

Assessing the Impacts of Treated Wastewater on the Mechanical Properties and Corrosion Resistance of Concrete

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ABSTRACT

This study evaluates the impacts of treated wastewater (TWW) as a sustainable alternative source of water for mixing and curing purposes in concrete production. Through a comprehensive experimental approach, various tests were conducted to evaluate the mechanical and durability properties of fresh and hardened concrete. Therefore, initial, and final setting times of cement paste, workability of concrete, compressive and tensile strengths, water absorption, porosity, pH value, and ultrasonic pulse velocity tests were performed on different concrete groups that were casted and cured with different water types. Additionally, the half-cell potential test to determine the corrosion potential and, even, the accelerated corrosion test to assess the corrosion resistance of reinforced concrete have been conducted.

It was detected that the utilization of TWW had a negligible impact on the workability of concrete and did not significantly affect the initial and final setting time of cement paste. Moreover, a significant improvement in the compressive strength of concrete specimens incorporating TWW was observed during the extended curing period of six months. Additionally, a comparable trend in the splitting tensile strength of the concrete specimens was evident. Although utilizing TWW slightly reduced the porosity and water absorption, the corrosion rate was found to be 24% higher when compared with the control specimen. Additionally, for different time intervals up to 4 months the half-cell potential test results constantly exhibited, higher potential difference in the specimens produced with TWW compared to the control specimen.

Therefore, based on the results of this study the feasibility of utilizing TWW in concrete production has been confirmed by ASTM standards. However, when dealing with reinforced concrete, it is important to exercise caution.

Keywords: Mixing Water, Curing Water, Treated Wastewater, Reclaimed Water, Compressive Strength, Durability, Corrosion Test.

ÖZ

Bu çalışma, beton üretiminde karıştırma ve kürleme amaçları için sürdürülebilir bir alternatif su kaynağı olarak arıtılmış atıksuyun (TWW) etkilerini değerlendirmektedir. Aracılığıyla kapsamlı deneysel yaklaşımla, taze ve sertleşmiş betonun mekanik ve dayanıklılık özelliklerini değerlendirmek için çeşitli testler yapılmıştır. Bu nedenle, farklı su tipleri ile dökülmüş ve kür edilmiş farklı beton gruplarında çimento hamurunun ilk ve son priz süreleri, betonun işlenebilirliği, basınç ve çekme dayanımları, su emme, gözeneklilik, pH değeri ve ultrasonik darbe hızı testleri yapılmıştır. Ek olarak, korozyon potansiyelini belirlemek için yarım hücre potansiyel testi ve hatta betonarme korozyon direncini değerlendirmek için hızlandırılmış korozyon testi yapılmıştır.

TWW kullanımının betonun işlenebilirliği üzerinde ihmal edilebilir bir etkiye sahip olduğu ve çimento hamurunun ilk ve son priz sürelerini önemli ölçüde etkilemediği tespit edilmiştir. Ayrıca, altı aylık uzatılmış kür süresi boyunca TWW içeren beton numunelerin basınç dayanımında önemli bir gelişme gözlemlendi. Ek olarak, beton numunelerin yarmada çekme dayanımında karşılaştırılabilir bir eğilim belirgindi. TWW kullanılması gözenekliliği ve su emilimini biraz azaltsa da, kontrol numunesiyle karşılaştırıldığında korozyon oranının %24 daha yüksek olduğu bulundu. Ayrıca, 4 aya kadar farklı zaman aralıklarında, yarım hücre potansiyel testi sonuçları sürekli olarak, TWW ile üretilen numunelerde kontrol numunesine göre daha yüksek potansiyel farkı göstermiştir.

Bu nedenle, bu çalışmanın sonuçlarına dayanarak, TWW'nin beton üretiminde kullanılmasının uygulanabilirliği ASTM standartları tarafından onaylanmıştır. Bununla birlikte, betonarme ile uğraşırken dikkatli olmak önemlidir.

Anahtar Kelimeler: Karışım Suyu, Kür Suyu, Arıtılmış Atık Su, Arıtılmış Su, Basınç Dayanımı, Dayanıklılık, Korozyon Testi.

To Hedieh
my beloved wife and best friend

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LIST OF ABBREVIATIONS

ACTIV	Accelerated Corrosion Test by an Impressed Voltage
BOD	Biochemical Oxygen Demand
COD	Chemical Oxygen Demand
EC	Electrical Conductivity
FW	Fresh Water
GW	Grey Water
ppm	Part Per Millions
PTW	Primarily Treated Wastewater
PW	Potable Water
STW	Secondary Treated Wastewater
SW	Sewage Water
TDS	Total Dissolved Solids
TS	Total Solids
TSS	Total Suspended Solids
TTW	Tertiary Treated Wastewater
TW	Tap Water
TWW	Treated Wastewater

Chapter 1

INTRODUCTION

1.1 General

Water is a vital resource that plays a crucial role in sustaining life on Earth and profoundly impacts ecosystems, human health, and economic development. Despite the fact that water covers 71% of the planet's surface, only a small fraction is readily available and suitable for human consumption. Remarkably 97.5% of water on earth is saline water, and just 2.5% is freshwater, which is primarily locked in ice caps, glaciers, and within deep aquifers. Consequently, less than 1% of the total water supply is accessible in the form of freshwater present in rivers, lakes, reservoirs, atmosphere, and reachable aquifers. The uneven distribution of freshwater resources globally adds to the complexity of water scarcity in various regions [1].

Furthermore, according to the United Nations, the global population has experienced a substantial growth, reaching 8 billion in 2022, compared to approximately 2.5 billion in 1950. This remarkable raise signifies that the world population has tripled over a span of seven decades. Future estimates indicate that by 2050, the population is expected to reach around 9.7 billion. Such rapid growth in population will generate a heightened need for essential resources such as water, food, and infrastructure [2]. Additionally, UNICEF reports that two-thirds of the world's population lives in regions where they are facing water scarcity at least one-month a year. These alarming statistics highlight the urging requirement for applying sustainable water management

strategies and adopting resource-efficient practices to effectively deal with the challenges that arise from population growth. Addressing these issues becomes increasingly crucial in ensuring the availability of an adequate water supply for present and future generations [3].

Cement, an essential ingredient in the production of cement-based materials such as mortar and concrete, holds the position of being the most manufactured product on Earth by mass. After water, it is the most widely utilized substance by humans. Cement production witnessed a substantial rise, increasing by more than 30-fold from 1950 and 4-fold since 1990. Only in 2020, a staggering amount of 4.1 billion tons of cement were produced globally. Moreover, with an annual production of approximately 55 billion tons of concrete, the demand for cement is expected to rise by 2050, driven by population growth and the pressing need for housing and infrastructure development [4]–[7].

Concrete is highly favored due to its exceptional strength, durability, versatility, and cost-effectiveness. However, the extensive production of concrete carries significant environmental implications, particularly concerning CO₂ emissions and natural resource utilization. A case study conducted by Vergara et al. reveals that while the required mixing water for 1 cubic meter of concrete was around 95 to 130 liters, the actual water consumption rises to a minimum of 520 up to 2821 liters when considering additional water needed for curing and washing aggregate and equipment so as an average of 1670 liters of water consumed for every cubic meter of concrete. This excessive water usage, considering the scale of annual concrete production with more than 55 billion tons reaches to enormous amount of almost 40 billion tons of water, increasing water stresses and placing substantial strain on freshwater reserves.

It emphasizes the need for sustainable practices in the concrete industry to mitigate the negative impacts on water resources and address the challenges of water scarcity [8], [9].

On the other hand, the production of wastewater has now reached a significant volume of around 380 billion cubic meters. Future projections indicate a noteworthy 24% increase by 2030 and a substantial 51% increase by 2050. These forecasts underscore the increasing amount of wastewater being generated and the pressing need for its effective management and treatment [10]. In addition, wastewater treatment levels exhibit significant differences based on regional development and income levels, ranging from 70% in wealthier areas to only 8% in less affluent regions. Consequently, a substantial portion of approximately 80% of generated wastewater which consist of 99% pure water and only 1% impurities such as solids, dissolved or suspended substances, and microorganisms, is released into the environment without any treatment. This untreated wastewater puts a massive potential risk of polluting water resources, adding to the shortage of suitable water for human consumption and worsening the scarce situation of fresh water [11].

As a result, a promising solution for reducing freshwater consumption in the concrete industry lies in the utilization of treated wastewater. By treating wastewater to meet the requirements of the concrete industry, this sustainable resource can be utilized, and freshwater reserves can be relieved. It is worth noting that the properties of treated wastewater may vary depending on the source, treatment method, and level of treatment. Nonetheless, the use of treated wastewater in accordance with ASTM C1602 standards offers a viable approach to improving sustainability and addressing the growing demand for water resources [11]–[13]. Among all conceivable sources,

treated wastewater is the most important long-term solution for freshwater conservation. Wastewater is a byproduct of water consumption in which pollutants can be removed by physical, chemical, and biological processes. Although it is usually discharged to water bodies, treated wastewater frequently has a high final quality for use in nondrinking, and for indirect urban operations [14].

Therefore, the use of TWW in concrete production offers numerous benefits:

- Firstly, it can significantly reduce the demand for fresh water, which is a valuable and scarce resource.
- Secondly, it can lead to substantial cost and efficiency savings, while simultaneously promoting long-term sustainability in the construction industry.
- Thirdly, using TWW in concrete production can help to minimize the environmental impact of releasing wastewater into the environment by reducing the amount of untreated wastewater that is discharged into nature.
- Finally, the use of TWW can lower the carbon footprint of concrete production by minimizing the energy required for treating and transporting freshwater to the concrete plants.

Nonetheless, water quality is a crucial factor in the concrete industry, as it affects the properties and durability of concrete specifically due to contaminants that exist in TWW. Yet, there is a lack of clear and consistent standards for the acceptable levels of various parameters in water used for concrete production [15]. If these thresholds were established and verified through extensive testing, this could potentially allow for the utilization of TWW in concrete production. Also, wastewater treatment plants could adjust their processes to produce TWW that meets the necessary requirements.

However, it is important to note that this study is not designed to pursue such an endeavor.

1.2 Aims and Objectives of This Thesis

This study focuses on utilizing treated wastewater (TWW) from the Gazimağusa wastewater treatment plant in concrete production. It aims to explore the impact on the mechanical and durability properties of concrete, as well as investigate corrosion behavior, in comparison to conventional tap water (TW).

Despite the growing interest in using TWW as a sustainable source of water for concrete manufacturing, the literature still lacks a comprehensive understanding of how the use of TWW affects the performance and durability of plain and reinforced concrete. Therefore, this study will critically review the existing literatures of water quality in concrete production and provide an in-depth analysis through a comprehensive experimental study on the effects of TWW on key properties, including workability, setting time, compressive strength of mortar, compressive strength of concrete, splitting tensile strength of concrete, ultrasonic pulse velocity (UPV), porosity, water absorption, density, and pH value of concrete. Meanwhile, the physical and chemical properties of TWW and TW were examined through laboratory tests, and their characteristics were compared with the limits set by ASTM standards. Furthermore, to investigate the impact of TWW in reinforced concrete, the half-cell potential test was conducted to evaluate the corrosion potential and importantly an accelerated corrosion test by impressed voltage (ACTIV) technique was employed to investigate the potential impact of TWW on reinforced concrete corrosion resistance, which is a critical issue in infrastructure durability and an important gap in the literature.

1.3 Research Questions

1. What are the characteristics of TWW, and how does it meet the water quality standards?
2. How does the utilization of TWW in concrete production affect the properties of fresh concrete?
3. How does the substitution of TWW in concrete mixing impact the mechanical properties of concrete?
4. What are the impacts of curing concrete with TWW on the mechanical properties of concrete?
5. How does the use of TWW for mixing and curing of concrete impact the corrosion resistance?
6. What is the influence of using TWW with a higher pH value on the pH value of hardened concrete?

1.4 Methodology

The results in this study were obtained through experimental methods conducted at the laboratories of the Civil Engineering Department at Eastern Mediterranean University in Gazimağusa, North Cyprus. The study aims to investigate the chemical and physical characteristics of tap water (TW) and treated wastewater (TWW), as well as the mechanical and durability properties of concrete specimens mixed and/or cured with TW and TWW. Moreover, the corrosion behavior in reinforced concrete specimens was critically examined. Specifically, the study evaluated:

- The physical and chemical characteristics of TW and TWW,
- The initial and final Setting time of cement paste,
- The workability of fresh concrete,
- The compressive strength of mortar and concrete,

- The splitting tensile strength of concrete,
- The ultrasonic pulse velocity (UPV) of concrete,
- The pH value of hardened concrete,
- The water absorption, Density, and Porosity of concrete,
- The corrosion potential (Half-cell potential) of reinforced concrete,
- The accelerated corrosion test by impressed voltage (ACTIV) of reinforced concrete.

In order to evaluate the objectives of this study, three different group of concrete specimens were cast and utilized:

- Group I: Mixed and cured with TW as the control sample (TT),
- Group II: Mixed with TWW and cured with TW to evaluate the effects of mixing water (WT),
- Group III: Mixed and cured with TWW to understand the full impact of using TWW (WW).

