

Feasibility Studies of Using Harvested Rainwater in Concrete Mixtures

Fatin Noorazlinda Binti Ali¹, Hazrina Binti Ahmad^{1*}, Jalina Binti Kassim¹, Mohd Hisbany Mohd Hashim¹

¹ Faculty of Civil Engineering, University Teknologi Mara, 40450 Shah Alam, Malaysia

*Corresponding author Email address: hazrina180@uitm.edu.my

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Abstract

This study investigates the mechanical performance of concrete mixed with harvested rainwater collected at the Civil Engineering Laboratory, Universiti Teknologi MARA (UiTM) Shah Alam. In consonance with practices towards sustainable construction and efficient utilisation of water resources, this study aims to assess the suitability of harvested rainwater as an alternative source of mixing water for concrete production. The objectives of this study are to determine the chemical properties of the harvested rainwater, to evaluate the effects of harvested rainwater on the mechanical properties of concrete and to determine the optimum harvested rainwater content for sustainable concrete mixing. The water quality testing was carried out through measurement of pH, total dissolved solids (TDS), sulphate, and chloride in accordance with BS EN 1008:2002. Three water sample mixes were prepared for the concrete mix: 100% tap-water, 100% rainwater, and 50% tap-water mixed with 50% rainwater. Grade M30 concrete was produced and tested for workability by a slump test and for mechanical properties by compressive and flexural strength tests at 7, 14, and 28 days of curing. On the basis of this study, it can be concluded that harvested rainwater is a potential, sustainable and dependable alternative source of water for concrete production, and its utilisation could contribute towards environmental protection and sustainable development of the Malaysian construction sector.

Keywords: rainwater harvesting system, water quality testing, compressive strength, and flexural strength

1 Introduction

Concrete is a building material that is frequently utilised in the fields of civil engineering, including roads, hydraulics, and building construction (Siregar et al., 2023). One of the most popular building materials in the world is concrete and water is essential to its production. Water is essential for cement hydration, and its chemical properties may influence the performance of concrete. Therefore, the suitability of harvested rainwater depends on its physicochemical properties, such as pH, TDS, sulphate and chloride content. In this study, the suitability of harvested rainwater was evaluated through water-quality, slump, compressive strength and flexural strength tests. However, cement hydration and drying shrinkage were not directly measured; therefore, their effects are not specifically evaluated in this study. According to Shivashankara & Vidya (2024), each cubic meter of concrete requires 150 – 210 litres of water per year, with a total water mix amounting to one billion tons. According to BS EN 1008:2002, in Malaysia, the water used in concrete production that is considered suitable is reused water, and it must meet certain quality requirements. Concrete is used extensively in civil engineering projects and is a composite building material composed of water, cement, fine and coarse aggregates, and sometimes additional components known as admixtures (Mohe et al., 2022).

According to Mbuh et al. (2024), it is utilised in nearly every aspect of civil engineering, such as building beams and pillars, slabs for bridges, pavements for rigid pavements, retaining walls, etc. In addition to its availability, relative cost-effectiveness, flexibility in forming into the necessary shape, comparatively cheap labour costs, and resistance to corrosion and fire, concrete is by far the strongest, durable, and reliable building material. Rainwater is cost-effective since its impurities have lower concentrations and naturally occur in large quantities. Rainwater usually has a pH level of 5.0 to 6.5, making it acidic and soft. Low mineral content and total dissolved solids (TDS) may be beneficial when the relevant water-quality parameters are satisfied, but the effect on cement hydration is a concern since it results in mild acidity (Mbuh et al., 2024). Previous research indicates that, if chemical rainwater composition is within acceptable parameters, rainwater can still be utilised. According to MS EN 1008:2002, the impurities in concrete water must not cause corrosion of reinforcement steel or have an adverse effect on the concrete's strength, setting time, or long-term durability. Concrete produced using rainwater must align with sustainable construction methods that can reduce the need for treated water, save money, and conserve freshwater resources.

To ensure that the performance of the structure is not compromised, the quality of rainwater and the mechanical properties of concrete, such as setting time, durability, and compressive strength, must be considered. The rainwater harvesting (RWH) system can be used to store and collect rainwater from other catchment areas or rooftops for other activities that cannot use it as drinking water, such as construction, and can also be used as a concrete mix. According to Musa et al. (2017), the purpose of rainwater harvesting is to collect and reuse rainwater, thereby conserving public water supplies and meeting the demand for water in times of scarcity. It also aims to reduce the occurrence and risk of flash flood incidents. The results should provide insight into whether rainwater can be employed as a sustainable alternative to potable water in Malaysia's construction industry.

A significant amount of freshwater is used each year to make concrete, and a large quantity of water is required to mix concrete. Martinez et al. (2024) estimate that concrete production alone requires more than 825 billion litres of water each year. Malaysia demands huge amounts of concrete, especially in areas where rapid urbanisation is taking place, which works to render this set of circumstances even more urgent (Siregar et al., 2023). Besides, the issue of water management has been compounded by the increased frequency of heavy rainfall and storms. The high rate of rainfall in Malaysia is due to the long rainy season, leading to frequent flooding; for beneficial purposes, it can be recycled effectively, e.g., for mixing concrete. Martinez et al. (2024) state that during the rainy season, most of the water becomes runoff, which is mostly not well utilised. In this country, the occurrence of rain is often closely related to flooding events, which can increase public concern. Floods have occurred in several states in Malaysia, including Johor and Pahang, due to prolonged heavy rainfall. According to many media reports, many areas in Malaysia often experience flash floods due to heavy thunderstorms, including Shah Alam and the Klang Valley.

