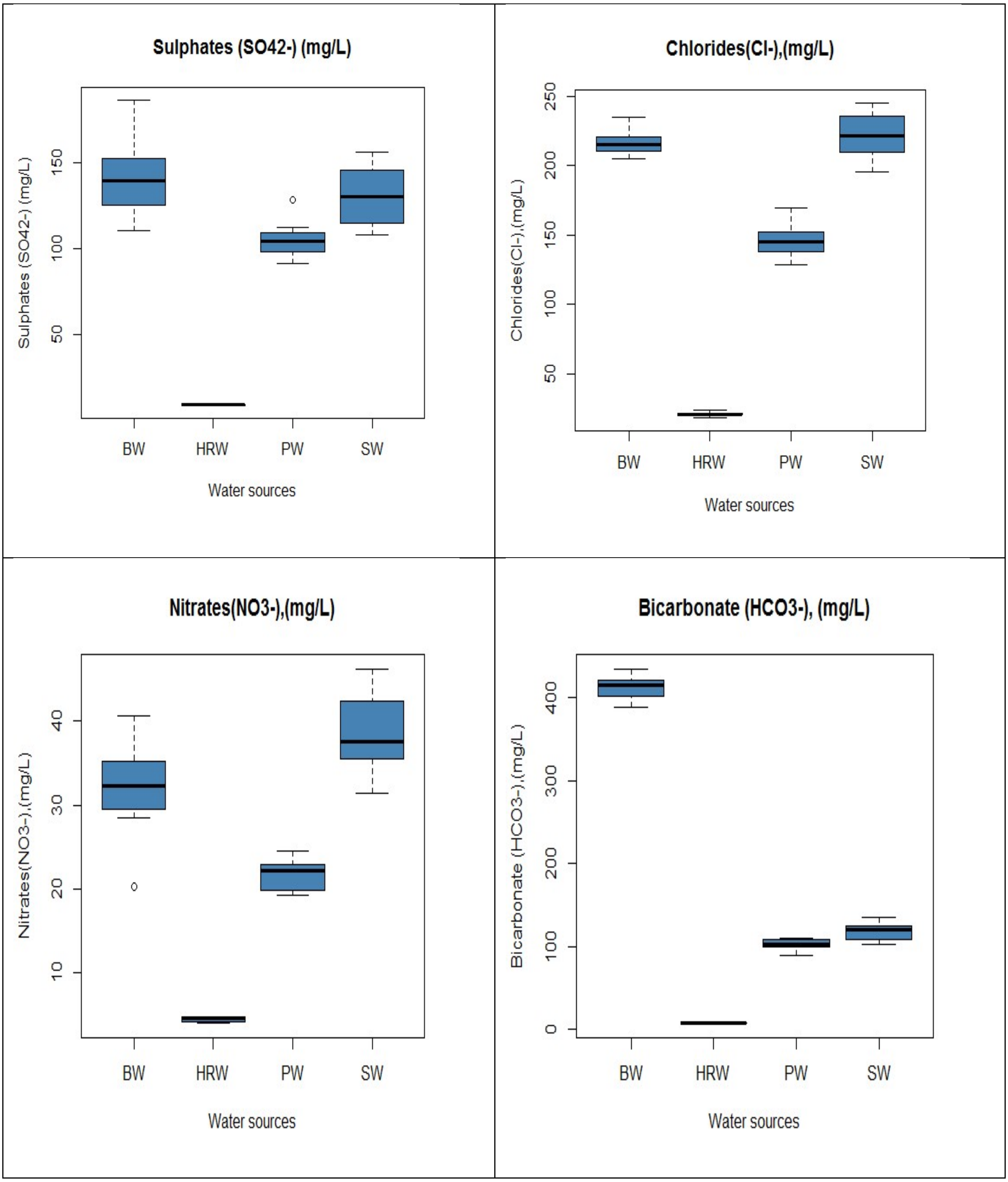

Fig. 3 Sulphate, chloride, nitrate, and bicarbonate concentrations in water sources.

3.2 Fresh and mechanical properties of the concrete

Setting time

The results of an initial setting time test on cement pastes made by combining different amounts of total dissolved solids (TDS) in each of the four types of water, namely, potable water, harvested rainwater, stormwater, and borehole water, are shown in (Fig. 4). As the TDS concentration increased, the cement set more rapidly. There are two known contributing elements to this phenomenon. First, as [31] ,[32], [33],[34],[35],[36],[37] noted, the cement's hydration reaction was speed up by the presence of chloride in the TDS. Second, by reducing their initial proximity, more solid particles were able to strengthen the contact between cement grains. Additionally, the results indicate that the addition of potable water, harvested rainwater, stormwater, and borehole water to ordinary Portland cement (OPC) mortars during mixing and curing resulted in a minor 1–2% improvement in the 7-day compressive strength (refer to Table 3). Regarding the influence of various water-to-cement ratios (w/c) such as 0.45, 0.5, and 0.55, respectively, it was observed that increasing the w/c ratio tends to decrease the compressive strength of concrete.

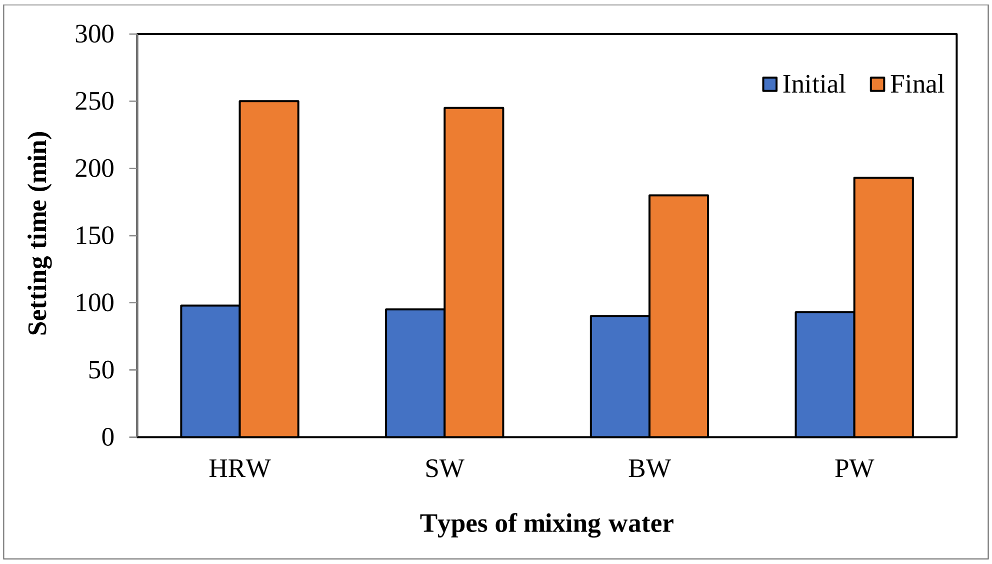

Fig. 4: Setting times for cement paste in various types of water mixes.