1.5 The Structure of Thesis

The structure of this thesis will be as follows:

- Chapter 1: Introduction - This chapter provides an overview of the research problem, the rationale for conducting this study, and the research questions that will guide the investigation.
- Chapter 2: Literature Review - In this chapter, relevant literature will be reviewed to provide a comprehensive understanding of the current state of research on the topic of using treated wastewater in concrete production. The literature review focuses on the mechanical and durability properties of concrete and the effects of using TWW as mixing and curing water.

- Chapter 3: Background of study - This chapter provides a background on the study, including the context, scope, and significance of the research problem. It also discusses the research objectives and hypotheses.
- Chapter 4: Methodology - This chapter explains the research design, methods, and procedures that were used to conduct this study. It also discusses the selection of materials and equipment, the sample preparation and testing procedures.
- Chapter 5: Results - this chapter presents the findings of the study, including the results of the tests conducted to evaluate the mechanical and durability properties of the concrete samples.
- Chapter 6: Conclusion - This chapter provides a summary of the main findings, conclusions, and implications. It also discusses the limitations of the study and recommendations for future relevant research.

Chapter 2

LITERATURE REVIEW

2.1 Introduction

This chapter aims to explore the potential of treated wastewater (TWW) as a viable water source for concrete production, along with the challenges and opportunities associated. It begins with a concise overview of the current situation regarding wastewater production and treatment. Subsequently, it delves into the water quality limits for concrete and provided an explanation of the relevant standards. This chapter also examines the related research papers and their findings concerning different types of water utilized in concrete production. By addressing these aspects, this chapter will contribute to a comprehensive understanding of the feasibility of using treated wastewater as an alternative water source in the concrete industry.

2.2 General

There is a common assumption among civil engineers that if water is suitable for drinking, it is also suitable for using in concrete production. However, this is not always true, some types of water may contain mineral components or sugar that are not suitable for concrete, and conversely, some types of water that are not suitable for human consumption may work perfectly well in concrete production [16], [17].

Considering the global situation of water scarcity and ever-increasing demand, it is not sustainable to use drinking water in concrete production, especially when according to the United Nation in 2050, 52% of people will live under water stress condition [18].

On the other hand, the annual global production of domestic wastewater surpasses 380 billion m³, with more than 80% of this volume being discharged into the environment without undergoing any form of treatment. Such untreated wastewater discharge introduces a significant risk of water body pollution, thereby highlighting the urgent need for appropriate wastewater management practices. As mentioned before, the concrete industry consumes a significant amount of around 40 billion tons of freshwater annually just to produce concrete. However, by adopting wastewater recycling and utilizing it as a viable water source for concrete production, it becomes possible to redirect a substantial portion of the water resources currently consumed by this industry to other sectors. This approach not only optimizes resource utilization and preventing water body pollution but also offers promising financial opportunities [10]. Therefore, it is worth exploring the possibility of using TWW in concrete industry while satisfying the standard requirements.

2.3 Feasibility of Using Treated Wastewater in Concrete

Researchers have been trying to answer this question for about half a century: Is treated wastewater suitable for using in concrete? The answer is still unclear. There are studies that support the use of TWW in concrete and claim that it does not affect the properties of concrete adversely. However, there are also studies that contradict this claim and show TWW can have negative impacts on concrete performance. So, what determines the suitability of water in concrete production are its characteristics. TWW can have various substances and properties depending on its source, type, and level of treatment. Therefore, it is not possible to reach a general conclusion about its suitability for concrete without considering its specific characteristics.

2.3.1 Treated Wastewater Sources and Properties

As mentioned before, TWW can be sourced from various origins such as domestic, industrial, and urban runoff. The characteristics of these treated wastewaters vary depending on its source and the quality of treatment it undergoes. Domestic wastewater, which comes from sources such as households, commercial buildings, restaurants, and hospitals, among others, usually contains organic matter and pathogens. Conversely, industrial wastewater from factories may contain different chemicals and metals that necessitate specialized treatment. Additionally, different industries may have varying water usage requirements. For instance, concrete production necessitates water with low sulfate and chloride content to prevent deterioration and corrosion.

2.4 Water Quality Standards for Mixing Water in Concrete

In this case, ASTM and other international standards prescribe specific limitations for parameters such as pH value, detergent, color, solids, chloride, alkali, nitrate, sulfate, and other parameters. Nonetheless, it is important to acknowledge that existing standards may not encompass all potential contaminants found in wastewater [14].

However, for the purpose of comparison, the values for these parameters, as outlined by different standards, are presented in Table 1:

Table 1: International standards for mixing water quality in concrete [14]

Parameter		British	ISO	ASTM
pH		≥ 4	≥ 5	-
Total Solids		≤ 4 mL of sediments suspended solids	≤ 4 mL of sediments suspended solids	$\leq 50,000$ mg/L
Chloride (Cl ⁻) (mg/L)	Pre-stressed	≤ 500	≤ 500	≤ 500
	Reinforced	≤ 1000	≤ 1000	≤ 1000
	Simple	≤ 4500	≤ 4500	-
Alkali (Na ₂ O) (mg/L)		≤ 1500	≤ 1500	≤ 600
Nitrates (NO ₃ ⁻) (mg/L)		≤ 500	≤ 500	-
Sulfate (mg/L)		≤ 2000 (SO ₄ ²⁻)	≤ 2000 (SO ₄ ²⁻)	≤ 3000 (SO ₄)
Oils and fats		No more than visible traces		-
Detergent		Any foam should disappear within 2 min		-
Color		The color shall be assessed qualitatively as pale yellow or paler		-
Odor		Odorless and without the smell of hydrogen sulfide after the addition of hydrochloric acid		-
Organic matter		The color of water should be lighter than or equal to that of the standard solution after addition of sodium hydroxide		-

2.5 Literature Studies on the Impacts of TWW on Concrete Properties

Several researchers have conducted studies on utilizing TWW in concrete production, and they have reported varying results. Here are some of these findings:

Shekarchi et al., conducted a comparative analysis on the water quality of water samples obtained from three steps of treatment on the domestic wastewater treatment

plant, the primary treated wastewater (PTW), the secondary treated wastewater (STW), and the tertiary treated wastewater (TTW). The analysis results indicated that TWW samples met the standard requirements, except for the suspended particles in STW which slightly exceeded the permissible limit. Tests on the initial and final setting time of cement paste, the compressive strength of mortar and concrete, and the slump results, revealed that the use of this type of water did not have any adverse effects on the tested parameters and the requirements specified in the standards were satisfied. Moreover, no harmful effects were detected on the flexural strength of mortar, except for a 10% reduction after 28 days when using STW. Regarding the feasibility of using TWW as curing water, the study found no adverse effects on compressive strengths up to at least 6 months, except for a reduction of 18% when using STW. The study also evaluated water absorption and electrical resistivity tests, which suggested the feasibility of using TWW as mixing and curing water in concrete production [19].

Meena et al., utilized PTW, STW, and TTW for casting and curing the concrete samples. In their study the workability of concrete was reduced 25% and 50% by using the TTW and STW, respectively. Also, the compressive strength of concrete was slightly lower when mixed with TTW and cured in either TW or TTW. The results of compressive strength in different types of concrete group ranged from 85% to 94% compared to the control sample. Meanwhile, the carbonation resistance of concrete groups using all types of treated wastewater was lower than the control sample. Also, their concrete had comparable durability properties with control sample concrete, and they reported that chloride concentration in the hardened concrete is related with the quality of TWW [20].

The study conducted by Abushanab et al., showed a negligible influence on fresh properties of concrete and reduced the compressive strength and flexural strength by 6% to 12% and 8% to 10%, respectively. Yet, having a significant negative effect on the durability of concrete, due to an increase in the porosity and chloride permeability by 40% to 77% compared with the samples using fresh water (FW). Additionally, replacing FW resulted in a decrease of 5% to 7.5% in electrical resistivity [21].

Yahyaei et al., reported that utilizing TWW in concrete production had a marginal impact on the filling and passing ability of self-compacting concrete and satisfied the standards. However, utilization of TWW in the self-compacting concrete reduced the compressive and tensile strength of concrete at 90 days in all mixes by up to 2% and 13%, respectively. Also, utilization of TWW reduced the electrical resistivity and altered the homogeneity and structure of the hardened self-compacting concrete microstructure, which may affect the development of Calcium Silicate Hydration (C-S-H) formation [9].

Hassani et al., conducted an experiment and found that the concrete made with potable water (PW) exhibited a more uniform and compact surface, while concrete made with wastewater contained more pores and voids. Their study also demonstrated that by using the wastewater in the concrete production the chloride ion diffusion coefficient has increased [22].

According to the findings of Noruzman et al., the chemical properties of different types of TWW used in their study met the requirements of the ASTM standard, with the exception of total solids (TS) in treated effluent from heavy industry. Interestingly, the higher TS in treated effluent from heavy industry resulted in better strength

development in concrete. Fresh concrete mixed with treated effluent from heavy industry and treated effluent from domestic sewage exhibited acceptable setting time and workability properties. In terms of compressive strength, concrete samples mixed with treated effluent from heavy industry showed better results than samples mixed with treated effluent from domestic sewage, and even the control sample concrete. Additionally, treated effluent from heavy industry concrete was less permeable and more water-resistant compared to concrete mixed with other effluents. These results suggest that the use of effluents from heavy industry as a mixing water for concrete production is feasible. Nonetheless, further research are required to evaluate the long-term durability of concrete mixed with treated effluent against environmental degradation factors [23].

According to the study conducted by Al-Jabri et al., on the usage of wastewater in mortar and concrete, the chemical composition of the wastewater used satisfied the standard limits of the ASTM standard. However, the high concentration of certain substances in wastewater raises concerns about corrosion potential and sulfate attack in reinforced concrete structures. Additionally, the compressive strength of concrete samples increased with a longer curing period. Specifically, after 28 days of curing, there was no significant difference in compressive strength of concrete among different mixes. Moreover, concrete mixtures with wastewater showed similar water absorption compared with the control sample, and the use of wastewater from car wash stations had a negligible effect on the strength of concrete [24].

Saricimen et al., conducted a study which showed that, although the potable water (PW) and treated wastewater (TWW) used in their experiment showed different substance concentrations, all water sample types met the limits of the standards. The

use of TWW resulted in a slight decrease in setting time of cement pastes compared to control samples. Compressive strength was higher in mortar specimens with TWW compared to control samples, with an increase in strength of about 28% after 90 days of curing. The pH of the pore solution was not affected by the TWW utilization. The use of TWW resulted in an increase in chloride concentration in the pore solution of mortars. However, the actual chloride concentration in the pore solutions was very low after 90 days of curing [25].

Ghrais et al. conducted a study that concluded TWW can be used in concrete production without negatively affecting the water absorption and durability of the concrete. However, untreated wastewater reduced the compressive strength of the concrete by up to 13.9% after 120 days, while the use of TWW had no negative effect on the compressive strength of mortar [26].

In a study conducted by Sushma, the effects of different water sources on concrete production were examined. The study revealed that the use of sewage water (SW) in concrete production led to significantly lower compressive, flexural, and split tensile strength compared to fresh water (FW). Specifically, SW resulted in a remarkable 33.34% decrease in compressive strength, an 11.12% decrease in flexural strength, and a 14.89% decrease in split tensile strength when compared to fresh water (FW) sample. Moreover, the study highlighted the impact of water pH levels on concrete strength, indicating that an increase in pH levels resulted in a notable decrease in concrete strength. Furthermore, the presence of high levels of suspended solids and pH in SW was found to deteriorate the C-S-H responsible for concrete strength. These findings emphasize the significant influence of water source and quality on the mechanical

properties of concrete, with PW demonstrating superior performance compared to SW [27].

Gautam et al. found that using the primary treated wastewater (PTW) in concrete samples leads to lower strength, whereas the strength of samples mixed with secondary treated wastewater (STW) is comparable to control sample. The study suggests that concrete mixed with a combination of STW and PW can be used with an average characteristic strength of 23 MPa, thus increasing sustainability by reducing the amount of fresh water used in concrete [28].

In a comprehensive study conducted by Al-Ghusain et al., the researchers investigated the effects of different types of mixing water, namely the primary, secondary, and tertiary treated wastewater (PTW, STW, and TTW) on various properties of concrete. The study revealed that the impact of different water types on the slump and density of concrete was negligible. However, it was observed that the quality of the mixing water had a significant influence on the initial and final setting times of the concrete, with lower water quality leading to prolonged setting times. Furthermore, the study found that concrete mixed with PTW and STW exhibited lower strength and slower strength development over a period of up to one year. On the other hand, concrete mixed with TTW demonstrated higher strength at early ages, specifically at 3 and 7 days. The use of TWW in concrete mixing was also associated with an increased risk of steel corrosion, particularly when PTW was employed. In contrast, TTW was identified as a suitable alternative for mixing with concrete, as it exhibited similar properties to control samples in the properties of fresh concrete, strength development, and the corrosion potential [29].

Based on the experimental findings reported by Arooj et al., the use of TWW in plain concrete production was found to have no negative impact on its strength. The study specifically examined the effects of admixtures in conjunction with TWW and observed that it can yield comparable or even improved strength outcomes when compared with freshwater (FW). This suggests that TWW utilization can contribute to addressing water scarcity concerns. Notably, concrete made with polished filtered wastewater and TWW demonstrated enhanced tensile strength [30].