Furthermore, the demand for the availability of alternative water sources and fresh water is increasing. Using drinking water to mix concrete in the construction industry is environmentally inefficient and unsustainable. For concrete production, there is an urgent need to investigate sustainable and alternative water sources because freshwater supplies are becoming increasingly limited. One alternative is to use harvested rainwater and surface runoff water instead of drinking water during concrete mixing. Existing research shows that in concrete production, rainwater can be used even though it has a slightly acidic pH without significantly affecting the material's strength, which is between 5.2 and 6.5 (Siregar et al., 2023). There are two benefits of using rainwater, including its ability to reduce flooding by redirecting all runoff water and lowering the demand for drinking water (Martinez et al., 2024).

Additionally, the feasibility of using collected rainfall from rooftops and stormwater systems has been investigated, demonstrating that such systems might greatly reduce the dependence on conventional water sources. This strategy can help achieve water and environmental conservation targets while ensuring more environmentally friendly construction practices (Siregar et al., 2023). This strategy helps Malaysia manage its water resources more efficiently by reducing urban flooding, supporting water sustainability, and promoting environmentally friendly construction practices. In concrete production, the use of rainwater not only aligns with Malaysia's national water sustainability goals but also enhances overall resilience to climate variability by reducing the risk of urban flooding caused by heavy rainfall. In conclusion, mixing concrete with rainwater and stormwater is a feasible, sustainable way to deal with the dual issues of flooding and water scarcity. Concrete is a durable and necessary building material and promoting the use of such practices can help the construction industry's environmental impact be greatly reduced (Siregar et al., 2023).

This study aims to determine the physicochemical properties of the harvested rainwater, to evaluate the effects of harvested rainwater on the mechanical properties of concrete and to determine the optimum harvested rainwater content for sustainable concrete mixing. For this research, rainwater was collected from the catchment system at the Concrete Laboratory, UiTM Shah Alam, in a clean portable rainwater barrel, and the potential of rainwater for use in concrete mix base is determined by comparing physical (total dissolved solids) and chemical (pH, sulphate, and chloride) characteristics. To make concrete samples, M30 grade concrete was used for 28 days of curing. The concrete was mixed with varying proportions of water to study the impact of rainwater on the concrete properties. Three water mixtures were used: Sample A with 100% tap-water, Sample B with 100% rainwater, and Sample C with 50% rainwater and 50% tap-water. The total number of concrete samples for the three water samples was 36. For each water sample, 12 samples of concrete were tested in the laboratory. These include 9 samples for the compressive strength test, and 3 samples for the flexural strength test. After the concrete mix was prepared, the concrete was poured into cube moulds measuring 150 mm x 150 mm x 150 mm for the compressive strength test, to ensure the uniformity and precision of samples. For the flexural strength test, prism moulds measuring 100 mm x 100 mm x 500 mm were used. This research is conducted using a consistent mix design in a controlled laboratory environment and is limited to M30-grade concrete. After 7, 14, and 28 days of curing, the samples were tested for their mechanical properties. The applicability of the results to other water mixtures or concrete proportions was limited because only three water-sample categories were investigated. It focuses on assessing concrete's mechanical properties including slump tests (workability), compressive strength tests and flexural strength tests at 7, 14 and 28 days. A comprehensive understanding of the concrete's mechanical performance is provided by these tests.

2 Literature Reviews

2.1 Harvested Rainwater Properties

Rainwater harvesting is the collection of rainwater from roof catchment areas that is harvested during rainfall (Musa et al., 2017). According to a study by Bahry et al. (2021), the rainwater harvesting system (RWH) is the best management method applied in Malaysia. This is because of its ability to be a safe and freely available alternative water supply. Physical and chemical analysis of harvested rainwater should be conducted to ensure it does not contain any harmful substances or adversely affect the performance of concrete (Vidya & Shivashankara, 2024). Rainwater harvesting is an excellent way to reduce dependence on urban water infrastructure and fight against environmental problems such as floods and water pollution while cities become more urbanised (Vidya & Shivashankara, 2024).

2.2 Water Quality

2.2.1 pH

Recent research suggests that the pH of harvested rainwater is usually slightly acidic or around neutral but within the safety limits for the production of concrete to have no detrimental effect on the setting and strength of concrete (Vidya & Shivashankara, 2024; Singh et al., 2025). With higher pH values, the processes of concrete maturation can be affected, where pH values below 7.0 indicate an acidic solution (Vidya & Shivashankara, 2024). According to Mohe et al. (2022), the results of the tests conducted on the water source showed that the pH values ranged from 6.4 to 6.75, which is within the pH range of 6.5–8.5 recommended by the WHO, except for rainwater, which has a pH value of 6.4. The alkalinity and pH value of rainwater are low compared with those of the other identified water sources. Water with a high pH gave concrete with an appreciably high strength value, whereas the acidic water showed very low strength values (Mohe et al., 2022).

2.2.2 Total Dissolved Solids (TDS)

The practical quantitation limit for TDS in water by this method is 10 mg/litre (M. Forbes, personal communication, 1988). A study by Elshami (2024) emphasised that water with excessive dissolved solids could interfere with correct hydration, thereby weakening concrete's final strength. A study by Puttaswamaiah & Raju (2024) stated that the total dissolved solids in harvested rainwater are typically low and well within the limits set by standards such as IS 456 (2012) and ASTM C94/C1602. This is essential to prevent harvested rainwater from having a detrimental effect on the setting time and strength of concrete (Vidya & Shivashankara, 2024).

2.2.3 Sulphate

The test evaluates the resistance against internal sulphate attacks and the formation of external sulphates, resulting in the formation of ettringite, thaumasite, and gypsum, causing concrete to crack due to expansion from the interior. According to Elshami (2024), chloride is the most aggressive since its maximum allowable limit is 0.3, and its permissible limit of sulphate is 4.0. Additionally, chloride is the most aggressive since its maximum permissible limit is 0.3, and the allowable limit of sulphate is 4.0%. Concrete is always on the safe side regarding sulphate (Elshami, 2024).