Compressive Strength of Mortar

Table 3 presents the maximum compressive strengths (in MPa) of mortar samples cured for different durations (7 days, 28 days, and 90 days) using various types of mixing waters: Harvested Rainwater (HRW), Stormwater (SW), Borewell Water (BW), and Potable Water (PW). Finally, after 90 days, the strengths further improve to 45 MPa for HRW, 49 MPa for SW, 48 MPa for BW, and 47 MPa for PW. This data indicates that over time, all types of mixing waters lead to increased compressive strengths, with Stormwater consistently showing the highest values across all curing periods. Borewell Water and Potable Water also demonstrate competitive performance, while Harvested Rainwater generally lags slightly behind but still achieves substantial strength gains.

Table 3: Compressive Strength of Mortar.

Max. Compressive Strength (MPa)				
Age (days)	Types of mixing Waters			
	HRW	SW	BW	PW
7	32	35	34	32
28	41	46	45	44
90	45	49	48	47

Workability test

Fig. 6 displays the slump test findings, which range in value from 78 to 128 mm. It was found that adding stormwater to concrete during mixing increased the slump due to its special properties.[38],[39],[40],[41],[42],[43],[44],[45],[46],[47] Previous research by revealed that slumping was impacted by the presence of solid particles in mixed water, most likely because higher water content elevated the slump of the concrete. When comparing mixes with potable water to those with harvested rainwater, stormwater, and bore well water, their investigation revealed slight variation. Increasing the (w/c) ratio increases the slump in concrete.

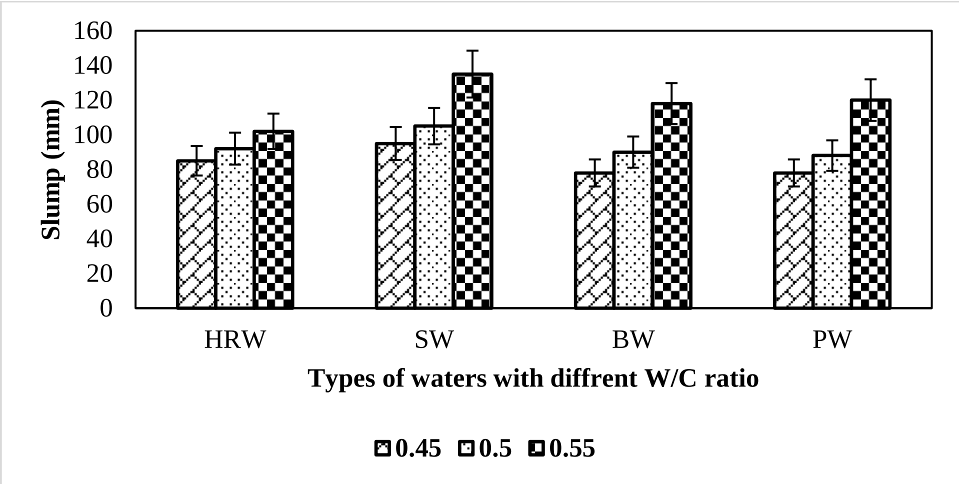

Fig. 6 Fresh property results for concrete

Compressive strength of Concrete

The compressive strength values at 7, 28, and 90 days for samples that were manufactured and cured with cement contents of 427, 384, and 350 kg/m^3 without the super plasticizer are displayed in Figure 7. The samples were made and cured using potable water, harvested rainfall, stormwater, and borehole water. The compressive strength of the cubes for collected rainwater, stormwater, and borehole water at the 28-day mark was greater than that for potable water. The differing physical and chemical features of stormwater and borehole well water, such as the presence of particulates, chloride ions, organic matter, and tiny particles, are responsible for the stronger concrete. These components are important contributors that can boost concrete strength by reducing voids[48],[49] closing concrete matrix cracks, and improving strength properties. When comparing samples of potable water to stormwater, harvested rainwater, and borehole water samples with varying W/C ratios of 0.45, 0.5, and 0.55, respectively, the compressive strength decreased as the W/C ratio increased.

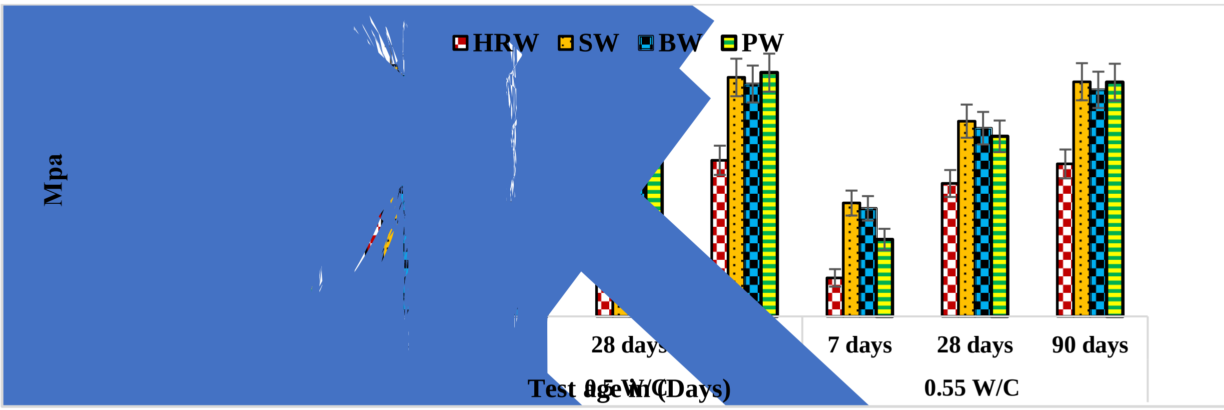

Fig. 7. Compressive strength for different W/C ratios of concrete

Split Tensile Strength

The results showed that the split tensile strength of the M30 grade concrete ranged from 3.75 to 4.20 MPa for the different types of water. Concrete produced with stormwater had the maximum strength (4.20 MPa), whereas concrete formed with harvested rainwater had the lowest strength (3.75 MPa). The suitability of water can be examined with performance tests such as split tensile strength tests. Comparable outcomes with different water-to-cement ratios (0.45, 0.5, and 0.55) were obtained for the seven-day concrete samples using potable water, harvested rainwater, stormwater, and borehole well water. The following strengths in MPa were recorded: bore well water (2.93, 2.78, 2.68), harvested rainwater (2.88, 2.61, 2.42), stormwater (2.96, 2.87, 2.76), and potable water (2.89, 2.53, 2.64). As the water-to-cement ratio increased, the split tensile strength of every sample decreased.