Keneshlo et al., conducted an experimental study to explore the incorporation of TWW in self-compacting concrete. The findings revealed that increasing the pH of TWW from acidic to alkaline conditions resulted in a decrease in the flowability of self-compacting concrete samples. Substituting TWW for tap water (TW) led to a 10% reduction in compressive strength at both 28 and 90 days, but increasing the pH of TWW had a positive effect on compressive strength. Additionally, the fracture toughness of the concrete decreased when using TWW instead of TW, but a higher pH value of TWW resulted in an increased fracture toughness. The study also detected that the use of TWW increased carbonation and water adsorption, but when TWW with a higher pH was utilized, carbonation and capillary water adsorption slightly decreased [31].

In their study, Bouaich et al., concluded that TWW can be effectively utilized in concrete production, considering the water quality met the limits of mixing water in the standard. The research indicated that concrete samples prepared with TWW exhibited slightly lower consistency compared to groundwater and had a negligible effect on the density or mechanical strength of the concrete. The use of TWW also led to a slight increase in the initial and final setting times. [32].

In the laboratory analysis conducted by Halawa et al., the impact of using different types of TWW as mixing water for reinforced concrete was examined, revealing diverse effects on concrete strength. Their study observed that when using PTW and STW, the strength of the concrete was lower compared to FW, and while TTW was utilized in concrete production better strength was exhibited after 28 days compare to the control sample [33].

Ahmad and Ayyad conducted a study affirming the suitability of treated sewage water for the production of concrete and mortar. The research revealed a significant enhancement in both compressive and flexural strength of concrete made with treated sewage water [34].

In the research conducted by Peighambarzadeh et al., the utilization of domestic TWW in concrete samples was investigated. The results revealed that substituting domestic TWW with FW in concrete led to an increase in both initial and final setting time, while workability remained unaffected. The use of TWW showed a slight improvement in fracture toughness, with an increase of 2-6%, although this effect was not significant [35].

In the study conducted by Asadollahfardi et al., the effects of industrial TWW on various properties of concrete were examined. It was found that the use of industrial TWW had minimal impacts on properties such as normal consistency of hydraulic cement, air content of freshly mixed concrete, final setting time of cement paste, as well as durability characteristics including water absorption and concrete density. Additionally, the electrical resistivity of concrete made with industrial TWW showed an average increase of 7.7%, indicating improved resistance to electrical conductivity,

while the potential for chlorine ion penetration was very low. Although the compressive strength of cement mortar was reduced by approximately 6.9% when industrial TWW was used, the compressive strength of concrete made with TWW still exceeded 90% of that control sample. Despite a decrease in tensile strength by 11.8% at 90 days, the overall findings support the utilization of industrial TWW in concrete [36].

In the study conducted by Ramkar AP et al., it was detected that the consistency, initial setting time, and final setting time of cement paste mixed with STW fall within the limits of Indian standard. Moreover, the utilization of STW in mortar production resulted in a higher compressive strength at both 28 and 60 days. No significant difference was observed in tensile strength, while flexural strength improved when STW was used [37].

Based on the experimental findings reported by Kanwal et al., the workability of concrete using various water types falls within the range of 25-50 mm, which is considered suitable for regular applications. The compressive strength of concrete made with treated SW is comparable to that of FW, indicating that treated SW can be effectively employed for both mixing and curing processes without compromising the strength of the concrete [38].

Chapter 3

THEORETICAL BACKGROUND OF THE STUDY

3.1 Introduction

The aim of this chapter is to establish a comprehensive background for the study, covering multiple aspects related to global concrete consumption and the vital role of concrete as a construction material. Investigation on mechanical and durability properties of fresh and hardened concrete, as well as exploring concrete ingredients and their specific properties. Furthermore, this chapter addresses the potential effects of various impurities in different types of water sources used in concrete production. Moreover, the critical topic of corrosion in concrete, identifying the elements that can contribute to its occurrence are studied. By understanding these influential factors, a deeper knowledge of concrete performance and durability is attained.

3.2 Concrete Definition and Consumption

Concrete is a composite material composed of carefully selected components. These components include cement, fine and coarse aggregates, and water. In a concrete mix, the combination of cement and water creates a cement paste. This paste not only fills the voids within the fine aggregates but also coats the surfaces of both the fine and coarse aggregates while effectively bonding them together. Typically, the cement paste occupies approximately 22-34% of the total volume of the concrete mixture.

In its initial state, before setting, the concrete is referred to as fresh or wet concrete. Once it has undergone the process of setting and hardening, it is known as hardened

concrete. Through the chemical reaction between water and cement, the molded concrete mix gradually cures and hardens, resulting in a hardened structure comparable to stone [39].

Today, concrete has attained the status of being the most extensively utilized construction material worldwide. Its widespread adoption is evident in the amazing global production of cement, which has reached an impressive amount of 4.1 billion tons. This substantial production signifies the vital role that concrete plays in the construction industry and its significant contribution to infrastructure development globally [5], [6]. In fact, the consumption of concrete is second after water among all materials used by humans with production of almost 55 billion tons, annually [4]. It's durability, strength, and cost effectiveness have made it an indispensable tool for architects, engineers, and builders worldwide [8].

The complexity of concrete requirements gives rise to the pursuit of attaining the most economically optimized mixture of concrete ingredients, thereby meeting performance criteria and specifications. The indicator of a suitably designed concrete composition is marked by the following physical attributes, which are to be noted as:

- **Workability:** The concrete, while still in its plastic state, must possess a sufficient level of flexibility.
- **Compliance with Strength Parameters:** The concrete mixture must satisfy the required strength.
- **Durability:** Concrete should demonstrate the ability to endure external forces and environmental factors.

- Additional characteristics, such as permeability and appearance, may exhibit variable degrees of significance depending on the concrete's location within a structure [40], [41].

3.3 Concrete Ingredients

Understanding the composition of concrete is crucial for realizing its structural and mechanical properties. This section provides an in-depth examination of the various ingredients that constitute plain concrete, including cement, aggregates, and water. By exploring the role of each component and their interplay, one can understand the complexity of concrete as a composite material and its significance in achieving desired performance characteristics.

3.3.1 Aggregate

Aggregates are essential granular materials utilized in the formation of cement-based materials such as concrete or mortar, generally speaking aggregate occupy 60 to 75% of the concrete volume and 70 to 85% of the concrete mass, and it can be in the form of sand, gravel, and crushed stone. It is worth noting that aggregates are usually stronger than concrete. Therefore, to ensure concrete strength, durability, and workability, it is crucial that the aggregates used are composed of hard particles and are free from harmful substances [41]–[43].

Aggregates can be classified in several ways, considering factors such as shape, size, material, and source. In the context of this discussion, the size classification of aggregates, which categorizes them into coarse and fine aggregates are focused specifically. According to the ASTM standard, aggregates smaller than 4.75 mm are considered fine aggregates, conversely are classified as coarse aggregates. The acceptable range of fine and coarse aggregates are set by ASTM C33. Figure 1

illustrated this limitation for fine and one range of coarse aggregate size from 4.75 to 25 mm [40], [44].

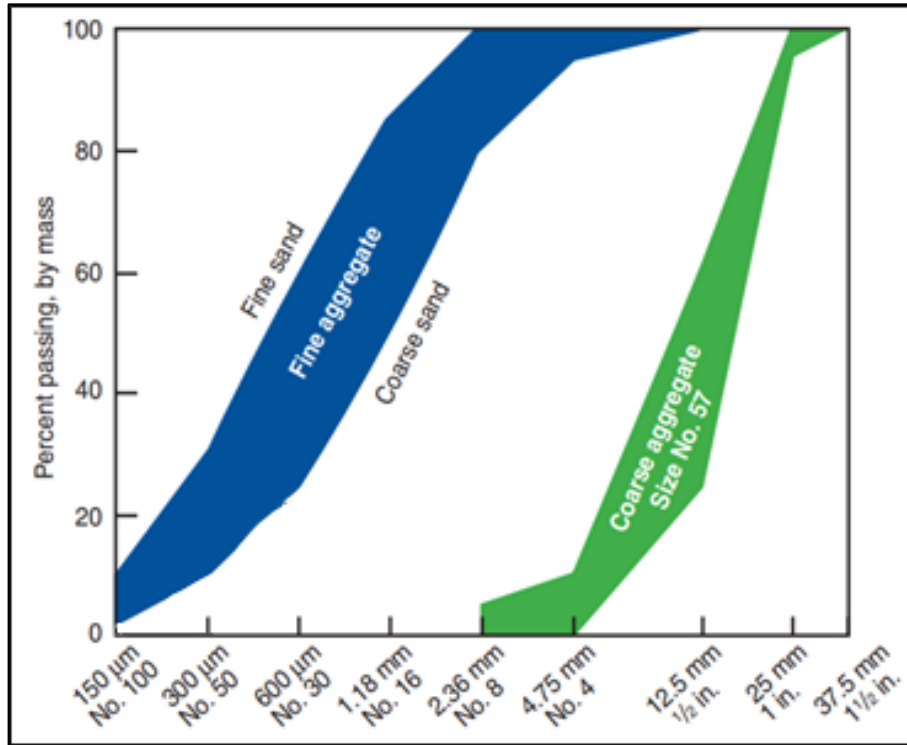


Figure 1: ASTM C33 limitations for aggregate size distribution [41]

3.3.1.1 Fine Aggregate

The source materials for fine aggregates are the same as those for coarse aggregates, with the exception that naturally occurring sand is used instead of gravel. Fine aggregates can be defined as the portion of an aggregate that passes through the 4.75 mm (No. 4) sieve and is retained on the 75-μm (No. 200) sieve [40], [42].

Table 2: Grading requirement for fine aggregate [45]

Sieve size		Percent passing by mass
9.5 mm	3/8 in.	100
4.75 mm	No. 4	95 to 100
2.36 mm	No. 8	80 to 100
1.18 mm	No. 16	50 to 85
600 μm	No. 30	25 to 60
300 μm	No. 50	5 to 30
150 μm	No. 100	0 to 10

The utilization of well-graded fine aggregate, adhering to regulations as it illustrated in Table 2, is crucial in achieving workable and cost-efficient concrete. Coarser aggregate can result in unworkable and harsh mixtures, while very fine aggregate increases the surface area, requiring more water and cement, making the concrete uneconomical. Well-graded fine aggregate ensures a balanced particle size distribution, maintain a favorable water-to-cement ratio, ensuring both workability and cost-effectiveness in concrete production [4].

3.3.1.2 Coarse Aggregate

Coarse aggregates play a vital role in the construction of concrete structures and are typically sourced from materials such as gravel and crushed stone. These materials encompass a range of geological compositions, including trap rocks, granite, limestones, and sandstones, which have been found to be suitable for producing crushed stone aggregate predominantly retained on the 4.75-mm [17], [40].

It is important to note that the physical, chemical, and mechanical properties of coarse aggregates have a massive impact on the overall properties of concrete. Their

characteristics can influence the workability, strength development, and resistance to environmental factors [43].

In addition to considering the properties of coarse aggregates, the ASTM C33 standard provides specific requirements for the use of coarse aggregates in concrete based on their ranging size. This classification is essential in ensuring the appropriate selection and proportioning of aggregates for concrete mixtures, Table 3 is the standard limits for the coarse aggregate utilized in this study [45].

Table 3: Grading requirement for coarse aggregate (4.75 to 19 mm) [45]

Nominal size	Amounts finer than each sieve, Mass (%)				
	25.0 mm	19.0 mm	9.5 mm	4.75 mm	2.38 mm
19 to 4.75 mm	100	90 to 100	20 to 55	0 to 10	0 to 5

3.3.2 Water in Concrete

Water quality and quantity are crucial parameters that significantly influence various properties of concrete, including strength, workability, durability, and permeability. The quantity of water, which is often specified by using the water-to-cement (w/c) ratio parameter, plays a vital role in determining the properties of fresh and hardened concrete [17], [46].

3.3.2.1 Importance of Water Quantity in Concrete

To ensure sufficient hydration of cement, a w/c ratio of 0.25 is typically adequate. However, if workability is a consideration, a higher ratio, typically above 0.35, may be necessary, especially without the use of admixtures. It is important to strike a balance between the water content and workability to achieve the desired concrete performance [47].

Nevertheless, a higher water content in concrete results in an augmented pore structure and heightened permeability following the hardening process. Excessive permeability enables the penetration of detrimental substances, consequently diminishing the long-term durability. Conversely, a lower water content detrimentally affects the workability and compaction of the concrete. Also leads to a higher porosity and therefore permeability, reducing the strength and durability of the concrete. Hence, careful control of water quantity is essential to optimize concrete properties [17].

3.3.2.2 Importance of Water Quality in Concrete

The quality of water used can have significant implications for various aspects of concrete, including its setting time, strength development, and durability properties. Despite an extensive review of the available literature [4], [17], [46]–[48], a dearth of comprehensive studies on this particular topic is apparent. Adam Neville used the title "Water, Cinderella Ingredient of Concrete" in his article to draw attention to the significance of water quality and the lack of standards in this aspect [49]. Among the references consulted, a common clause regarding water quality emerges: "If the water is fit for drinking, it can be used in making concrete." Although this clause may appear suitable, there are instances where water with low concentrations of sugar, considered suitable for drinking, can adversely impact the characteristics of concrete. Conversely, there are water sources that are not suitable for drinking but have shown promise as viable water sources in the concrete industry [50], [51]. Given the current global challenges of population growth, urbanization, and climate change leading to water scarcity, it may not be appropriate to prioritize the use of potable water in concrete production. Efforts have been made globally to address this issue by exploring the impacts of different source of water with various concentration of impurities in concrete production as it mentioned in the last chapter [41], [52]–[60].