2.2.4 Chloride

AlHarthy et al. (2005) indicate that the higher chloride ion content in mixing water is attributed to the higher early strength of cement concrete. As the concentration of TDS rises, cement sets faster (Vidya & Shivashankara, 2024). Both factors may cause cement to set faster. The hydration process of cement initially advances faster in the presence of chloride as a constituent of TDS (Cheung, 2011). The higher compressive strength of the surface water and BW concrete can be attributed to the varying physical and chemical properties of solids and chloride ions, oils, organic materials, and fine particles, which are key factors that may facilitate the strength of the concrete (Vidya & Shivashankara, 2024).

2.3 Concrete Mix

According to Elshami (2024), different water sources, such as deep well water, rainwater, and river water, can produce concrete mixtures with different ultimate properties. It was noted in the research that although rainwater can be used in the manufacture of concrete, slightly lower compressive strength may be produced than when drinking water is utilised (Elshami, 2023).

2.4 Fresh and Hardened Properties of Concrete

2.4.1 Slump

According to Mbuh et al. (2024), the slump test is used to assess the workability of fresh concrete. Previous studies have reported varying effects of different mixing-water sources on concrete workability. As presented in Table 1, Vidya and Shivashankara (2023) reported slump values of 85, 92, and 102 mm for harvested rainwater at water–cement ratios of 0.45, 0.50, and 0.55, respectively. The increasing slump values indicate that workability increased with increasing water–cement ratio. Similarly, Siregar et al. (2023) reported a slump value of 100 mm for both rainwater and clean-water mixtures. These findings suggest that concrete workability may be influenced by both the water–cement ratio and the characteristics of the mixing water.

Table 1. Slump test results (Vidya & Shivashankara, 2024)

Types of Mixing Water	Water-cement Ratio (%)	Slump (mm)	Compaction factor values
Harvested Rainwater	0.45	85	0.85
	0.5	92	0.88
	0.55	102	0.91
Stormwater	0.45	95	0.92
	0.5	105	0.94
	0.55	135	0.95
Bore well water	0.45	78	0.91
	0.5	90	0.92
	0.55	118	0.94
Potable Water	0.45	78	0.90
	0.5	88	0.92
	0.55	120	0.94

2.4.2 Compressive Strength

The quality of mixing water plays an important role in determining the compressive strength of concrete, as dissolved salts, organic matter, suspended solids, and other impurities may interfere with cement hydration and affect the resulting microstructure. Studies involving alternative water sources have reported that the use of treated wastewater and other non-potable waters can result in lower compressive strength than concrete produced with conventional tap-water, although the magnitude of the effect depends on the characteristics and contamination level of the water (Mahasneh, 2014; Thangamani et al., 2025). Similarly, Ikpa et al. (2021) demonstrated that variations in water quality can influence the compressive strength of concrete, highlighting the importance of assessing the chemical and physical characteristics of mixing water before its use. Figure 1 shows the compressive strength development reported by Siregar et al. (2023) for concrete prepared with rainwater and clean water.

The results show that the rainwater concrete generally achieved comparable compressive strength to the clean-water concrete, particularly at 14 and 28 days. At 28 days, the compressive strength of the rainwater concrete was 17.982 MPa, compared with 21.490 MPa for the clean-water concrete. In contrast, some studies have reported that concrete produced using river, estuary, or other non-potable water sources can achieve compressive strengths comparable to those obtained using freshwater when the water quality is within an acceptable range (Min et al., 2023). These findings suggest that the effect of an alternative water source on concrete strength is governed more by its water quality and contaminant concentration than by whether the water is potable or non-potable.

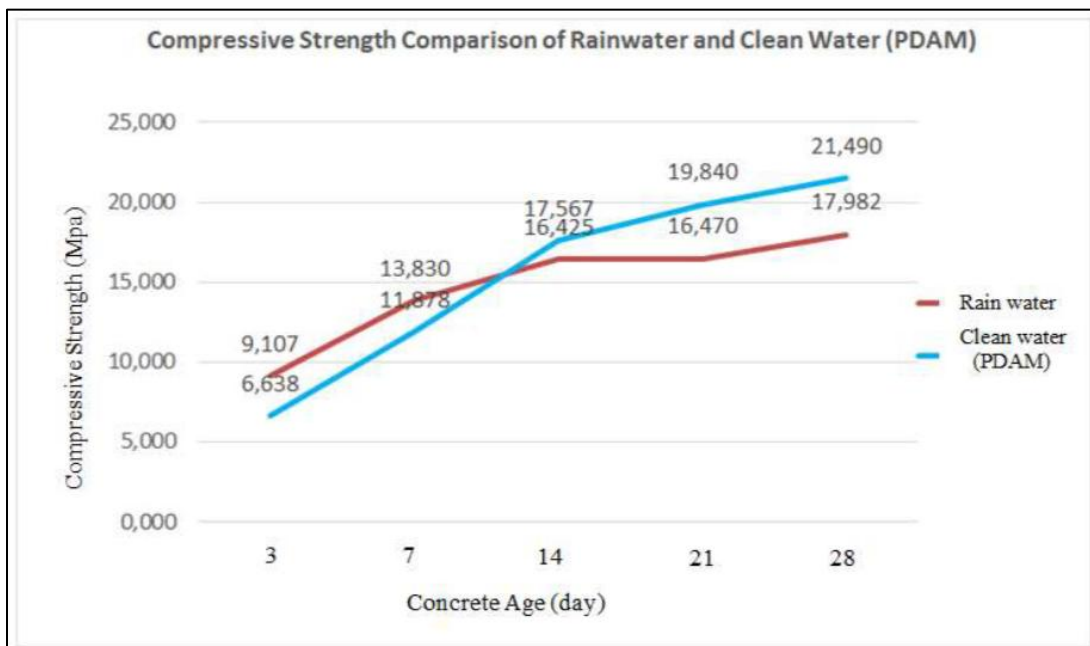


Figure 1. Comparison of compressive strength development of concrete prepared with rainwater and clean water (Siregar et al., 2023)