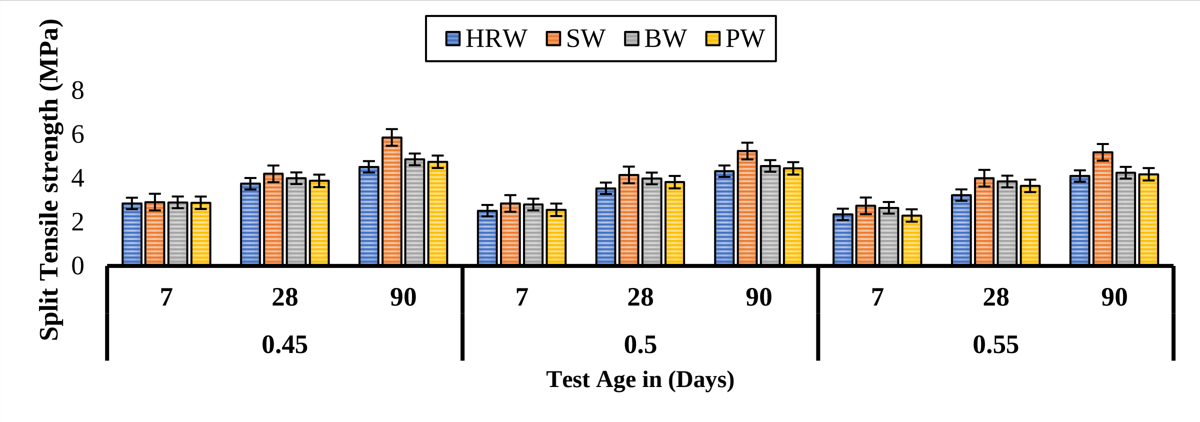

Fig. 8 Split tensile strength for different W/C ratios of concrete

Flexural strength

The flexural strength of concrete grade M30, as assessed by the study stormwater, harvested rainwater, potable water, and borehole water, varied from 4.37 to 6.98 MPa (Fig. 9). The harvested rainwater concrete mix had the lowest value (4.37 MPa), while the stormwater concrete mix had the highest value (6.98 MPa). Due to the slow hydration of cement, the layer that divides the cement matrix from the aggregates increases, known as the interfacial transition zone (ITZ). Flexural strength tests can be used to assess the suitability of water. When potable water, stormwater, harvested rainwater, and borehole water were compared, the results were remarkably similar. Like for flexural strength, for every sample, the water-to-cement (W/C) ratio decreased as it increased. This is explained by the fact that the suspended particles in stormwater weakened and struck the ITZ layer that sits between the aggregates and the cement matrix. [50].

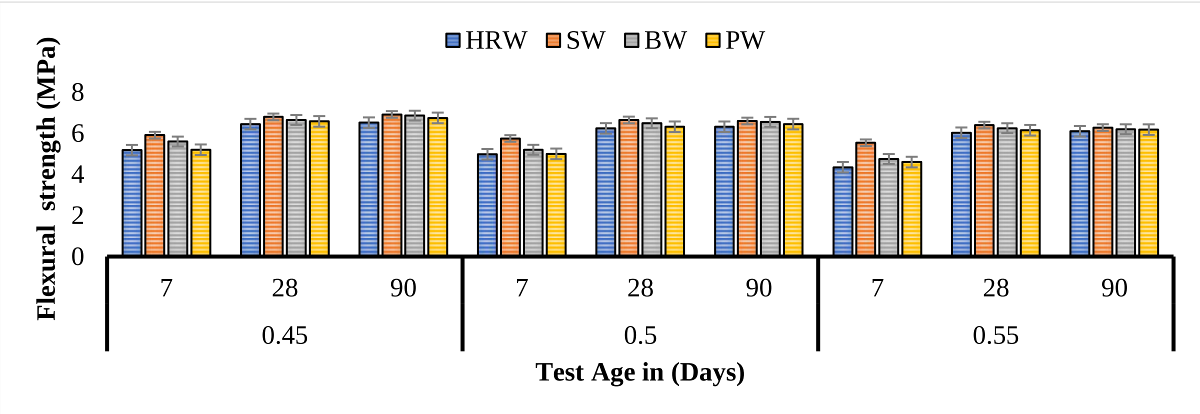

Fig. 9. Flexural strength for different W/C ratios of concrete

Statistical Analysis of Mechanical Properties

To study the individual effects of cement content, water type, curing age and their interaction effects on compressive strength, factorial ANOVA was performed, and the results in Table 4 indicate that the main effects of cement content, water type, and curing age were highly significant on the compressive strength, with F values of 63.728**, 81.473**, and 315.786**, respectively (P<0.001). Additionally, two-factor interactions, such as C × W, C × D and W × D, and three-factor interactions, C × W × D, were also found to be significant, with F values of 4.165**, 2.957*, 3.176**, and 2.374**, respectively. Since all the factors were found to significantly impact the compressive strength, post hoc tests were subsequently performed to assess the pairwise comparisons of the different levels of each factor, and the results are presented in Table 5. These findings indicate that three levels of cement (C1, C2, and C3), four levels of water (W1, W2, W3, and W4), and four levels of curing days (D1, D2, D3, and D4) were significant since the mean difference between any two levels of each factor was less than the CD value. Subsequently, all the levels of each factor significantly differ from one another. Similarly, the interaction also showed a significant difference.

Table 4. One-way ANOVA results

Source of variation	df	Mean square	F	P value
Cement Content (C)	2	225.973	63.728**	0.0000
Water Type (W)	3	288.893	81.473**	0.0000
Curing Day's (D)	3	1,828.91	515.786**	0.0000
Interaction of C x W	6	14.769	4.165**	0.0009
Interaction of C x D	6	10.484	2.957*	0.0108
Interaction of W x D	9	11.26	3.176**	0.0021
Interaction of C x W x D	18	8.417	2.374**	0.0037
Error	96	3.546		

** &* : Significant at 1% and 5% respectively

Table. 5. Post hoc test for pair-wise comparison of treatment and their levels

Factor	Levels	Mean Value	CD	SE(m)
Cement Content	C1	36.47	0.763	0.384
	C2	33.96		
	C3	32.15		
Water Type	W1	30.36	0.881	0.444
	W2	36.92		
	W3	35.57		
	W4	33.93		
Curing Day's	D1	24.32	0.881	0.444
	D2	34.18		
	D3	37.43		

	D4	40.85		
Interaction of C x W			1.526	0.544
Interaction of C x D			1.526	0.544
Interaction of W x D			1.762	0.628
Interaction of C x W x D			3.052	1.087

3.4 Durability properties of concrete

3.4.1 Rapid chloride penetration test

The results shown in Figure 10 represent chloride permeability tests, including the charges that passed and the related grades of chloride permeability for each concrete mixture. The concrete mixture made from harvested rainwater had a value of 752.4 Coulombs, which is classified as very low by ASTM C1202. However, higher concentrations of total dissolved solids (TDS) increased the chloride permeability of combinations of potable water, stormwater, and borehole water by 799.6, 1325.5, and 1812.4, respectively. This indicates that because chloride ions in concrete have a higher conductivity at higher TDS concentrations, the presence of TDS in mixing water has a considerable negative impact on the resistance to chloride permeability. This implies that concrete became more resistant to the ingress of chloride ions as it hardened. This can be explained by an increase in the amount of calcium silicate hydrate (CSH) that filled the pores of the concrete as a result of the cement hydration process being more complete. Because of its higher conductivity and higher concentration of chloride ions, stormwater concrete demonstrated increased chloride permeability at 90 days. These findings are consistent with those of [51],[52],[53],[54],[55], who reported that at 90 days, freshwater and treated wastewater had "very low permeability" and "low permeability," respectively, regarding their chloride permeability.