Nonetheless, due to the environmental concerns, ASTM C1602 was established to fulfill this gap. This standard permits the use of questionable water and the water from concrete batching plant, as it demonstrated in Table 4, if the resulting samples reach 90% of the strength of samples made with fresh water. Additionally, the setting time of concrete made with questionable water should not deviate more than 60 minutes earlier or 90 minutes later compared to the setting time of concrete made with fresh water, and additionally there are some limitations for water quality as it covered in Table 5. However, beyond these provisions, there is still a lack of standardized tests to determine the suitability of water quality, making it challenging to make definitive judgments [13].

Table 4: Concrete performance requirements for feasibility of mixing water [13]

Performance	Limit
Compressive strength, min % of control at 7 days	90
Time of setting, deviation from the control sample	1:00 hr earlier to 1:30 hr later

Table 5: Chemical limitation for suitability of mixing water [13]

Maximum concentration in combined mixing water		Limits (ppm)
Chloride (Cl ⁻)	Prestressed concrete	500
	Other reinforced concrete	1,000
Sulfate (SO ₄)		3,000
Alkalies (Na ₂ O + 0.658 K ₂ O)		600
Total solids by mass		50,000

3.3.2.3 Water Sources in Concrete Production

The followings are the different type of water sources used in concrete production:

- Potable water: water that is suitable for human consumption and complies with national and international drinking water standards.
- Non-potable water: Water that is not suited for human consumption due to taste or odor, such as well water, streams or lakes water, and municipal reclaimed water.
- Concrete batching plant sourced water: this includes processing water or collected stormwater in the concrete batching plants.
- Mixed water: a mixture of above sources, addressing that water sources may be mixed during concrete production [41].

3.3.3 Impacts of Water Impurities on the Properties of Concrete

Excessive impurities in the mixing water used for concrete production can have detrimental effects on the properties of the resulting concrete. These impurities can give rise to undesirable consequences such as efflorescence, discoloration, reinforcement corrosion, and decrease in strength and durability of concrete. Consequently, it becomes crucial to establish either optional limits for specific characteristics like chlorides, sulfates, alkalis, and total solids, or conduct appropriate tests to assess their impact on the concrete's properties. It should be noted that even impurities that may appear to have minimal influence on strength and setting time can still adversely affect the durability and other critical properties of the concrete. Hence, careful consideration of the quality of water is essential to ensure the overall performance and longevity of the concrete structure. Table 6 showed common impacts of high solid content on the properties of concrete [41].

Table 6: Effect of water quality on concrete properties [41], [61]

Water source with	Water demand	Setting time	Compressive strength	Permeability
Solid contents within ASTM C94 limits	↔	↔	↔	↔
Solids contents more than ASTM C94 limits	↑	↓	↓	↑

3.3.3.1 Chloride and Sulfate

The presence of high concentration of chloride ions in the water raises concerns about their potential adverse impact on the corrosion of reinforcing steel in concrete. Chloride ions in forms of acid soluble by concentration of more than 0.2 to 0.4% by the mass of cement can damage the oxide film on the steel, resulting in a highly alkaline chemical environment within the concrete. These chloride ions can ingress the concrete through various sources, including deicing salt and the environment, and mixing water. Establishing an acceptable limit for chloride content in mixing water is challenging, as it depends on the specific structure and the environmental conditions.

Natural water with high dissolved solids may include substantial amounts of sodium sulfate and/or sodium chloride, which can be allowed in greater proportions. However, when dealing with a high sulfate content in mixing water, concerns arise regarding the potential for expansive reactions and deterioration due to sulfate attack. While water with up to 10,000 ppm, sodium sulfate has been utilized effectively in some studies, it is advisable to consider the limits outlined in ASTM C94 [12], [41]. Further insights into the effects of these impurities can be found in Table 7.

Table 7: Impacts of chloride and sulfate on the properties of concrete [12]

Impurity	Effects
Chloride (Cl ⁻)	Caused calcium hydroxide to leach.
	Induces compound modifications in Portland cement, leading to a loss of strength.
	Causes gypsum formation, products of cation exchange reactions that cause expansion but are usually associated with weight and strength loss.
Sulfate (SO ₄)	A post-hardening period of ettringite formation.
	Consumes portlandite
	Decalcification of C-S-H gel cause expansion, propagation, and disintegration.
	Significant weight and strength loss.

3.3.3.2 Alkali Bicarbonate and Carbonate

The presence of sodium and potassium carbonates and bicarbonates (e.g., potassium carbonate is mainly used in the production of soap and glass and sodium bicarbonate is commonly called as baking soda and used in cooking) in concrete can have diverse effects on the setting time of cement paste. For example, sodium carbonate can cause faster setting, but bicarbonates can either accelerate or retard the setting process depending on the chemistry of the cement. However, it is important to note that high concentrations of these substances can have a negative impact on the concrete's strength. Furthermore, it is crucial to consider the potential risks associated with alkali-aggregate reactions, which can be worsened by the presence of these substances [41].

3.3.3.3 Acidic Waters

The suitability of mixing water with acidic characteristics can be assessed by examining the concentration of acids present in parts per million (ppm). While pH measurement is sometimes used as an indicator, it does not supply the most accurate assessment of acid or base reactivity as it only measures intensity. Generally, mixing

water that has common inorganic acids like hydrochloric and sulfuric acid, with concentrations up to 10,000 ppm, does not have detrimental effects on concrete strength. However, it is important to avoid mixing water with pH values below 3.0, as they may pose handling difficulties. Therefore, when considering the suitability of mixing water with acidic properties for concrete production, it is advisable to evaluate the concentration of acids in ppm rather than relying solely on pH measurements [41].

3.3.3.4 Alkaline Waters

Sodium hydroxide (NaOH) in the mixing water with concentration of below 0.5% by the cement mass has little influence on concrete strength. However, higher concentrations can potentially lead to a decrease in concrete strength, as long as it does not result in a rapid setting. Potassium hydroxide (KOH) concentration, up to 1.2% by the mass of cement have marginal impact on concrete strength when used with certain types of cement. However, with other types of cement, the same concentration may result in a reduction in 28-day strength. It is important to consider the possibility of increased alkali-aggregate reactivity when using potassium hydroxide in concrete mixtures [41].

3.3.3.5 Organic Impurities

The impact of organic substances on the setting time and strength of Portland cement and concrete is a complicated problem. Natural waterways include organic elements such as surface loams. When dealing with strongly colored waters, those with notable odors, or those with obvious green or brown algae, extreme caution is advised. Common organic impurities include humus-based substances having tannates or tannic acid [41].

3.3.3.6 Sugar

The introduction of minor quantities of sugar to cement has the potential to delay the setting process. Although the 7-day strength of the concrete may be adversely affected, there could be an improvement in the 28-day strength. However, if the sugar content reaches 0.25% of the mass of cement, it can result in rapid setting and a significant reduction in the strength. When the mixing water contains less than 500 ppm of sugar, it typically does not have a detrimental impact on the concrete strength. [41].

3.3.3.7 Oil

The presence of oil in mixing water can vary, with petroleum-based mineral oil being one type that is often encountered. If the mineral oil does not contain animal or vegetable oils, its impact on the development of concrete strength may be less significant compared to other oils. However, when the concentration of mineral oil exceeds 2.5% of the cement's mass, it can result in a reduction in strength by more than 20%. Additionally, oils can interfere with the effectiveness of air-entraining agents in the concrete mixture [41].

3.3.3.8 Algae

To mitigate the potential adverse effects on concrete strength, it is advisable to avoid using water that contains algae in concrete production. The presence of algae in water can have detrimental impacts on concrete strength, either by hindering the hydration process of cement or by introducing excessive air content into the concrete. Furthermore, if aggregates are contaminated with algae, it can weaken the bond between the cement paste and the aggregates [41].

3.3.4 Cement

Cement, a fundamental component of concrete, is available in various types that are carefully formulated to suit specific concrete applications and environmental

conditions. The process of hydration, wherein cement chemically reacts with water, plays a crucial role in the transformation of cementitious materials, such as mortar and concrete, into hardened structures. One notable type of cement is hydraulic cement, characterized by its ability to solidify and gain strength through a chemical reaction with water, even in submerged or moist conditions. Among the different varieties of hydraulic cement, Portland cement stands out as the most commonly utilized type. Additionally, natural, and artificial pozzolans (such as fly ash and silica fume) are frequently used as cementitious components in concrete. [41]

3.4 Properties of Cement Paste

The properties of cement paste have a considerable influence on the quality and performance of fresh concrete. These properties, including consistency, workability, and setting time, are critical for determining the rheological behavior of the concrete mixture. In the initial stages, the rheological properties of the cement paste dictate the flow characteristics of the concrete, as it can be viewed as a suspension of aggregate particles in the cement paste.

As the concrete ages, the cement paste continues to play a crucial role in various aspects. It significantly impacts the development of concrete strength, the evolution of temperature after placement, drying shrinkage, and swelling during wetting. Furthermore, the phase composition of the cement paste strongly influences the corrosion resistance and durability of concrete structures. The specific composition and interactions within the paste are crucial factors that determine the long-term performance and service life of concrete constructions [62].

3.4.1 Setting Time of Cement Paste

The introduction of water to cement initiates a process in which the resulting paste undergoes simultaneous changes, including stiffening, strength development, and a reduction in consistency. The term "setting" refers to the hardening process of the cement paste.

The setting process can be categorized into two stages: initial setting and final setting, representing different degrees of stiffening of the cement. The initial set refers to the onset of hardening, indicating the point at which the cement paste becomes unworkable. It signifies the beginning of the transition from a fluid state to a solid state. On the other hand, the final set represents the complete hardening of the cement paste. It is important to note that the final set does not occur over an excessively prolonged period to ensure that construction activities can resume within a reasonable period after the concrete placement [39]. The overall process of setting time after adding water to the mixture can be seen in Figure 2.

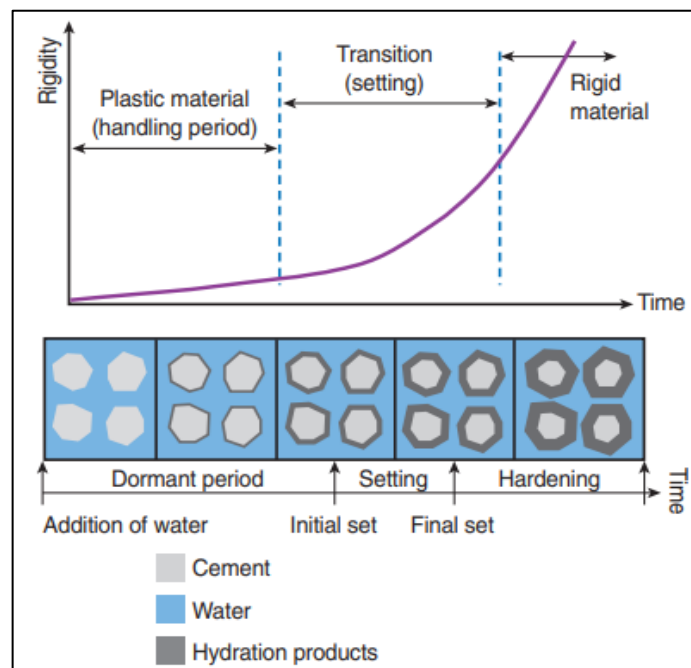


Figure 2: Setting process in concrete after adding water [41]

3.5 Workability of Concrete

The properties including the ease of placing, compacting, and finishing freshly mixed concrete, as well as its ability to resist segregation, are collectively referred to as workability. Workability comprises two fundamental aspects: consistency, related to the flow behavior, and stability, indicating resistance to segregation. The adequate level of workability required for the placement of concrete is influenced by the method of placement, the compacting technique employed, and the concrete type.

Several factors influencing the workability of concrete, such as: [41]

- The method of transportation and its duration,
- The quantity and characteristics of cementitious materials,
- The consistency of the concrete, as indicated by its slump value,
- The grading, shape, and surface texture of both the fine and coarse aggregates,
- The presence of entrained air within the mixture,
- The water content within the concrete,
- The concrete and the surrounding ambient air temperatures,
- The implementation of admixtures.

3.6 Compressive Strength of Concrete

Compressive strength refers to the maximum resistance exhibited by a concrete when subjected to axial loading. This parameter is typically measured and expressed in unit of megapascals (MPa) in the SI unit at the age of 28 days, although alternative test ages may also be employed. It is critical to understand the relationship between 28-day strength and other test ages. In general, seven-day strengths are considered to be roughly 75% of the 28-day strength, whereas 56-day and 90-day strengths are 10% to 15% greater than the 28-day strength.

The achievement of compressive strength in concrete is influenced by various factors, including the water-to-cement ratio, the quality of water, the degree of hydration progression, the curing methods and environmental conditions employed, as well as the age of the concrete specimen.

3.7 Splitting Tensile Strength of Concrete

Tensile strength refers to the maximum load a material can bear without fracturing when subjected to stretching, divided by the original cross-sectional area of the material. It is commonly expressed in units of force per unit area (MPa). When the applied stress is below the tensile strength, the material exhibits either complete or partial elastic recovery, returning to its original shape and size. However, once the stress surpasses the tensile strength, the material undergoes plastic deformation and rapidly forms fracture.