In the context of harvested rainwater, its relatively low concentration of dissolved minerals and salts may allow it to function as a suitable alternative to potable water for concrete mixing, particularly when the collected water is relatively clean. Nevertheless, the quality of harvested rainwater can vary depending on atmospheric conditions, the collection environment, roof or catchment materials, storage conditions, and the presence of accumulated contaminants. Consequently, contaminated rainwater may adversely affect cement hydration and concrete strength, whereas adequately collected and stored rainwater may produce compressive strength comparable to that of concrete mixed with conventional water. This consideration is consistent with observations from studies using seawater and other alternative water sources, where the influence on compressive strength varies according to the chemical composition of the mixing water and the concrete mixture (Guo et al., 2018; Wegian, 2010; Shi et al., 2015). Therefore, the use of harvested rainwater in concrete should be evaluated based on its physicochemical properties and the resulting mechanical performance rather than assuming that all rainwater will have the same effect on compressive strength.

2.4.3 Flexural Strength

According to Shivashankara & Vidya (2024), the flexural strength of M30 grade concrete incorporating harvested rainwater, surface water, borewell water, and potable water varies from 4.35 to 6.92 MPa. The surface water concrete mixture possessed the highest split tensile strength of 6.92 MPa compared to all other forms of M30 grade concrete mixtures, and the lowest was provided by the harvested rainwater concrete mixture of 4.35 MPa. According to Mohe et al. (2022), the average flexural strength results at curing ages of 7 and 28 days varied among the potable-water control, river-water, deep-well, and rainwater concretes: river water showed variations of 20% and 1.2%, deep well 4.3% and 11.8%, and rainwater 22.7% and 14.5%, respectively, compared with the control. River water, at the curing age of 28 days, shows an improved result in comparison to other identified sources of water.

2.5 Cement Properties

Research by Siregar et al. (2023), found that in concrete mixtures, the use of acidic rainwater (pH 5.8) resulted in very low strength compared to slightly alkaline or neutral water. In cement concrete, the cement used must be carefully selected because if high-quality cement is combined with high-quality water, hydration will be more effective and faster (Mohe et al., 2022).

3 Research Methodology

3.1 Rainwater Collection

Rainwater collection in this study was carried out using a catchment system in a portable rainwater barrel placed in an open area at the Civil Engineering Laboratory, UiTM Shah Alam. This system allows rainwater to flow directly into the portable rainwater barrel when it rains. Filters like plastic mesh have been placed over the barrels to filter out foreign materials and large particles before rainwater enters the portable rainwater tanks. The collected water is used in the study as a substitute for part of the tap-water in the concrete mixing process. The collected water was suitable for concrete work when the catchment area and storage system are clean and uncontaminated. The objective of the storage system is to ensure that the collected rainwater is free from large debris and that the rainwater is ready to be used in concrete mixing. Figure 2 presents the portable rainwater barrel for this study.



Figure 2. Portable rainwater barrel

Three types of water samples were used: 100% tap-water, 100% rainwater, and a 50% tap-water + 50% rainwater mixture. Each sample was collected in a volume of at least 1 litre for chemical, physical and microbiological analyses. All three water samples were collected using clean and labelled polyethylene bottles. All samples were labelled with date, time, location and water type information before being transported to the UiTM Shah Alam Environmental Laboratory. Duplicate samples, field blanks, and laboratory blanks were also provided for quality control (QA/QC).

3.2 Water Quality Analysis

The water quality analysis was conducted to achieve the first objective, which is to determine the physicochemical properties of harvested rainwater. The quality of the collected rainwater should be tested before being used in concrete mixing, as the quality of rainwater needs to be tested to ensure its suitability for construction. The first component tested was pH, which determines the acidity or alkalinity of the water. The pH value was measured using a calibrated glass electrode pH meter. Readings are taken at least twice, and the average value is reported. The next test is Total Dissolved Solids (TDS), which measures the total amount of dissolved solids in water. TDS is measured using a calibrated TDS/conductivity meter. TDS readings were recorded, and TDS values were reported to two decimal places. Readings are taken at least twice, and the average value is reported. Furthermore, the purpose of the sulphate test on water is to assess the content of sulphate ions (SO_4^{2-}) in the water and determine whether the water is safe and suitable for use. The sulphate concentration was analysed using SulfaVer 4 reagent (powder pillow) and a spectrophotometer according to standard laboratory procedures.

Consequently, the content of one SulfaVer 4 reagent powder pillow was added to 10 mL of the sample. This solution should be stirred until the powder dissolves. White turbidity will form if sulphate is present. Allow it to react for 5 minutes. The sulphate concentration reading was then measured using a spectrophotometer (680-sulfate). Duplicate analyses were performed on each sample to ensure accuracy. Apart from that, the chloride concentration test was performed using the chloride method, which involved the addition of a mercury thiocyanate solution and a ferric ion solution, and was measured on a spectrophotometer. Three types of water samples were used: 100% tap-water, 100% rainwater, and a 50% tap-water + 50% rainwater mixture. A 10ml water sample was placed in a clean sample cell; after that, using a pipette, 1.0 mL of mercury thiocyanate solution was added. This acted as a stabilising and coagulant agent to assist in the colour reaction. Consequently, the ferric ion solution was added based on the amount specified in the analysis procedure, which was 0.5 ml. The solution was shaken gently so that the two reagents were completely mixed with the sample, and allowed to remain for a specific reaction period of 2 minutes until a stable colour formed. After the completion of the reaction, the sample was run using a spectrophotometer at program 70 for the chloride test. These tests are conducted meticulously to ensure that only rainwater meeting quality standards were used in concrete mixing. All tests were done according to the standards for non-beverage applications in the British Standard BS EN 1008:2002. This aims to prevent any defects or damage to the performance of the concrete produced.