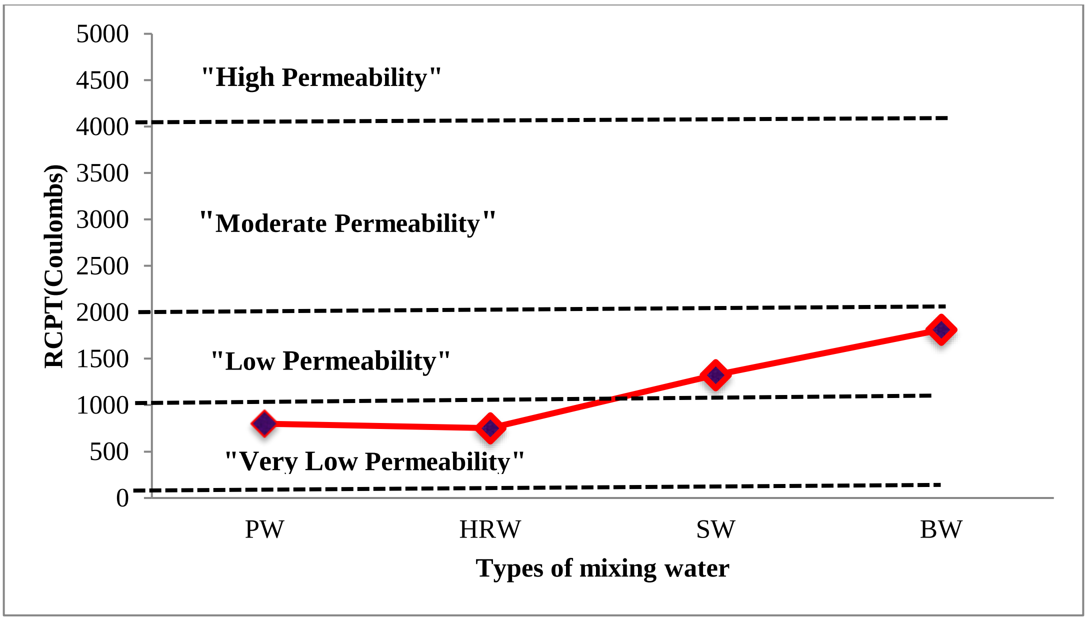

Fig. 10. RCPT for different types of mixing concrete

3.4.2. Chloride content test

The Nord test technique for determining the chloride ion content in hardened concrete, NT BUILD 208, was used to determine the chloride ion content of the concrete using the Volhard method. Chloride ion concentration tests were carried out on potable water, stormwater, harvested rainfall, and borehole water after 90 and 150 days. The method aims to quantify the total chloride ions present in the concrete sample. Figure 11 shows that all the formulations demonstrated chloride contents at relatively low levels. Although the literature does not provide a specific threshold for the amount of chloride in concrete, research results generally suggest a crucial value between 0.20% and an average maximum, as proposed by [56],[54]. As a result, samples with a percentage less than 0.20% in any combination are thought to have a comparatively low chance of steel corrosion.

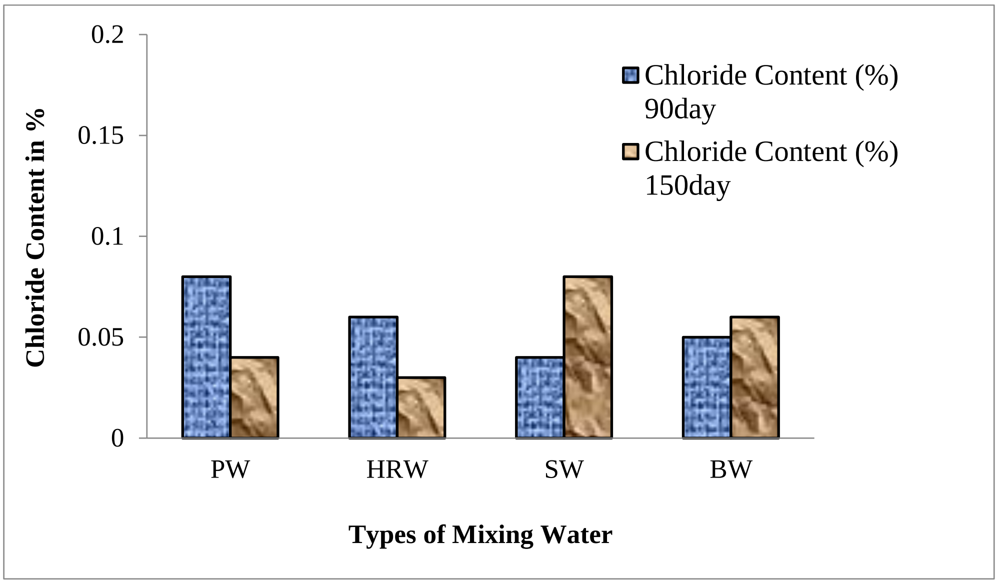

Fig. 11. Chloride content [Nord test] for the different water mixes.

Physical Sulphate Attack on Concrete

The figure presents the mass losses (in grams) due to physical sulfate attacks for different water sources over various cycles (days) and different water-to-cement ratios of 0.45.