Methods for determining the tensile strength of concrete can be broadly classified into direct and indirect methods. Direct methods encounter difficulties in properly holding the specimen in the testing machine without introducing stress concentrations and ensuring the application of uniaxial tensile load without eccentricity. To overcome these challenges, indirect methods have been developed. In these tests, a compressive force is applied to a concrete specimen in a manner that induces tensile stresses leading to failure. The tensile strength of concrete is then defined as the stress at which failure occurs. One well-known indirect test for determining tensile strength is the splitting tensile strength test.

The splitting test is gaining popularity due to its advantages, including simplicity of execution, more uniform results compared to other tests, closer proximity to the actual

tensile strength of concrete, and the ability to use the same molds and testing machine for both compression and tension tests. Direct tensile strength is normally between 8% to 12% of compressive strength. Furthermore, the splitting tensile strength of concrete is generally between 8% and 14% of its compressive strength.

3.8 Durability and Permeability of Concrete

The durability of concrete is an important property that ensures its ability to withstand the environmental conditions throughout the lifespan of a structure. Maintaining durability is crucial, as both external environmental factors and internal concrete agents can compromise it. The causes of durability issues can be classified as physical, mechanical, or chemical in nature. Physical causes arise from frost action and thermal property disparities between aggregates and cement paste, while mechanical causes primarily result from abrasion. Chemical causes, including sulfate and acid attack, exposure to seawater, and chloride-induced electrochemical corrosion of steel reinforcement. Since these chemical attacks occur within the concrete mass, the aggressive agents must penetrate the entire concrete volume, necessitating a permeable concrete matrix.

Permeability refers to the ease with which liquids or gases can penetrate through concrete. The permeability of concrete is influenced by the presence of capillary pores, with capillary porosity playing a key role. The permeability of concrete is primarily governed by the water cement ratio (w/c) and the degree of hydration. Lower water quantity results in reduced permeability, particularly below a w/c ratio of approximately 0.6 when the capillaries become segmented or discontinuous. Moreover, as hydration progresses and fills some of the original water space, the

permeability decreases for a given w/c ratio, with a more pronounced reduction observed at lower w/c ratio [46].

3.9 Water Absorption and Porosity

The physical properties of concrete, particularly absorption and porosity, are crucial factors influencing its strength and durability. Absorption refers to the ability of concrete to absorb moisture through capillary action, permeation, and diffusion, and it is directly linked to its durability.

Porosity, also known as void content, represents the presence of voids within the hardened concrete and has an inverse relationship with its strength. Higher porosity and absorption rates can increase the permeability of concrete, making it more vulnerable to damage from aggressive substances such as chlorides, sulfates, and carbon dioxide. This increased permeability can also make the concrete more prone to corrosion of the reinforcement.

3.10 Corrosion Resistance of Concrete

In high-quality concrete, the reinforcing steel is protected against corrosion due to its exposure to a cement paste covering with a pH level between 12.5 and 13.5. This protective environment leads to the formation of a passive film on the steel surface, ranging in thickness from 1 to 100 nanometers. The role of the cement paste in concrete is to maintain this passivation effect as long as specific requirements, including lower permeability, higher homogeneity, a greater thickness of paste cover surrounding the reinforcement, and higher calcium hydroxide content.

However, concrete is susceptible to external factors such as CO₂, SO₂, chloride, and sulfate solutions, which can cause the pH to decrease below 11. In the presence of

chloride ions, the passivation of steel requires a higher pH value. Hypotheses have been proposed to explain the mechanism of passive film destruction in the presence of chlorides, including chloride ion penetration into the passive film and the influence of an electric field generated around adsorbed chloride ions, promoting the diffusion of Fe_2^+ ions from the metal surface.

The corrosion of iron in concrete is an electrochemical process that occurs in the presence of an electrolyte and access to oxygen. Due to variations in ion concentrations and the heterogeneous nature of steel, local electrical cells in the form of anodic and cathodic micro-areas are formed on the metal surface. The anode undergoes the process of iron oxidation. Once the anode and the cathode are connected by a metallic conductor, allows the flow of electrons, while the surrounding medium acting as an electrolyte, facilitates ion transport through diffusion, thus completing the cell circuit as detailed in Figure 3.

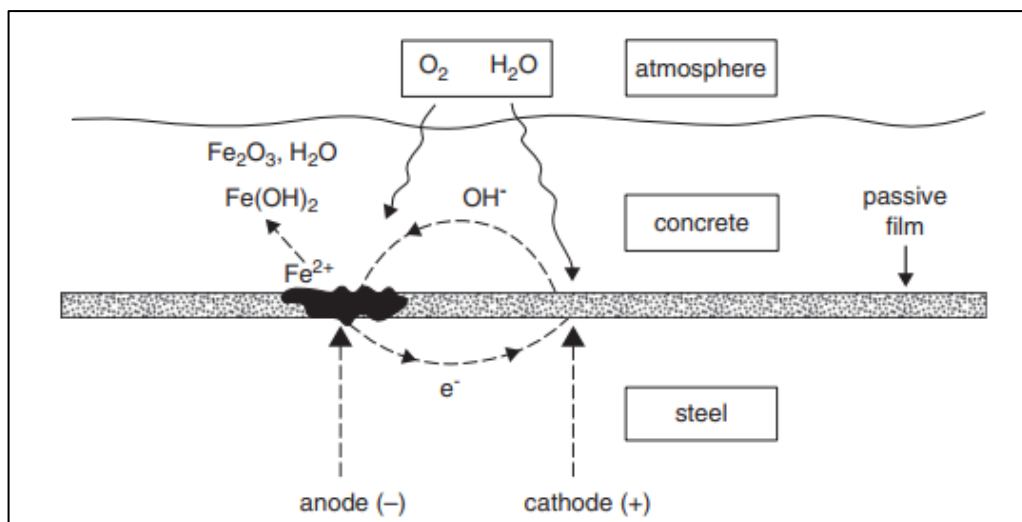


Figure 3: Visual representation of corrosion process in reinforced concrete [62]

The corrosion rate depends on the electrolyte conductivity and the potential difference between the anode and cathode. The availability of oxygen, necessary for the cathodic

reaction, can also limit the corrosion rate. The polarization of electrodes occurs because of the corrosion current, causing their potential to increase compared to equilibrium potential values. The dynamically maintained potential value plays a significant role in determining the corrosion rate. In the case of steel in a paste environment, strong polarization of anodic micro-areas occurs, increasing the anodic potential and reducing the potential difference with the cathode. This leads to the passivation of steel through the formation of oxide films.

The corrosion rate of steel in concrete is higher in the presence of chloride ions, as they reduce the anodic polarization and enhance the paste's conductivity. Other factors influencing concrete resistivity include a low w/c ratio, low humidity, and decreased temperature, all contributing to an increase in resistivity. Therefore, in dry or water-immersed concrete, the corrosion of steel is negligible [62].

Chapter 4

MATERIALS AND EXPERIMENTAL PROCEDURES

4.1 Introduction

This chapter aims to provide a comprehensive overview of the materials utilized and the methodologies employed to investigate the research objectives. The selection and preparation of materials will be explained in detail, along with the experimental procedures followed to ensure the validity and reliability of the study outcomes.

4.2 Materials Used

In this section, the materials used in this study are extensively discussed. This includes an in-depth analysis of the primary ingredients of concrete, such as cement, aggregates, and water. The properties and specifications of the selected materials, including their chemical composition, particle size distribution, and physical characteristics, are thoroughly examined.

4.2.1 Cement

In this study, CEM II/B-S Portland slag cement of class 42.5 N was utilized. The physical and chemical properties of the cement adhere to the limits established by ASTM C150 standards is outlined in the Table 8.

Table 8: Physical and chemical properties of cement [63]

Property	Value	Property	Value
CaO	60.88%	Al ₂ O ₃	2.19%
SiO ₂	19%	Loss on Ignition	0.98%
Fe ₂ O ₃	2.89%	Specific Gravity	2995 kg/m ³
SO ₃	2.55%	28-day Compressive Strength	42.5 MPa
MgO	2.27%	Initial Setting Time	190 +/- 30 min

4.2.2 Fine Aggregate

The fine aggregate used in this study was crushed limestone from Besparmak Mountain in Northern Cyprus, with a maximum diameter of 5 mm. A sieve analysis was performed in accordance with ASTM C136-2019, and the results were compared by the ASTM C33-2018 standard as shown in Figure 4. Additionally, the physical properties, such as relative density and water absorption, were determined using the ASTM C128-2015 standard. The results for the relative density in the saturated surface dry (SSD) condition was 2.74, while the water absorption rate was 1.38% and the passing percentage from 600 µm based on the sieve analysis was 38% [44], [45], [64].

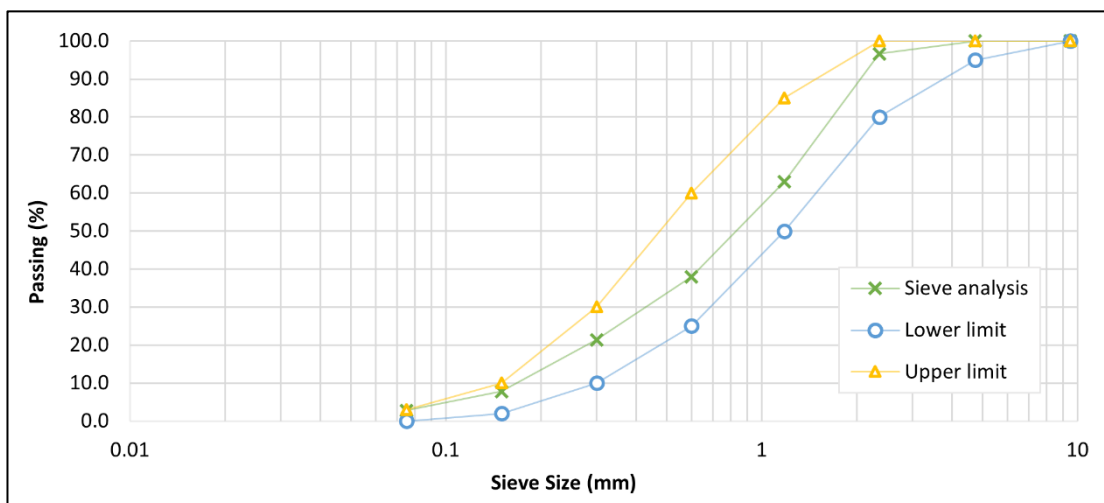


Figure 4: Sieve analysis of fine aggregate

4.2.3 Coarse Aggregate

The coarse aggregate used in this study was crushed limestone from Besparmak Mountain in Northern Cyprus. Sieve analysis was conducted in accordance with ASTM C136-2019, and the optimal proportion for each size was determined based on the ASTM C33-2018 limits. Sieve analysis of coarse aggregate is presented in Figure 5. The average relative density in the SSD condition was found as 2.70, while the average water absorption was 0.91% by following the ASTM C127-2015 [44], [45], [65].

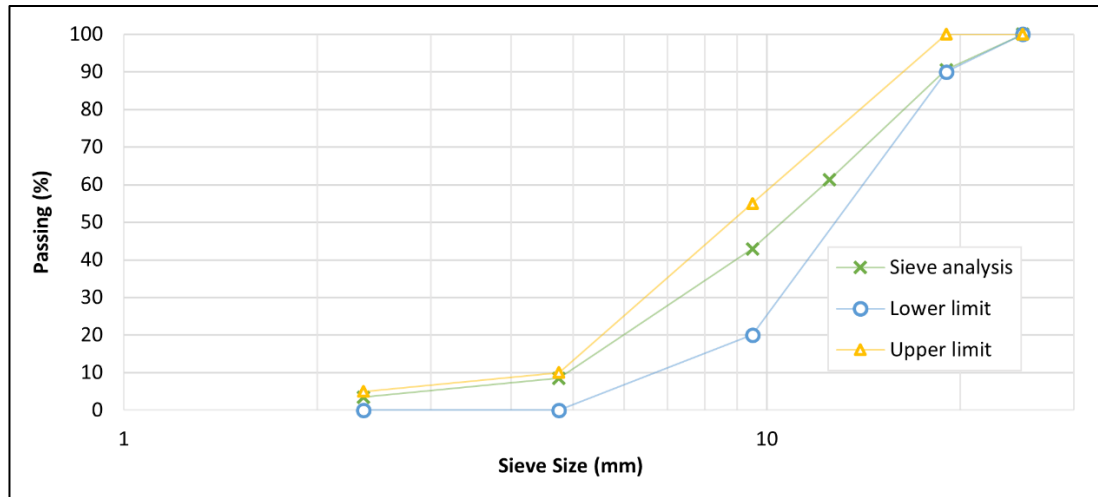


Figure 5: Sieve analysis of coarse aggregate

4.2.4 Corrosion Test Rebars

In this study, carbon steel rebar with the density of 7.86 g/cm³ and diameter of 14 mm were used. Table 9 provides the details of the rebars, including length and weight. For preparation of the rebars, they were first cut to the required length and then brushed to eliminate any impurities. Then, the rebars were rinsed with acetone to remove any oil residue and subsequently air-dried. Once the rebars were weighed, to ensure the required cover from the top of the specimen, they were painted as given in Figure 6.

As shown in Figure 7, spacers were placed for each rebar to secure their position during the molding process and then they were removed.