3.3 Preparation of Concrete Sample

Table 2 shows the concrete mix design. There were three groups of samples: Sample A with 100% tap-water, Sample B with 100% rainwater, and Sample C with 50% rainwater and 50% tap-water.

Table 2. Concrete mix design

Test	Water (L)	Cement (kg)	Fine Aggregates (kg)	Coarse Aggregates (kg)
Compressive Strength Test (cube)	6.99	12.10	28.63	32.10
Flexural Strength Test (prism)	3.95	6.38	14.42	16.10

Each water sample was used in two laboratory tests: compressive and flexural strength tests. A total of 12 concrete samples were required for testing each water variation. This includes 9 samples for the compressive test, and 3 samples for the flexural test. The total number of concrete samples for the three water samples was 36. After the concrete mix was prepared, the concrete was poured into cube moulds measuring 150 mm x 150 mm x 150 mm to ensure the uniformity and precision of samples. For the flexural strength test, prism moulds measuring 100 mm x 100 mm x 500 mm were used. Concrete cubes should be allowed to cure for a specified period (BS EN 12390 5:2019) before testing to ensure the hydration process goes on smoothly and the concrete achieves maximum strength at the specified testing age.

3.4 Slump Test

Before pouring into the mould, a slump test was performed for each type of concrete mix in order to determine its workability. This test was conducted using an Abrams cone with a height of 300 mm, a bottom diameter of 200 mm, and a top diameter of 100 mm. The cone was filled with three layers of concrete, and each layer was compacted with 25 strokes using a tamping rod. After that, the cone was lifted slowly, and the slump of the concrete was measured in millimetres. The slump value was recorded to ensure the mix was within the appropriate working range before the mould was filled for strength testing. Based on BS EN 12350-2:2019, the slump test is conducted on fresh concrete first to check the workability or viscosity of the concrete. Figure 3 (a) & (b) show the slump test for fresh concrete.



Figure 3. (a) & (b) Slump test for fresh concrete

3.5 Compressive Strength Test

Tests for compressive strength were conducted on concrete cubes measuring 150 mm × 150 mm × 150 mm. For each of the three types of water, nine cube samples were prepared, for a total of 27 cubes. The slump-tested concrete mix was poured into steel moulds and compacted in three layers, with each layer being tamped 25 times with a tamping rod. After filling, the surface was levelled and allowed to harden for 24 hours at room temperature. After that, the cubes were removed from the moulds and immersed in a water tank (curing tank) for periods of 7, 14, and 28 days. After the concrete hardened, the compressive strength test was conducted at three ages: 7 days, 14 days, and 28 days. This test was conducted using a compression testing machine according to BS EN 12390-4:2025 to find the maximum load that concrete can withstand before failure. The average value of three samples for each curing age is reported as the average compressive strength for that type of water. This experiment will determine the effect of using rainwater on the mechanical properties of concrete. Figure 4 (a) & (b) show the cube curing process and concrete compressive strength test machine.



Figure 4: (a) Cube curing process and (b) Concrete compressive strength test machine

3.6 Flexural Strength Test

The flexural strength test was conducted using concrete prisms measuring 100 mm × 100 mm × 500 mm. Three samples were produced for each of the three types of water, resulting in a total of nine concrete prisms. The pouring and compaction process was carried out in the same way as the compression test. After an initial curing period of 24 hours, the samples were removed from the moulds and immersed in water for periods of 7, 14, and 28 days. Based on BS EN 12390-5:2019, this test of flexural strength was conducted to assess the resistance of concrete to bending or to flexural forces that are imposed on the material. The concrete prisms were subjected to loading at their midpoint using a bending test machine. The flexural strength value (modulus of rupture) is calculated based on the maximum load sustained before cracking occurs and is reported in MPa units. This test is important for understanding how concrete behaves under loads that affect its cracking resistance and flexibility when there is a bending load, such as in applications on floors, bridges, or structures exposed to bending. This laboratory test is directly related to the second objective of this project, which is to evaluate the effects of harvested rainwater on the mechanical properties of concrete. Figure 5 (a) & (b) show the prism curing process and the concrete flexural strength test machine.



(a)



(b)

Figure 5. (a) Prism curing process and (b) Concrete flexural strength test machine

4 Results and Discussion

4.1 Introduction

The experimental work is focused on comparing concretes made from three different water sources: tap-water, harvested rainwater, and mixed-water consisting of 50% tap-water and 50% rainwater. The analysis included compliance with British Standards and the effects of the choices made on the concrete quality and performance. The mechanical strength was assessed through compressive strength and flexural strength tests at curing ages of 7, 14, and 28 days.

4.2 Chemical Properties of Water Samples

Table 3 shows a comparison of the average results of each water quality test used in this research and the limits required according to the British Standard (BS EN 1008:2002) for concrete mixing water.

Table 3. Comparison of the average results of each water quality test.