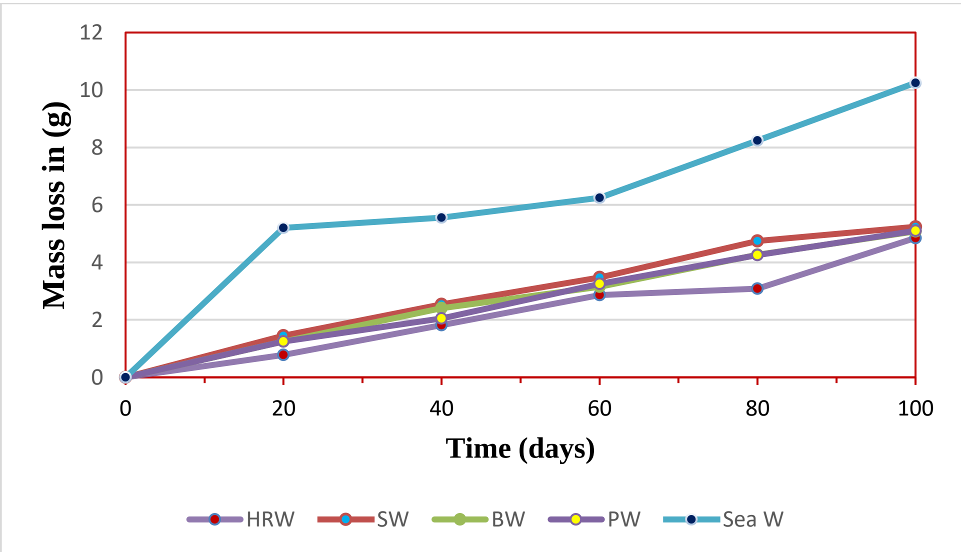

Fig.8. Mass loss of partially submerged in 10 % sodium sulfate solution

Concrete samples exposed to sulfate attack showed increasing mass loss with cycle duration, indicating susceptibility over time. Storm Water exhibited significant and rapid mass loss, followed by Borewell Water, Potable Water, and Harvested Rain Water, with Sea Water experiencing the highest mass loss, suggesting severe deterioration. A sulfate attack is a chemical reaction where sulfates present in the environment react with components of concrete, leading to deterioration and loss of mass over time. After 20 days of sulfate attack, the HRW concrete sample lost 0.78 grams, while the SW sample lost 1.45 grams, the BW sample lost 1.25 grams, the PW sample lost 1.25 grams, and the Sea W sample lost 5.2 grams. After 100 days of sulfate attack, the mass loss increased for all samples. For instance, the HRW sample lost 4.85 grams, the SW sample lost 5.24 grams, the BW sample lost 5.08 grams, the PW sample lost 5.1 grams, and the Sea W sample lost 10.25 grams. These values indicate the extent of degradation experienced by each type of concrete due to sulfate attack over time.

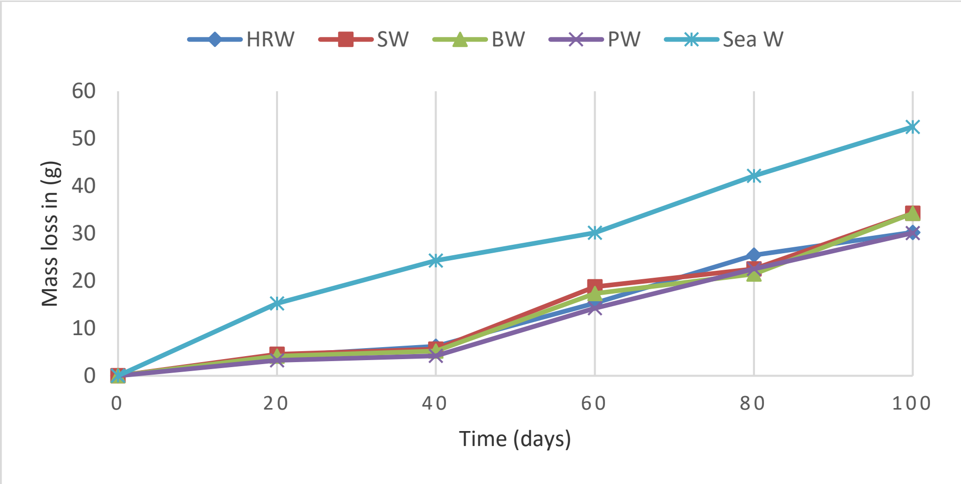

Fig.9. Mass loss of fully submerged in 30 % sodium sulfate solution

Sea Water concrete samples showed higher mass loss due to its elevated sulfate ion content, accelerating sulfate attack and concrete degradation. Additionally, chloride ions in Sea Water contribute to the corrosion of reinforcing steel (Lu et al., 2018), further exacerbating deterioration. Stormwater, carrying pollutants like heavy metals and organic compounds, can lead to accelerated degradation and increased mass loss compared to other water types due to its varied chemical composition and aggressive ion concentrations like sulfates, chlorides, and carbonates.