Table 9: Characteristics of rebars utilized in concrete for corrosion test

Rebars		
Number	Length (cm)	Weight (g)
1	29.7	346.0
2	29.8	361.0
3	29.5	355.9
4	30.0	373.7
5	29.5	365.5
6	30.3	371.8
7	29.9	364.3
8	30.1	358.3
9	29.4	354.1

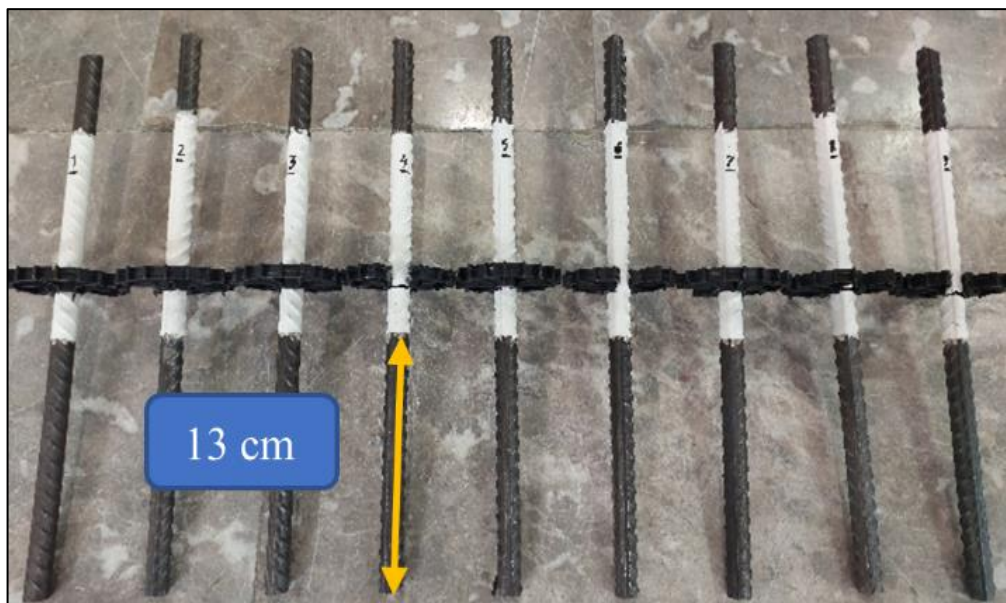


Figure 6: Preparation of rebars for corrosion test



Figure 7: Visual representation of fixed rebars in concrete specimens

4.2.5 Mixing and Curing Water

As mentioned in chapter 3, tap water (TW) and treated wastewater (TWW) were used for mixing and curing purposes of concrete in different groups combination. Their chemical and physical properties were evaluated through laboratory experiments in the Chemistry Department of Eastern Mediterranean University. The results are presented in Table 10 and the sources of these water are as follows:

1. Tap water (TW): Sourced from the Famagusta municipality,
2. Tertiary treated wastewater (TWW): Sourced from the Gazimağusa wastewater treatment plant prior to chlorination.

Table 10: Chemical and physical properties of TW and TWW

Parameter	TW	TWW
pH	8.18	10.12
Electrical Conductivity (EC) ($\mu\text{S}/\text{cm}$)	242.1	1083
Total Dissolved Solids (TDS) (mg/l)	121	541
Total suspended solids (TSS) (mg/l)	3	29
Total solids (TS) (mg/l)	124	570
Salinity (ppm)	120	540
Electric Resistivity ($\text{k}\Omega$)	4.13	0.92
Chemical Oxygen Demand (COD) (mg/l)	4.3	69.8
Biochemical Oxygen Demand (BOD_5) (mg/l)	1.4	3.3
Chloride (Cl^-) (mg/l)	24.6	276.7
Sulfate (SO_4^{2-}) (mg/l)	4.2	16.6

4.3 Experimental Procedure Adopted for This Study

This section focuses on the mix design and proportions, specimen types, casting and curing techniques, and specific standards that were utilized to evaluate the mechanical and durability properties of the produced concrete specimens. Conducted 13 tests were workability, normal consistency, setting time, compressive strength of mortar, compressive strength of concrete, splitting tensile strength of concrete, ultrasonic pulse velocity, density, water absorption capacity, voids percentage of concrete, corrosion potential through half-cell potential, and pH value measurement. Additionally, this study explores the corrosion rate, mass loss, and crack behavior of reinforced concrete through an accelerated corrosion test by an impressed voltage technique (ACTIV).

4.3.1 Concrete Mix Design, Specimen Types and Preparation

BRE method was utilized to develop the mix design [66]. The objective was to achieve the concrete with strength of 40 MPa and a slump value of 13 cm, while maintaining a water-to-cement ratio of 0.5 and allowing for a 10% defective proportion. Therefore, three groups of specimens were prepared and named as follows:

- Group I: (TT) Tap Water for mixing and curing as a control sample,
- Group II: (WT) Treated Wastewater for mixing and Tap Water for curing,
- Group III: (WW) Treated Wastewater for both mixing and curing.

Through a trial-and-error process, according to Appendix A the optimal proportions of ingredients in each concrete group were determined and presented in Table 11.

Table 11: Concrete groups mix design and utilized water type

Concrete group	Cement	Fine aggregate	Coarse aggregate			Water	Water type	
		5 mm	10 mm	14 mm	20 mm		mixing	curing
	kg/m ³							
TT	450	780	330	380	240	225	TW	TW
WT	450	780	330	380	240	225	TWW	TW
WW	450	780	330	380	240	225	TWW	TWW

A total of 159 specimens, in different shapes and sizes were prepared in accordance with the ASTM C192-2019 standard, and subjected to different curing conditions to cover the diversity of the testing aims. It is noteworthy that, each type of specimens and curing combination consisted of three replicates, allowing for reliable statistical analysis [67]. The concrete specimens include:

- 63 cubic specimens with dimensions of 150 x 150 x 150 mm for determining the Ultrasonic pulse velocity and compressive strength of concrete,
- 63 cylindrical specimens with dimensions of 100 x 200 mm for determination of splitting tensile strength and pH value of concrete,
- 18 cylindrical specimens with dimensions of 100 x 200 mm with a 14 mm rebar for determination of the half-cell potential and accelerated corrosion test,
- 9 cubic samples with dimensions of 100 x 100 x 100 mm for assessing the density, water absorption capacity and voids percentage of concrete,
- 6 cubic samples with dimensions of 50 x 50 x 50 mm for evaluating the compressive strength of mortar.

The concrete mixtures were prepared by following the mix design proportions of cement, fine and coarse aggregates and intended type of water. The machine mixing method was utilized to achieve thorough blending and uniform distribution of the constituents. The mixing duration adhered to the guidelines specified in the standard, ensuring proper homogeneity [67].

4.3.2 Concrete Curing Methods

The concrete specimens after preparation and demolding were cured in TW or TWW for varying durations in a controlled environment. The specific curing conditions were determined based on the concrete groups (TT, WT, WW). Careful monitoring of temperature and humidity levels was maintained throughout the curing process to provide optimal conditions as followed by ASTM C192-19 [67].

4.3.3 Setting Time of Cement Paste

The amount of water required to achieve normal consistency of the cement paste was determined before conducting the setting time test, following ASTM C187-16 and ASTM C305-20, and then the initial and final setting time of cement paste was

conducted with the Vicat apparatus by following the ASTM C191-21 standard [68]–[70]. The importance of this test is due to the requirement of ASTM C1602-22 on the feasibility of utilizing TWW in concrete production and to evaluate the impact of TWW on the setting properties of cement paste.

4.3.4 Workability

The workability tests were performed on freshly mixed concrete samples in accordance with the procedures outlined in ASTM C143-20. These tests aimed to assess the consistency and flowability of concrete. During the tests, the slump cone method was employed to measure the slump of the concrete. To ensure accurate and reliable results, multiple samples were tested under controlled conditions. The testing was conducted at a specified time interval after mixing [71].

4.3.5 Ultrasonic Pulse Velocity Test

The pulse velocity test is a non-destructive technique used to assess the quality of concrete based on the ASTM C597 standards. In this method, the concrete quality assessment is done by measuring the velocity of ultrasonic pulses as they pass through the concrete specimen. Afterward, by comparing the result with the quality grading range, we can draw a conclusion about the uniformity of the concrete and detect the presence of cracks, voids, or other anomalies in the specimens [72]. This grading range serves as a reference for evaluating the overall quality of concrete specimens.

In this study, the pulse velocity test was conducted for a total number of 63 samples with the dimension of 150*150*150 mm, and in 7 different curing intervals (7, 14, 28, 56, 90, 120, 160 days) by using the PUNDIT equipment, as it shown in Figure 8.



Figure 8: Ultrasonic pulse velocity test apparatus

4.3.6 Compressive and Tensile Strength Measurement

To assess the compressive strength of mortar, the procedures outlined in ASTM C305-20 were followed [73]. The water quantity in mortar was determined using a flow-table, following the guidelines specified in ASTM C1437-20 [74]. Subsequently, the mortars were cast with blinder and molded in accordance with ASTM C109-21 as in Figure 9a. For the first 24 hours, the specimens were sealed as in Figure 9b and cured in a curing room with 99% relative humidity and a temperature of around 25 °C. Afterward, the specimens were cured in tap water (TW) for 7 days to evaluate the impact of using TWW as mixing water on the compressive strength of mortar specimens.



Figure 9: a) Mortar specimen b) Curing condition of mortar specimens

In compressive strength determination of produced concrete specimens, the Impacts of utilizing TWW in mixing and curing purposes of concrete with curing period from 7 days to 180 days has been evaluated. For the accuracy of the result, each concrete group and curing intervals had three representative samples, where their simple average was used to determine the representative value. The compressive strength of these specimens was evaluated based on the ASTM C39 testing method [75].

In this test, the splitting tensile strength of concrete specimens were evaluated using the ASTM C496-17 testing procedure [76]. Here, concrete specimens were cast and cured with TW and TWW for various curing durations with 7 different duration periods, from 7 to 180 days. To ensure accuracy, three representative samples were selected for each concrete group and curing duration. These tests were conducted to investigate the effects of using TWW on splitting tensile strength and strength development rate in a long time period.

4.3.7 Density, Water Absorption, and Porosity of Concrete

A total number of 9 cubic samples, with three representative samples for each group, were used to evaluate the impact of utilizing TWW on the density, water absorption, and porosity of hardened concrete specimens. These properties of hardened concrete, specifically the porosity, had a significant impact on the overall durability characteristics of hardened concrete. This test was conducted on samples with 28 days of curing age, while the test procedure followed the ASTM C642-21 standard [77].

4.3.8 pH Value of Hardened Concrete

The pH value in concrete is typically maintained at a high value above 12, creating a protective environment for the reinforcing steel embedded within the concrete. This elevated pH value contributes to the formation of a passive oxide film around the rebar, which acts as a protective barrier against corrosive elements. However, if the pH value

drops below 9, it can compromise this protective passive layer, leading to the initiation of the corrosion process. Therefore, evaluating the pH value makes it possible to verify the stability of this protective environment [17], [78].

The pH of the hardened concrete was measured after 28 days of curing, using the method proposed by Kakade [79]. As shown in Figure 10, this method involves creating a concrete powder from the pre-cleaned concrete surface, dissolving it in distilled water, and measuring the pH of the concrete solution using a pH meter.



Figure 10: Concrete pH measurement process

4.3.9 Half-Cell Potential Test

The specimens were cured for 28 days. After curing, those specimens were kept in the laboratory environment for various time intervals of 28, 56, and 120 days for testing. After each interval the half-cell potential test has been conducted to evaluate the effects of using TWW in mixing and/or curing procedure on the corrosion potential of reinforced concrete (Figure 11). This experiment followed the ASTM C876-22b. In this test, copper/copper sulfate electrode was used as a reference electrode to measure the potential difference between the reference electrode and the rebar inside the concrete. Further, the result was then compared with the interpreted potential

difference presented by the ASTM standard to evaluate the probability of corrosion inside the reinforced concrete samples [80].



Figure 11: Half-cell potential test equipment

According to ASTM standard when using copper/copper sulfate reference electrode, potential measurements are interpreted as follows:

- If the potential is more positive than -200 mV, there is a less than 10% probability that corrosion is occurring.
- If the potential is between -200 mV and -350 mV, the likelihood of corrosion is uncertain.
- If the potential is more negative than -350 mV, there is a 90% or greater probability that corrosion is occurring.

4.3.10 Accelerated Corrosion Test by Impressed Voltage (ACTIV)

In this test, the specimens with dimensions of 100*200 mm and with a 14 mm centrally fixed rebar were produced for the evaluation of the corrosion rate, mass loss, and the observation of the crack expansion behavior in reinforced concrete specimens. Each

specimen has been cured for 28 days inside a different type of water based on their concrete groups.

As a side effect, utilizing TWW in concrete production introduces additional chloride ions to the concrete, which have the potential to damage the protective oxide film on the reinforcement, making it vulnerable to corrosion in the presence of oxygen and water. To investigate this side effect, an accelerated corrosion test using an impressed voltage was employed. This technique simulates and accelerates the corrosion process, which typically takes several years to occur naturally and makes it possible to analyze the corrosion behavior of reinforced concrete inside the laboratory.