Water parameters	Water Resources			BS EN 1008:2002
	Tap-water (Average)	Rainwater (Average)	Mixed-water (Average)	

pH	6.78	7.17	7.09	≥ 4.0
Total Dissolved Solid (TDS), (mg/L)	52.80	53.75	53.50	≤ 2000 mg/L
Total Coliform	Moderate	Low	Very High	No specific limit *
Sulphate, (mg/L)	4.50	0.00	2.50	≤ 2000 mg/L
Chloride, (mg/L)	17.15	1.60	8.10	≤ 500 mg/L (Reinforced Concrete)

4.2.1 pH Level and Total Dissolved Solid (TDS)

The pH of water used for concrete mixing is an important indicator of its suitability, although pH alone is not sufficient to assess overall water quality. Previous studies have reported satisfactory concrete or mortar performance when the mixing water was neutral to moderately alkaline, with pH values generally within approximately 7–12 (Çomak, 2018; Orie, 2012; Wicaksono & Nurwidayati, 2022). Highly acidic water may adversely affect cement hydration and compressive strength, while excessively alkaline water may also influence concrete properties at very high pH levels. Therefore, a pH range of approximately 7–12, with pH 12 considered a practical approximate upper value, may be used as a reference range for evaluating the suitability of harvested rainwater for concrete mixing, subject to compliance with other relevant water-quality requirements.

Based on Table 3, the pH levels of the water samples are between 6.78 and 7.17. The mean pH level of the tap-water was 6.78, the rainwater was 7.17, and the mixed-water was 7.09. BS EN 1008:2002 states that the cement mixing water shall have a minimum pH value of 4.0. Therefore, all water samples comply with this criterion. Even though tap-water has a slightly acidic component and rainwater has a neutral component, this confirms that rainwater used in the construction industry as a concrete mixture will be chemically adequate. A neutral component of the rainwater has the potential to provide a concrete hydration environment that will be free from any chemical reactions in the early stages. The results obtained in this study are also in agreement with a study by Shivashankara & Vidya (2024), which reported a pH range of collected rainwater within the range of about 6.42–7.28, hence within the permissible limits of the concrete mixing water standards. Moreover, Bertuzzi & Ghisi (2021) revealed that rainwater can be used for concrete production if the pH is above 5 and meets other relevant standards. In this circumstance, the pH level of the harvested rainwater, being near-neutral, initially indicates that the risk of adverse consequences on the performance of the concrete is very low and within the standard (less than 2000 mg/l) based on BS EN 1008:2002. Furthermore, all water samples showed low TDS values with an average value in the tap-water at 52.80 mg/L, rainwater at 53.75 mg/L, and mixed-water at 53.50 mg/L. All concentrations are summarised in Table 3.

According to BS EN 1008:2002, water with excessive dissolved solids may interfere with the setting time as well as the development of concrete strength. However, the recorded values of TDS are very low compared to the permissible limits and pose a very minimal risk to the performance of concrete. The relatively similar TDS values among all water types indicate that they had fairly identical values of TDS, showing that harvested rainwater does not contribute to hazardous levels of dissolved impurities and is no different from tap-water in terms of the content of dissolved solids. The TDS value for this study was relatively low (approximately 53 mg/L), which confirms that the dissolved salt or mineral content is low and will not influence the setting time or strength of the concrete. In practice, low levels of TDS normally minimise the chances of forming an accumulation of dissolved solids that can interfere with the chemical hydration reaction of cement, thereby supporting compliance with the requirements of BS EN 1008:2002.

4.2.2 Sulphate, Total Coliform and Chloride

From the results, the sulphate levels were found to be low in all water samples, with an average concentration of 4.5 mg/L in tap-water, 0 mg/L in rainwater, and 2.5 mg/L in mixed-water. A maximum level of 2000 mg/L was recommended for the sulphate content in the mixing water, as per BS EN 1008:2002 standards. All the values are well below the maximum recommended level, confirming their suitability for the concrete mix. The resultant low level of sulphates is encouraging, since high levels may cause delayed ettringite formation and expansion, leading to problems in concrete durability. The measured values are substantially below the relevant limits, indicating that the harvested rainwater collected under the specific catchment and storage conditions of this study contained low concentrations of sulphate and chloride. The low values should not be interpreted as representative of all harvested rainwater because water chemistry may vary with atmospheric conditions, catchment materials, storage duration and local environmental contamination. This result is consistent with the findings of Bertuzzi and Ghisi (2021), who reported very low sulphate levels in rainwater, which was considered suitable for concrete production based on the limit of 2000 mg/L for sulphate in conformance with standards by NBR 15900.

From the results, the total coliform levels, as presented in Table 3, exhibit considerable variation. Tap-water contains moderate levels of coliform, while rainwater contains very low levels of coliform, whereas mixed-water contains very high levels of coliform. Based on BS EN 1008:2002, the presence of organic matter and microorganisms is deemed non-problematic in general. Since there was no major effect on the strength performance based on the mechanical test results, coliforms at the levels present in the mixed-water sample did not significantly influence the performance capability of the concrete. From Table 3, the chloride ion values for tap-water, rainwater, and mixed-water samples were recorded to be 17.15, 1.60, and 8.10 mg/L, respectively. BS EN 1008:2002 regulations state that the maximum permissible value for the chloride ion is 500 mg/L in reinforced concrete. The values for all water samples fall well below the maximum permissible value. The absence of chloride ions to a large extent in the rainwater is quite favourable, as chloride ions are strongly associated with reinforcement corrosion in water. This is in agreement with the study by Shivashankara & Vidya (2024) that stated the values of chlorides in harvested rainwater were found to be low but still within the permissible limit as specified by the standards, thus reiterating the fact that chlorides should be maintained at a safe concentration because a higher concentration may indicate potential values in concrete. Therefore, the results of this study confirm that harvested rainwater and mixed water meet the BS EN 1008:2002 requirements regarding chloride suitability for use in reinforced concrete.