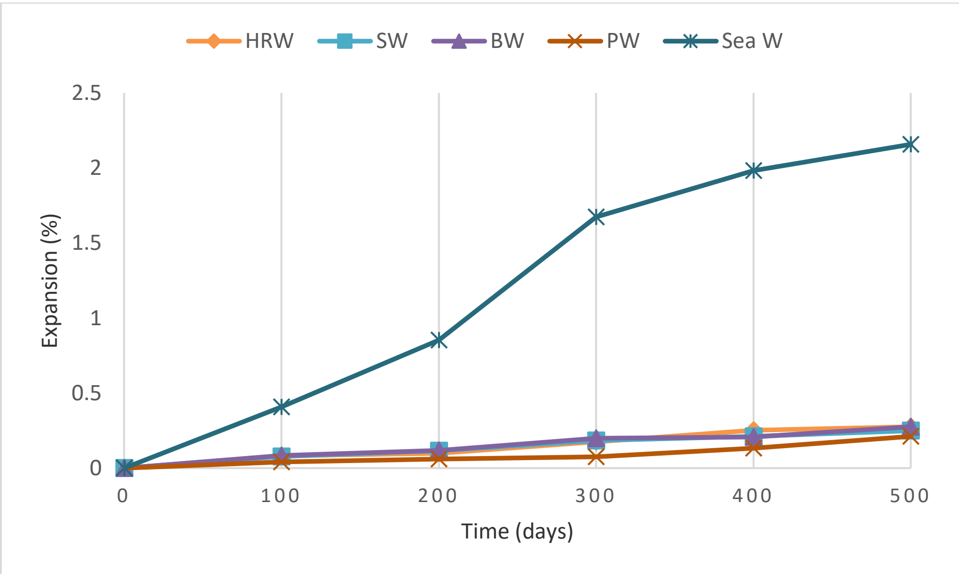

Fig.10. Expansion of partially submerged in 10 % sodium sulfate solution

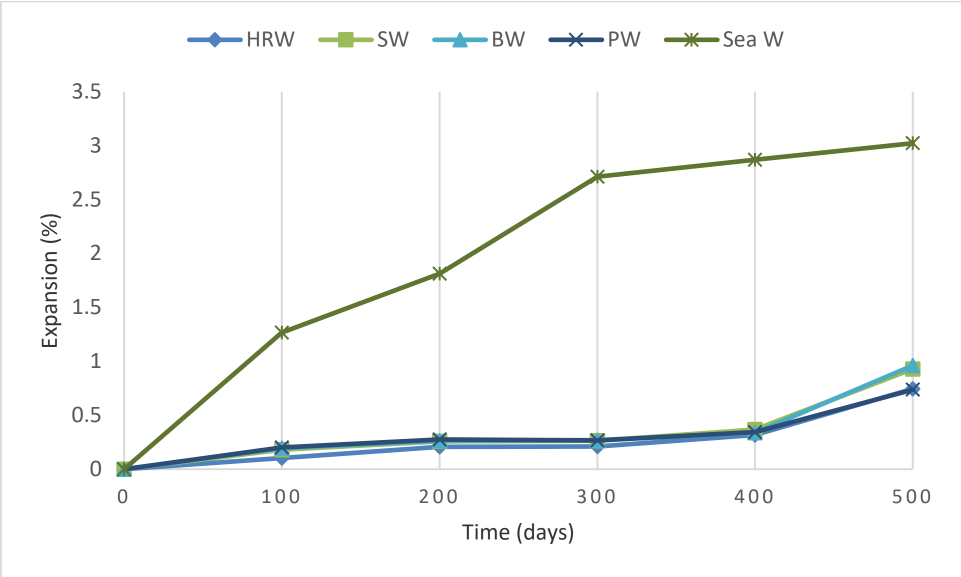

Fig.11. Expansion of fully submerged in 30 % sodium sulfate solution

The figure demonstrates the expansion (%) of concrete specimens exposed to sulfate attack across various water sources and cycles. Concrete subjected to Harvested Rainwater (HRW) shows increasing expansion (%) over time, indicating susceptibility to sulfate attack. Stormwater (SW) and Borewell Water (BW) concrete exhibit significant expansion (%) throughout the cycles, suggesting sustained vulnerability to sulfate exposure. Potable Water (PW) concrete also shows increasing expansion (%) with longer exposure durations, indicating potential deterioration. Sea Water (Sea W) concrete displays the highest expansion (%) among all water sources, escalating rapidly with the number of cycles, highlighting severe concrete degradation due to sulfate attack. These findings underscore the varying impacts of water sources on concrete durability under sulfate exposure, with Sea W demonstrating the most detrimental effects followed by SW, BW, PW, and HRW.

3.4.3. Microstructural analysis

Fig. 12-14 shows the SEM images of all concrete mixtures following a 28-day curing period. It was noted that harvested rainwater concrete examples showed more homogenous surface texture and densified microstructure than their counterparts with PW, irrespective of the addition utilized. As can be shown in Figs. 12 and 13, mix PW concrete mixes showed a faster rate of hydration for potable water specimens than SW concrete mixes. Portlandite is a result of cement hydration. Additionally, it is possible to observe that the addition of PW and SW to mixtures has steadily increased the black-colored concrete pores, the white-colored anhydrous cement, and the surface cracks. This is mainly because the ITZ layer between the cement and aggregates was alerted by the dissolved oxygen and suspended solid particles in the SW. The any alter in the mechanical and durability characteristics of the PW and SW concrete specimens that were previously displayed may be explained by these findings. On the other hand, Fig. 12 potable water concrete examples had an excessive amount of ettringite needle formation, which resulted in an increase in pores. This resulted from the sulfate present in PW reacting with C_3A and ettringite to form monosulphoaluminate hydrate. The microstructure of the concrete produced by SW specimens was densified, and there were less voids. Using EDX microanalysis, chemical characterizations of every concrete mix were acquired.

Comparing the HRW and SW concrete specimens to the reference concrete PW, as illustrated in Fig. 15, no new chemical element production was observed. The findings do, however, show that the calcium intensity in mixes HRW and SW was significantly lower than in mixes PW. Moreover, compared to their mixes of HRW and PW, silica was discovered in larger quantities in blends SW. This is explained by the ettringite needles that formed and ate the gypsum (or CSH). On the other hand, mix PW and SW had larger silica and calcium contents than mix

HRW, as shown in Fig. 12–13, because of the synthesis of calcium monosulphoaluminate hydrate (C_4ASH_{12}).[57],[58],[59],[60],[61].

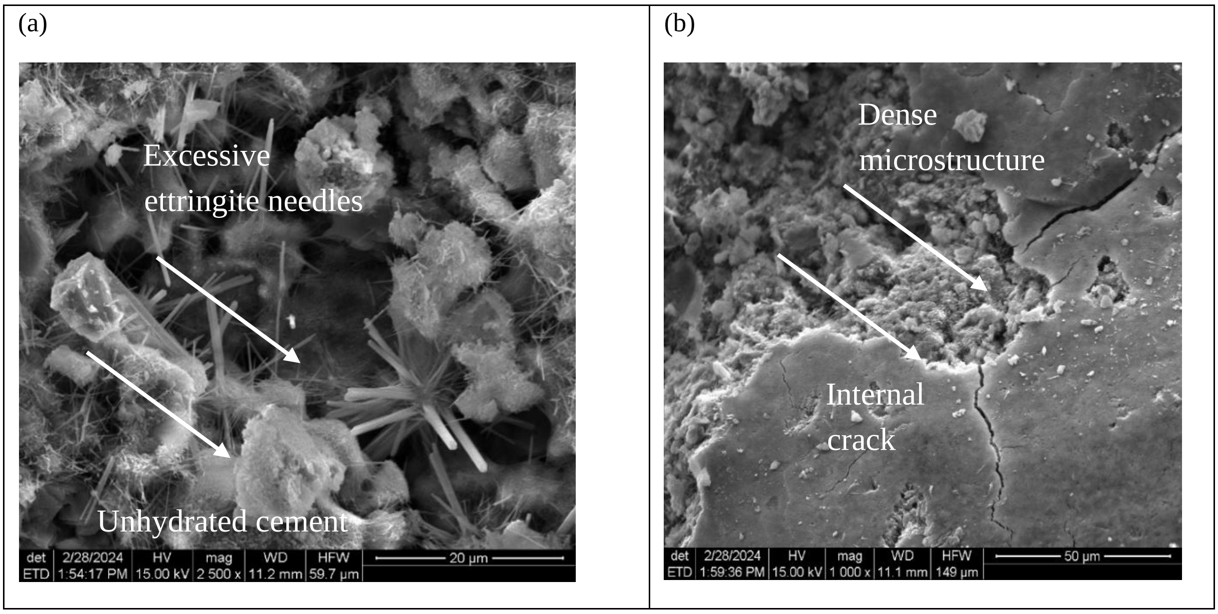

Fig. 12. (a) & (b) Potable water SEM images.