In this test, a constant 12-volt DC voltage applied to the rebar inside the concrete as an anode, which was partially submerged in a solution with 5% sodium chloride (NaCl) concentration to the weight of water and used a 20 mm copper wire with 25 cm length as cathode in the electrical current inside the solution, as depicted in the Figure 12. The electrical current through the circuit was accurately recorded every 24 hours. The initiation of the first visible crack (t_{ini}) was recorded, and the test was continued until the crack expanded to 1 mm width (t_{cr}). The measurement of crack width was done through a caliper as given in Figure 13.

This method allowed us to observe the starting and the progressing of the cracks on the concrete surface due to corrosion, by providing a more direct way to compare the durability of different concrete groups. Eventually, the rate of corrosion was determined based on the amount of current passing through the circuit over time and the electrochemical reactions emphasizing this setup were:

at the anode (rebar), iron undergoes oxidation, meaning it loses electrons and transforms into iron ions:



On the other hand, the reduction process takes place at the cathode (copper wire). Here, the electrons generated at the anode are consumed, typically leading to the reduction of hydrogen ions in the electrolyte to form hydrogen gas:



Finally, the complete reaction is:



In the present study, Faraday's Second Law of electrolysis was employed to calculate the mass loss. This law assumes that the mass of a substance altered at an electrode during electrolysis is directly proportional to the quantity of electrical charge passed through the cell. This relationship can be mathematically expressed as:

$$W = Q \times (M/zF) \quad \text{Eq. (1)}$$

where M is the molar mass of iron, (M = 55.845 g/mol), z is the number of electrons involved in oxidation of iron, (z = 2), F is Faraday's constant (approximately 96485 C/mol), and the quantity of charge (Q) was calculated by integrating the current over the time of the test [81].

To convert the calculated mass loss into a corrosion rate, according to ASTM G1-03:

$$C.R. (mm/y) = ((K \times W)/(A \times D \times T)) \quad \text{Eq. (2)}$$

where W is the mass loss during the accelerated corrosion test (gr), K is a conversion factor, approximately 8.76×10^4 , A is the total exposed area of the steel (cm²), D is the density of carbon steel (7.86 gr/cm³), and T is the duration of the test (hr) [82].

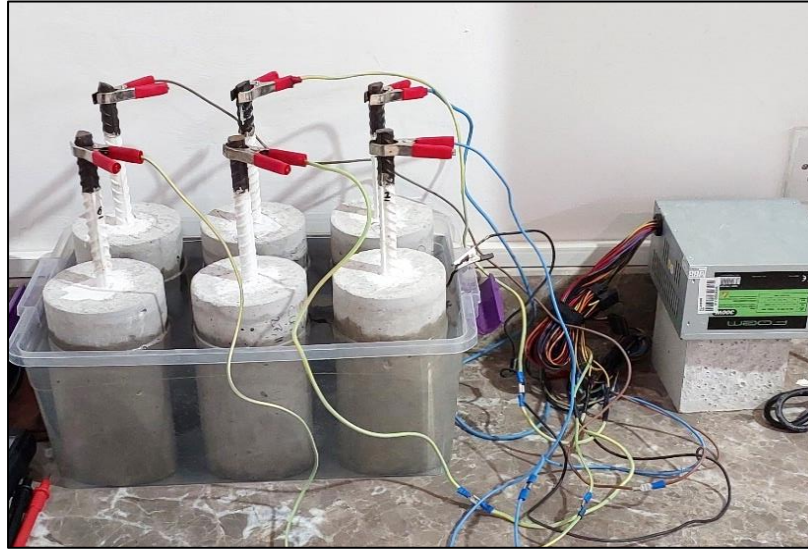


Figure 12: Accelerated corrosion test by impressed voltage test setup

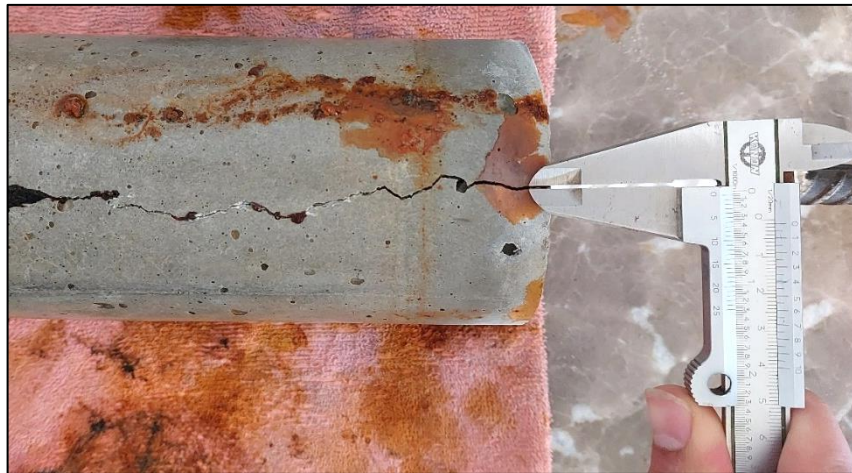


Figure 13: Crack width measurement by caliper

Chapter 5

RESULTS AND DISCUSSIONS

5.1 Introduction

This study investigates the impacts of using treated wastewater (TWW) in concrete mixing and curing procedure by evaluating a variety of properties, including workability, setting time of cement paste, compressive strength of mortar, compressive strength of concrete, splitting tensile strength, ultrasonic pulse velocity, density, water absorption, porosity, corrosion potential through half-cell potential test, and pH value of hardened concrete. Furthermore, the research explores the corrosion rate, mass loss, and crack behavior of reinforced concrete through an accelerated corrosion test by impressed voltage technique (ACTIV). The goal is to provide a comprehensive understanding of the potential benefits and limitations associated with substituting TWW instead of fresh water in concrete production.

5.2 Water Characteristics

Based on the findings presented in **Error! Reference source not found.** and ASTM standard limitation outlined in Table 5, it is evident that both water samples (TW and TWW) in this study met the ASTM requirements. Notably, it should be emphasized that TWW exhibited higher values in all the parameters compared to tap water (TW). For instance, the chloride content in TWW was measured as 276.7 mg/l, which is approximately 11.2 times higher than the chloride content in the TW. This higher chloride content highlights the higher risk of corrosion in reinforced concrete. However, it is important to note that the standard limitation for chloride content in

reinforced concrete is set at 500 mg/l. The pH level in the TWW was measured at 10.12. This higher pH level is due to the fact that the TWW was collected before chlorination at the wastewater treatment plant. This practice was implemented to mitigate the potential corrosive effects of chlorine on the corrosion resistance of reinforced concrete.

5.2 Workability

The workability of the concrete using TW and TWW was determined. Results illustrated in Figure 14 indicate that, the slump in TW sample was 140 mm, whereas for TWW sample exhibited a lower slump of 120 mm. This represents a reduction of approximately 15% in slump value of the TWW sample compared to the TW. These findings suggest that the incorporation of treated wastewater in concrete production had a modest impact on the workability of the concrete mixture as also observed in the experiment conducted by Shekarchi et al [19]. Nevertheless, it is important to note that the disparity in slump values is relatively minor, and both the TW and TWW samples exhibited slumps within the design range. Thus, indicating that the overall consistency and ease of handling remain comparable between the TW and TWW samples [71]. It is important to note that as it is mentioned in chapter 4, water with higher levels of total solids (TS) reduces the workability. However, the TS level of the water sample used in this study was not significantly high compared to the ASTM limit, hence allowing the workability to remain within the acceptable limits.

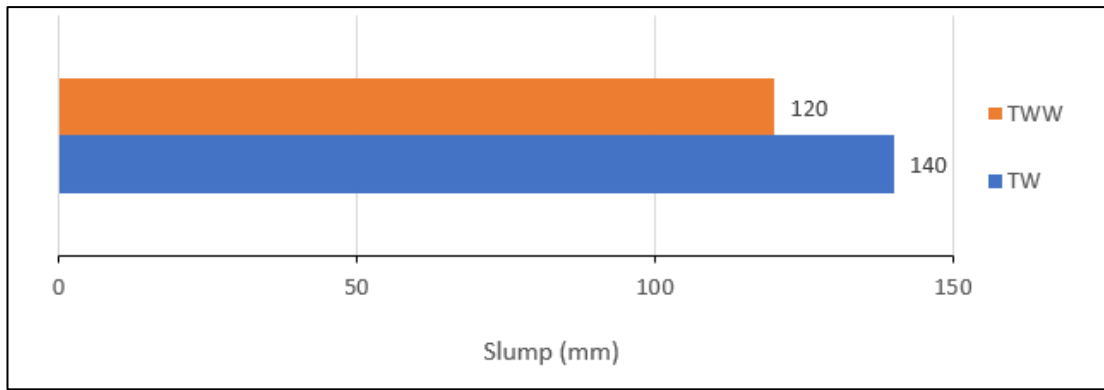


Figure 14: Workability of concrete using various source of mixing water

5.3 Setting Time of Cement Paste

Based on the results presented in Figure 15, the sample using TW had an initial setting time of 140 minutes, while the TWW sample exhibited the initial setting time of 143 minutes. The final setting time for the TW sample was 230 minutes, whereas the TWW sample showed a final setting time of 235 minutes. Overall, the application of TWW had a negligible effect on the setting time of cement paste, maintaining a similar behavior as observed with TW, with just about 2% retardation. In the study conducted by Lee et al., similar observations were reported [68]–[70], [83].

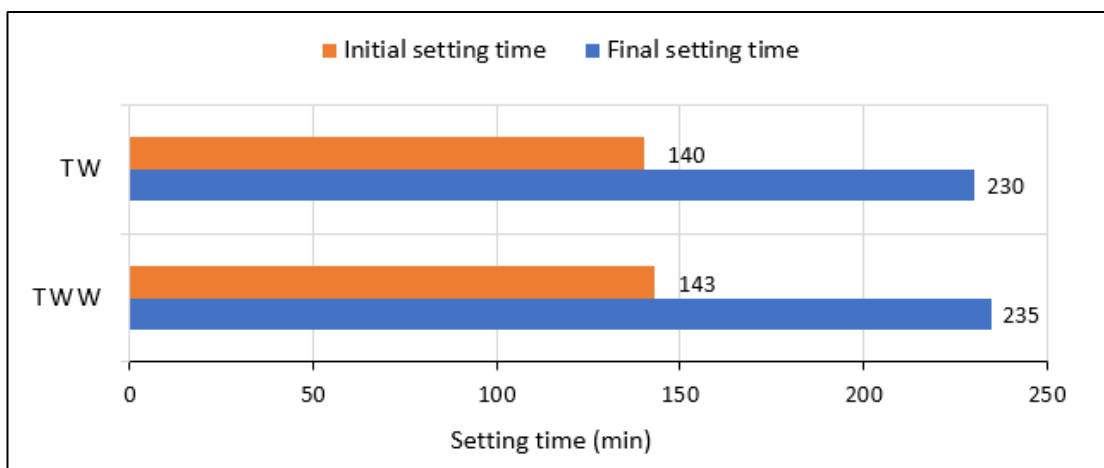


Figure 15: Initial and final setting time of cement paste

5.4 Compressive Strength of Mortar

According to the results presented in Figure 16, the average compressive strength of the control sample was 32.10 MPa, while that of the samples using TWW was 30.20 MPa. Using the TWW as a mixing water in mortar led to a 5.92% decrease in compressive strength after 7 days. In addition, similar observation was reported by Ramkar et al. [37].

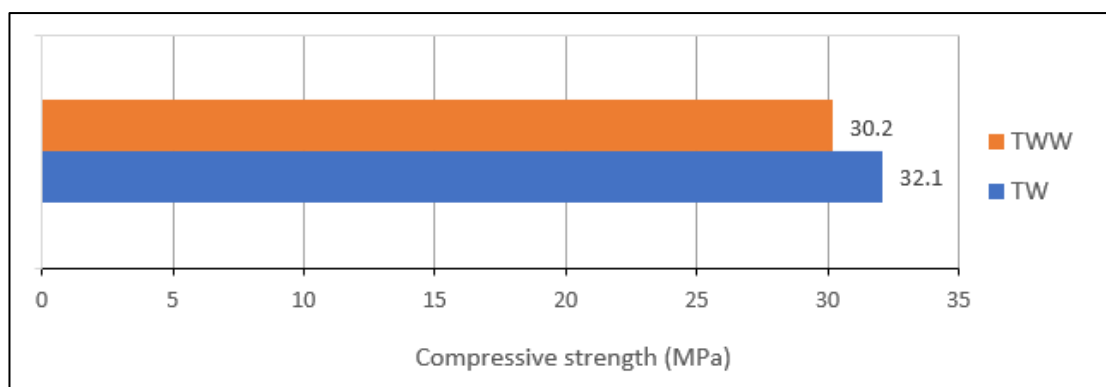


Figure 16: Compressive strength of mortar test results

5.5 Ultrasonic Pulse Velocity Test

According to the average results of three samples presented in Table 12 and the quality grading range outlined in Table 13, all the sample groups were classified as excellent quality level, with various intensity of improvements over an extended curing time. In the control sample, the pulse velocity value increased from 4620 m/sec at 7 days to 5020 m/sec at 180 days, representing the highest quality among all the concrete samples. Similarly, the WT group exhibited an increase from 4630 m/sec to 4990 m/sec at 180 days. These findings indicate that the use of TWW for mixing has a negligible impact on the overall quality of the concrete. It is worth noting that the WW group, despite also being classified in the excellent category, displayed the lowest pulse velocity value of 4600 m/sec at 7 days and 4890 m/sec at 6 months. This

difference might be due to the side effects of using TWW as curing water which influence the hydration rate [84].