4.3 Mechanical Performance of Concrete (Fresh Condition)

4.3.1 Slump Test

The slump test was done to assess the workability of the fresh concrete mixture prepared by three different sources of water, which included 100% tap-water, 100% rainwater, and a mixture of 50% tap-water and 50% rainwater. The slump test results were 49 mm for tap-water, 55 mm for rainwater, and 59 mm for the tap-water and rainwater mixture. The highest possible slump value according to the concrete mix design form in Grade 30 (M30) concrete was a slump of 60 mm. As stated in BS EN 12350-2:2019, concrete with a slump value of 30-60 mm is of low to medium workability, which is adequate for reinforced concrete jobs like beams, slabs, and columns. As such, all results of slump tests fall within the acceptable limits required in mix designs. The result illustrates a positive indication regarding whether the partial or complete usage of harvested rainwater will influence concrete workability. The rainwater and mixed-water concretes produced slightly higher slump values than the tap-water concrete, although all three mixtures remained within the target slump range of 30-60 mm. This difference does not necessarily indicate that rainwater intrinsically improves workability, as the observed variation may arise from the specific physicochemical characteristics of the water and experimental variability which is in line with the findings from Siregar et al. (2023).

4.3.2 Compressive Strength Test

Table 4 and Figure 6 present the average compressive strength of concrete prepared using tap-water, rainwater, and mixed-water at 7, 14, and 28 days. All mixtures showed an increase in compressive strength with increasing curing age.

Table 4. Concrete compressive strength test results

Specimens	Load (kN)			Compressive strength (MPa)		
	7 days (Average)	14 days (Average)	28 days (Average)	7 days (Average)	14 days (Average)	28 days (Average)
Tap-water	720.83	846.04	994.75	32.04	37.60	44.21
Rainwater	745.56	879.39	959.00	33.14	39.08	42.62
Mixed-water	776.32	874.71	882.90	34.50	38.87	39.24

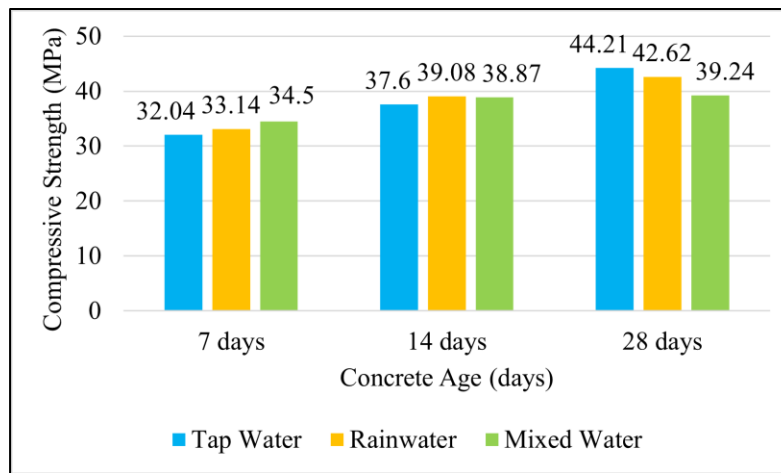


Figure 6. Compressive strength results

At 7 days, the tap-water concrete recorded 32.04 MPa, while the rainwater and mixed-water concretes recorded 33.14 and 34.50 MPa, respectively. At 14 days, the corresponding values were 37.60, 39.08, and 38.87 MPa. Although the mixed-water concrete recorded the highest average strength at 7 days, this difference should not be interpreted as a specific beneficial effect of combining tap-water and rainwater, as the present study did not investigate the hydration mechanism or microstructural changes. At 28 days, the tap-water concrete achieved the highest compressive strength of 44.21 MPa, followed by rainwater at 42.62 MPa and mixed-water at 39.24 MPa. Compared with the tap-water concrete, the rainwater concrete showed a reduction of 3.60%, while the mixed-water concrete showed a reduction of 11.24%. The rainwater concrete therefore retained approximately 96.4% of the control strength at 28 days.

The results are generally consistent with previous studies indicating that the performance of concrete using alternative water sources depends on the physicochemical characteristics of the water. Siregar et al. (2023) reported lower compressive strength for concrete prepared with acidic rainwater, while Martinez et al. (2024) reported that rainwater concrete could achieve approximately 90–100% of the control strength depending on water characteristics. In the present study, the 28-day strength of the rainwater concrete remained close to that of the tap-water concrete. Overall, the results indicate that the harvested rainwater used in this study did not cause a substantial reduction in 28-day compressive strength. However, the findings are limited to the specific rainwater quality, M30 concrete mix, and curing conditions investigated.

4.3.3 Flexural Strength Test

Table 5 shows the concrete flexural strength test results and Figure 7 shows the concrete flexural strength test results.

Table 5. Concrete flexural strength test results

Specimens	Load (kN)			Flexural Strength (MPa)		
	7 days	14 days	28 days	7 days	14 days	28 days
Tap-water	17.57	13.86	16.00	6.54	6.24	7.20
Rainwater	15.12	12.64	13.05	5.66	5.69	5.87
Mixed-water	13.71	13.70	13.29	5.13	6.16	5.94