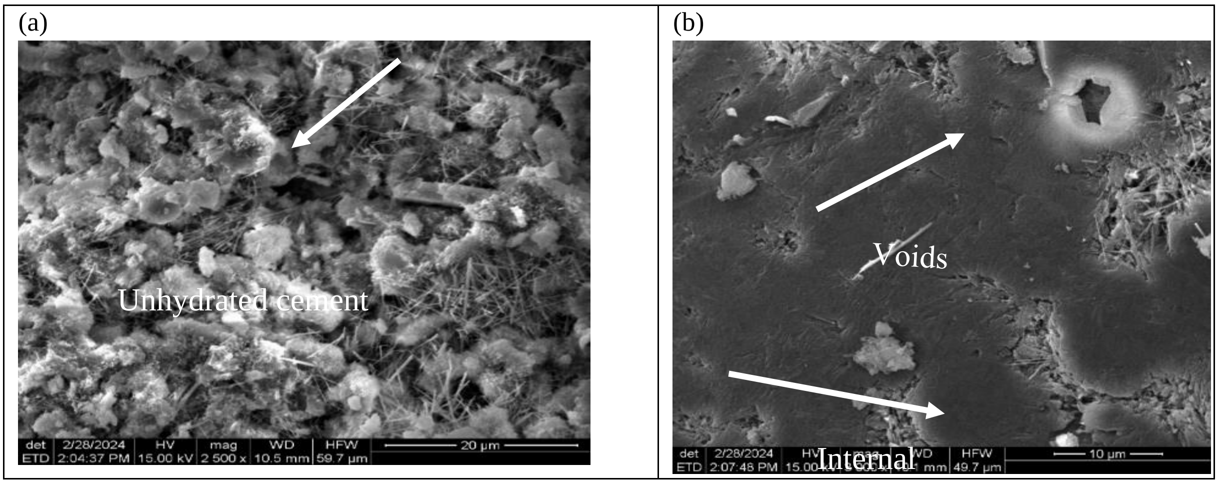

Fig. 13. (a) & (b) Storm water SEM images

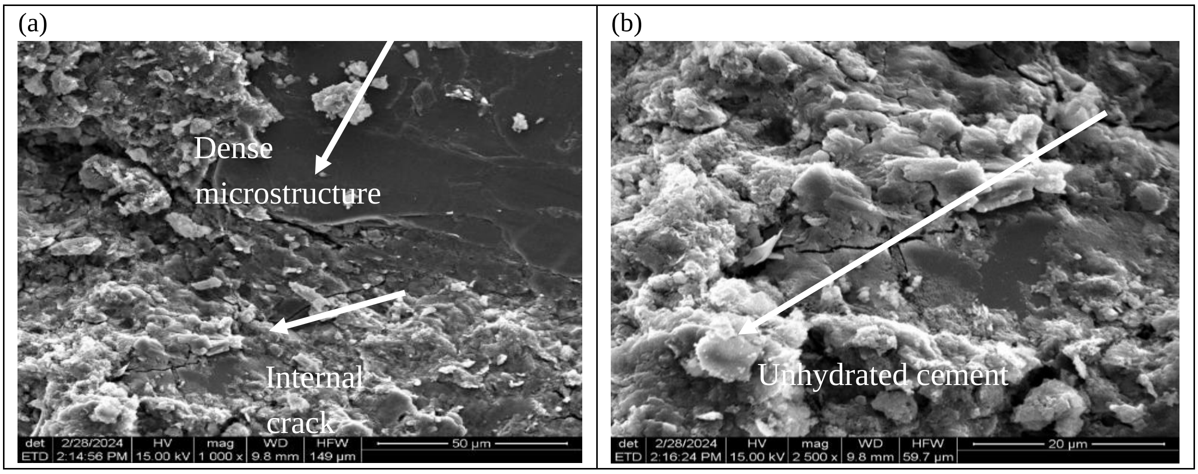

Fig.14. (a) & (b) Harvested rain water SEM images

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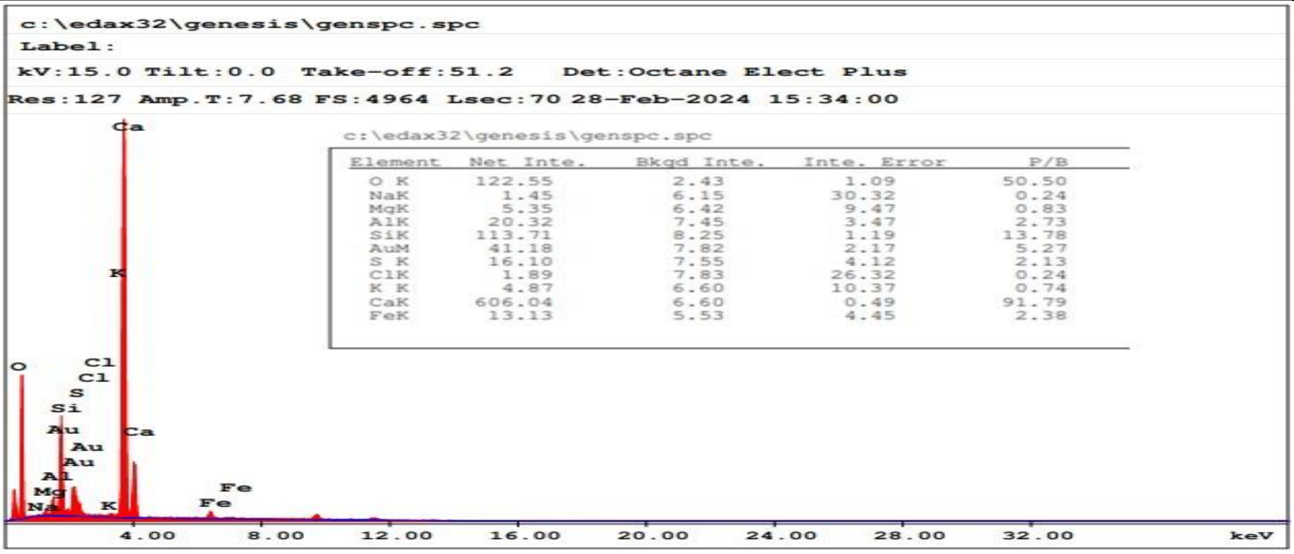
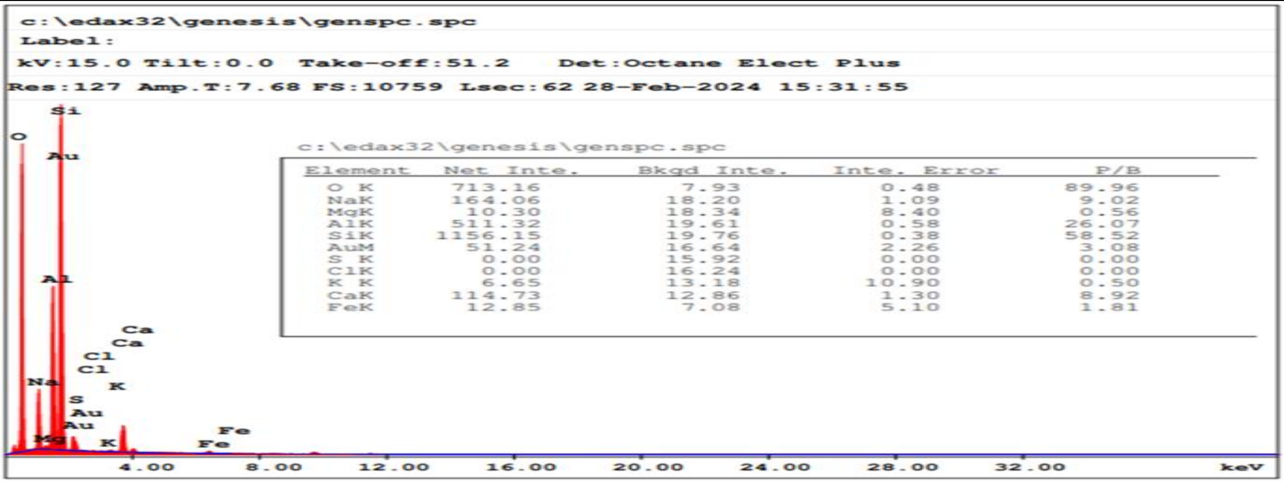
Potable water Sample