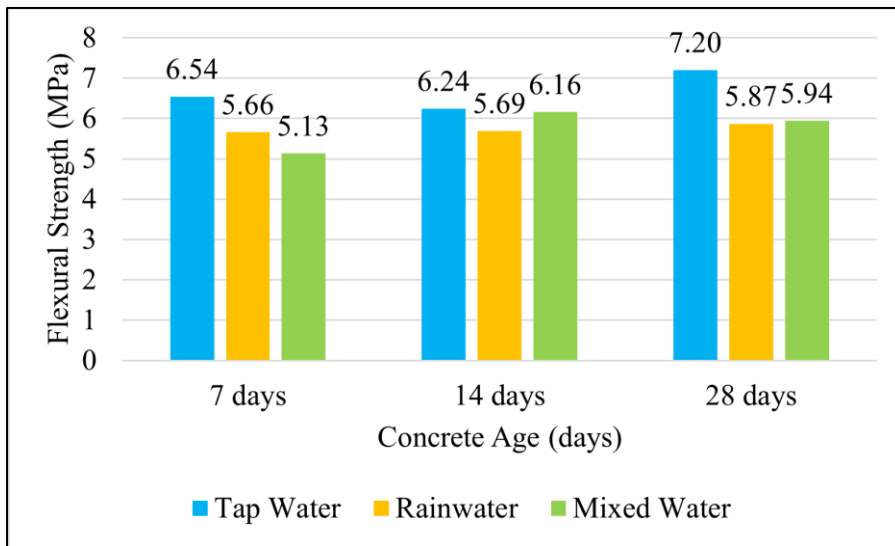


Figure 7. Flexural strength results

Figure 7 shows the flexural strength test results, which differ from the compressive-strength results, especially at early ages. At 7 days of age, the control concrete recorded a flexural strength of 6.54 MPa. Concrete using rainwater recorded 5.66 MPa, a percentage decrease of 13.46%, while concrete using mixed-water recorded 5.13 MPa, a decrease of 21.56% compared to the control. This result indicates that in the early age of curing, the use of rainwater and mixed-water impairs flexural performance. At the age of 14 days, the flexural strength of the control concrete slightly decreased to an average of 6.24 MPa. The rainwater concrete measured 5.69 MPa, which was lower by 7.63%. Interestingly, for the mixed-water concrete, there was an increase in strength to an average of 6.16 MPa, which was only lower by 1.30% compared with the tap-water concrete. This shows that the adverse effect on the flexural strength caused by mixed-water is temporary and decreases with age. After 28 days, the control concrete had the highest flexural strength of 7.20 MPa. Rainwater concrete had a value of 5.87 MPa, which decreased by 18.47%, and mixed-water concrete had a value of 5.94 MPa, indicating a decrease of 17.50%.

The result shows that despite the increase in flexural strength with age, the concretes made with rainwater and mixed-water have lower flexural strength than the control concrete. This is supported by previous studies, which confirmed that flexural strength is more affected by changes in water quality than compressive strength. The study carried out by Martinez et al. (2024) and other studies show that flexural properties are more affected than compressive strength because differences in pH and chemicals in rainwater can affect micro-structure formation in specimens. Hence, this study has established that its results agree with previous studies. Regarding the British Standard requirements for the tested specimens, BS EN 1008:2002 does not state particular limitations for the flexural strength but highlights that the water used in the concrete mix should not seriously influence the mechanical properties of the concrete. Despite the decrease in flexural strength, the concrete made with rainwater presented acceptable strength values.

Overall, this study shows that the use of rainwater as concrete mixing water gives compressive strength close to that of the control concrete at early and intermediate ages, with a slight decrease at 28 days, which is still within the limits according to the BS EN 1008:2002. The results of this research work have been consistent with those obtained by previous research works and support the use of rainwater as an alternative to tap-water for concrete production, provided that the water-quality requirements of BS EN 1008:2002 are satisfied.

5 Conclusion

The conclusions drawn from this study are as follows:

Water quality:

The harvested rainwater collected in this study exhibited a pH of 7.17, TDS of 53.75 mg/L, sulphate concentration of 0 mg/L and chloride concentration of 1.60 mg/L. These results indicate that the tested rainwater met the relevant water-quality criteria considered for concrete mixing under BS EN 1008:2002.

Workability:

The slump values of the tap-water, rainwater and mixed-water concretes were 49, 55 and 59 mm, respectively. All mixtures remained within the targeted 30–60 mm slump range, indicating that the use of harvested rainwater did not adversely affect the required fresh-concrete workability under the tested conditions.

Compressive strength:

At 28 days, the rainwater concrete achieved 42.62 MPa compared with 44.21 MPa for the tap-water concrete, representing a reduction of approximately 3.60%. This indicates that the use of the tested harvested rainwater resulted in compressive strength close to that of the control concrete.

Flexural strength:

The tap-water concrete recorded the highest flexural strength at all curing ages. At 28 days, rainwater and mixed-water concretes achieved 5.87 and 5.94 MPa, respectively, compared with 7.20 MPa for the control. Therefore, the effect of water source was more evident in flexural than compressive strength in the present study.

Overall, within the three water proportions investigated, 100% harvested rainwater provided the most favourable balance between compressive-strength retention and potable-water substitution. However, this finding is limited to the M30 concrete, water characteristics and curing conditions investigated, and should not be interpreted as a universal optimum for all concrete mixtures.

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Declaration of Conflicting Interests

All authors declare that they have no conflicts of interest.

Author Contribution

Conceptualisation, Fatin Noorazlinda Binti Ali; Methodology, Fatin Noorazlinda Binti Ali; Validation, Hazrina Ahmad; Analysis, Fatin Noorazlinda Binti Ali; Investigation, Fatin Noorazlinda Binti Ali; Resources, Fatin Noorazlinda Binti Ali; Writing-Draft Preparation, Fatin Noorazlinda Binti Ali; Writing-Review & Editing, Hazrina Ahmad; Visualisation, Mohd Hisbany Mohd Hashim; Supervision, Jalina Kassim; Project Administration, Hazrina Ahmad.

All authors have reviewed and approved the final version of the manuscript for publication.

Declaration of Generative Ai in The Writing Process

During the preparation of this work, the author(s) used Scopus AI in order to assist in identifying relevant literature and potential references for the study. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the publication.

Data Availability/Supplementary Materials

The datasets used and/or analysed during the current study are available from the corresponding author on reasonable request.

Ethics Statement

The authors declare that this research did not involve human or animal subjects. All experimental procedures were performed following the institutional Safety, Health, and Environmental (HSE) protocols of Universiti Teknologi MARA.

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