Storm water Sample



Harvested Rainwater Sample

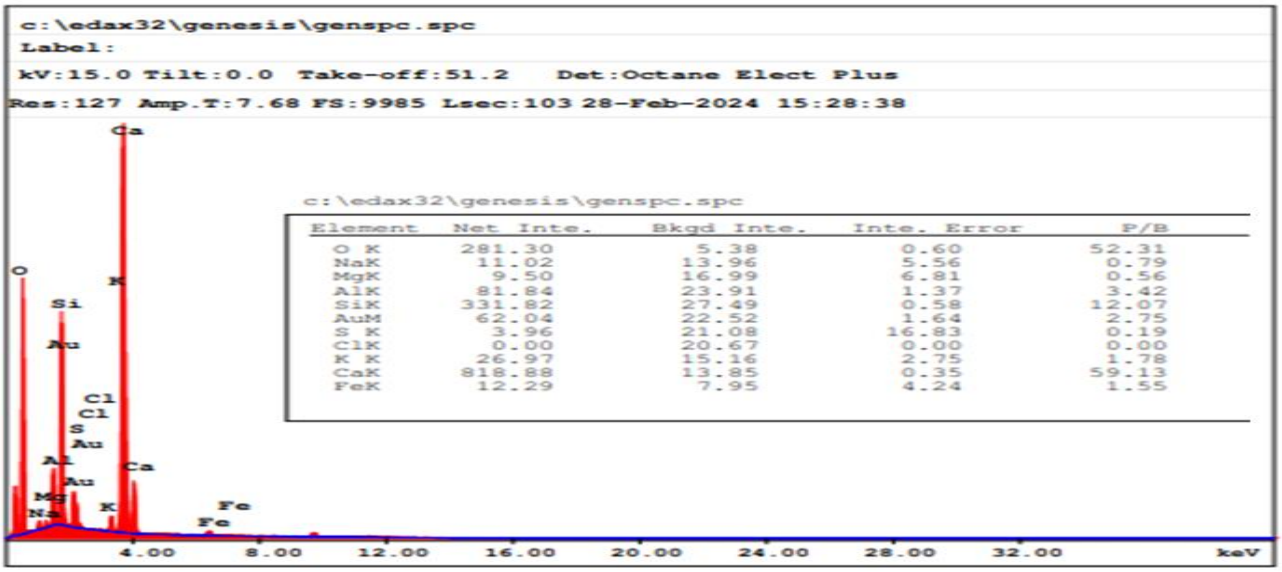


Fig.15. EDX microanalysis results for PW, SW and HRW.

4. Conclusions

In summary, the following conclusions are drawn from the experimental setups employed in this investigation.

- Based on pertinent concrete mixing criteria, the study's findings indicate that the physical and chemical properties of potable water, harvested rainwater, stormwater, and borehole well water are all within acceptable ranges. This highlights how crucial it is to ensure that water sources are as pure as possible.
- Freshly mixed concrete, which included potable water, harvested rainwater, stormwater and borehole water, was found to have a notably satisfactory and reasonable setting time and workability. Slumps have been found to be impacted by the presence of solid particles in stormwater used to mix concrete.
- Compared to potable water, concrete constructed with stormwater and borehole water exhibited better strength (compressive, split tensile, and flexural). Remarkably, stormwater concrete showed surprisingly better strength than potable concrete, indicating that stormwater might be used to mix concrete and lessen the need for freshwater.
- The results of the rapid chloride penetration test (RCPT), an indirect testing method, showed that the levels of chloride ion permeability in all combinations were extremely low to minimal. The chloride content of all the water mixtures, according to the direct Volhard test method, was within allowable limits.
- Stormwater and borewell water were susceptible to sulfate attack, with seawater exhibiting the highest vulnerability. Harvested rainwater and stormwater also showed denser microstructures compared to potable water. Before drawing firm conclusions regarding the endurance of these blends, it is important to take into account a variety of durability tests.
- In the context of megacity development, harvested rainfall and stormwater are emerging as feasible alternatives for the utilization of water resources. Guidelines covering physiological, chemical, economic, and environmental concerns are provided by Indian standards for the reuse of several types of water sources.

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Here's a general outline of the procedure for measuring the corrosion potential of concrete using a half-cell potential meter, as per ASTM C876/C876M-15:

Ensure the concrete surface is clean and free from any coatings or contaminants that could affect measurements.

Verify that the half-cell potential meter is calibrated and functioning correctly.

Measurement Points:

Identify and mark measurement points on the concrete surface where corrosion potential measurements will be taken.

Typically, these points are along reinforcing bars (rebar) or other embedded metals.

Half-Cell Potential Measurement:

Place the reference electrode (often a copper/copper sulfate electrode) firmly on the concrete surface at a distance from the reinforcing steel.

Connect the reference electrode to the half-cell potential meter.

Electrode Placement:

Position the half-cell potential meter probe near the reference electrode, maintaining consistent contact with the concrete surface.

Measurement:

Take readings at each marked point on the concrete surface.

Record the half-cell potential measurements as mV (millivolts) relative to the reference electrode.

Interpretation:

Higher (more positive) potentials generally indicate a lower risk of corrosion, while lower (more negative) potentials may suggest an active corrosion environment.

Compare measured potentials against established criteria or guidelines for corrosion risk assessment.

Reporting:

Document all measurement points, readings, and any relevant environmental conditions (e.g., moisture content, temperature).

Report results according to ASTM C876/C876M-15 requirements, including any deviations from standard procedures.

For precise details and adherence to ASTM standards, always consult the full text of ASTM C876/C876M-15 or its latest version, as it provides specific instructions and considerations necessary for accurate corrosion potential assessment in concrete structures.