Table 12: Ultrasonic pulse velocity test results

Concrete group	Curing time						
	7 days	14 days	28 days	56 days	90 days	150 days	180 days
TT (m/sec)	4620	4740	4870	4950	4990	4970	5020
WT (m/sec)	4630	4780	4870	4920	4960	4880	4990
WW (m/sec)	4600	4730	4730	4750	4880	4850	4890

Table 13: Velocity criterion for concrete quality grading [84]

Pulse velocity (m/sec)	Concrete quality grading
More than 4500	Excellent
In between 3500-4500	Good
In between 3000-3500	Moderate
Less than 3000	Doubtful

5.6 Compressive Strength of Concrete

Based on the results, presented in Table 14 and Figure 17, the compressive strength of the WT and WW samples at 7 days reached 91.4% and 90.6% respectively, compared with the control sample. This result satisfies the ASTM requirement, demonstrating the suitability of using TWW in concrete production. Notably, the overall trends for compressive strength were consistent for all groups, with improvements observed over extended curing time. Considering the rates of improvement varied among the different groups during the 180 days, the WT group exhibited the highest strength gain,

with 172% improvement compared to the control sample with 160% strength improvement during the same duration, while, the WW group ranked second in terms of strength gain, with a rate of 169%.

Nonetheless, it is worth mentioning that for 180 days of curing, compressive strength of the WT group maintained above 90% of the control sample strength for all the curing periods. For instance, after 28 days, the compressive strength was 92.4% of the control sample and the highest strength observed after 180 days of curing with 98.2% compared to the control sample. The WW sample showed a similar trend with slower improvement. This slower improvement might be due to the specific effects of using TWW for curing, which seemingly impeded the acceleration of strength development. After 28 days, the compressive strength was 84.6% of the control sample. However, after this point, strength gained in the WW sample exhibited an upward path, bringing it in line with the WT sample when compared to the control. This progress was highest in a compressive strength of 180 days, reaching 95.6% of the control sample.

Table 14 Compressive strength of concrete samples

Concrete group	Curing time						
	7 days	14 days	28 days	56 days	90 days	150 days	180 days
TT (MPa)	38.4	43.4	51.3	54.6	57.2	61.1	61.5
WT (MPa)	35.1	40.2	47.4	50.7	56.1	59.6	60.4
WW (MPa)	34.8	37.7	43.4	48.6	51.6	57.6	58.8

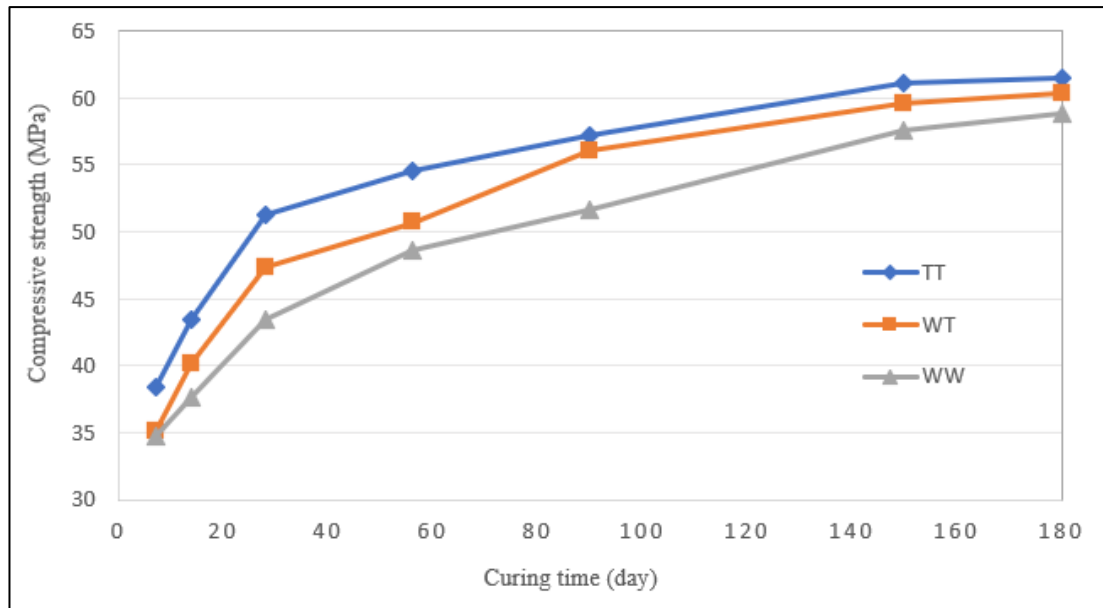


Figure 17: Compressive strength of concrete specimens

5.7 Splitting Tensile Strength of Concrete

It is evident from Figure 18 that utilizing TWW in concrete production leads to a decrease in the splitting tensile strength of the concrete. This impact becomes more noticeable when TWW is also used as curing water. Referring to Table 15, the splitting tensile strength in the WT group experienced a decrease of 3.03% at 7 days, 10.27% at 28 days, and 4.01% at 180 days. However, it is important to note that strength compensates for the initial decrease during early ages of curing, with improvement observed over prolonged curing time, approaching 96% of the control sample after 180 days. Although the overall trend for the WW sample is similar to that of the WT sample; the results, except for 28 days, demonstrate lower splitting tensile strength compared to the WT group. Nevertheless, in the WW group compared to the control sample, the splitting tensile strength decreased by 11.57% at 7 days, 9.65% at 28 days, and 7.29% at 180 days. Moreover, the rate of improvement after 28 days was lower in the WW sample compared to the WT sample, highlighting the retardation impact of TWW in the curing process.

Table 15: Splitting tensile strength of concrete samples

Concrete group	Curing time						
	7 days	14 days	28 days	56 days	90 days	150 days	180 days
TT (MPa)	3.63	3.80	4.87	5.19	5.32	5.41	5.49
WT (MPa)	3.52	3.63	4.37	4.68	4.93	5.18	5.27
WW (MPa)	3.21	3.57	4.40	4.57	4.7	4.92	5.09

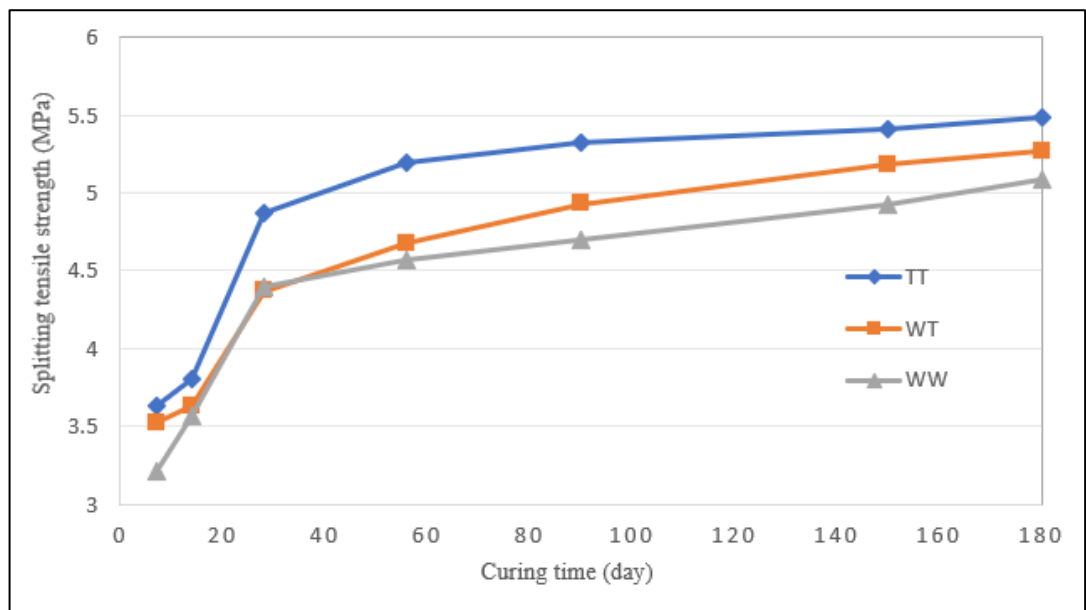


Figure 18: Splitting tensile strength results

5.8 Interrelations Between Compressive Strength and Splitting Tensile Strength of Different Concrete Group

As illustrated in Figure 19, a clear pattern emerges across all concrete groups, revealing a consistent linear relationship between compressive strength and splitting tensile strength. Notably, this relationship holds a remarkable level of accuracy. Additionally, a noticeable trend is evident, concrete groups with higher compressive strength values also exhibit higher splitting tensile strength values.

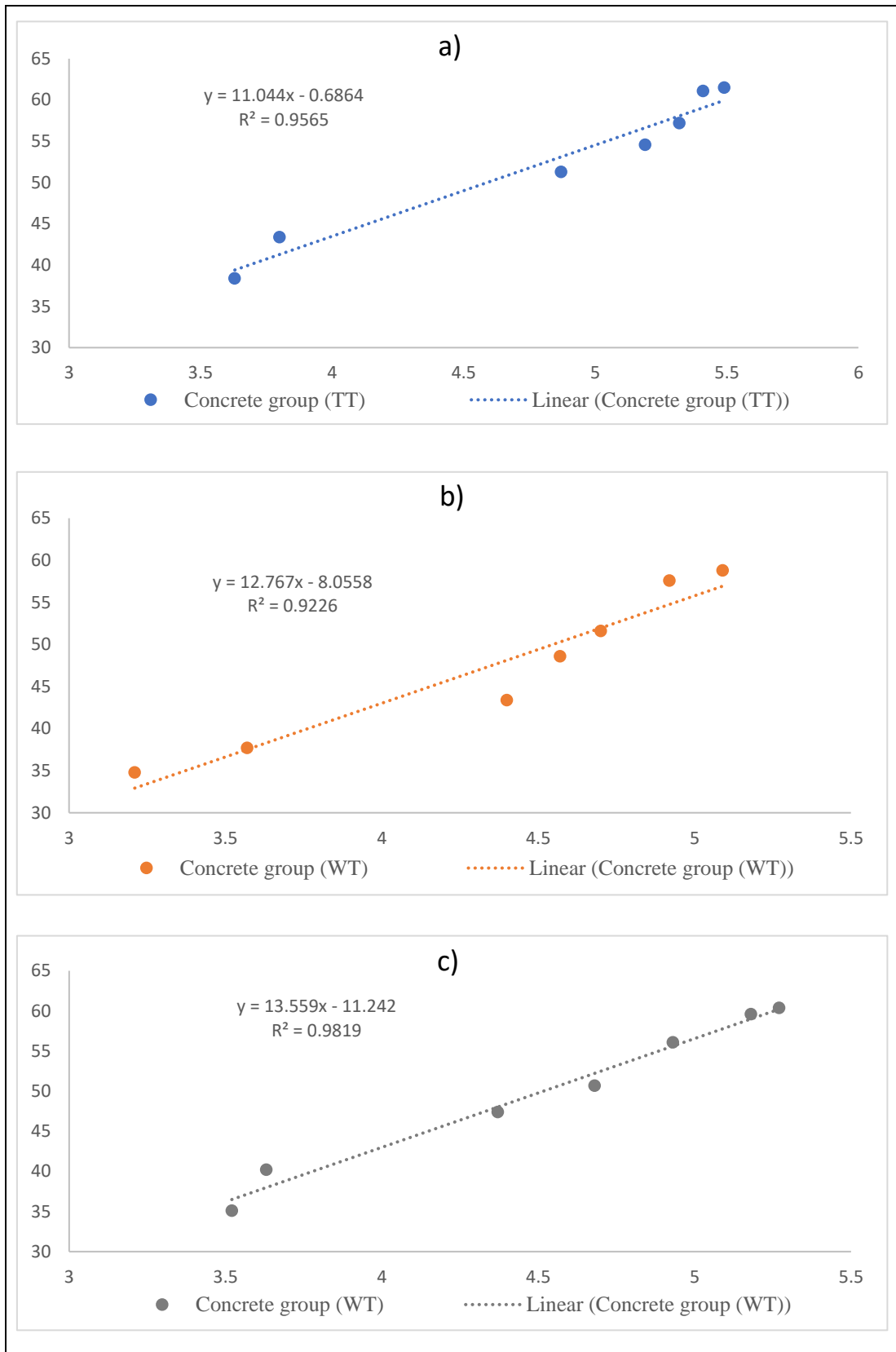


Figure 19 Interrelation between compressive and splitting tensile strength in different concrete group

5.9 Water Absorption, Density, and Porosity of Concrete

The results presented in Table 16, reveal that the utilization of TWW as a mixing or curing water source in concrete production has negligible effects on water absorption, apparent density, and void content. However, evidently both the WT and WW groups exhibited improved results compared to the control sample, with the WT group showing the optimal performance, followed by the WW group. The use of TWW in the WT and WW groups led to a decrease in water absorption by 3.41% and 1.48%, respectively, and a decrease in void content by 2.71% and 1.06%, respectively. The slightly lower void content observed in the WT and WW samples may be attributed to the higher total solids in the mixing water, which could enhance void filling [57]. These findings are consistent with previous research conducted by Brando et al., further confirming the limited influence of TWW on these specific properties of concrete [85].

Table 16: Water absorption, density, and voids percentage test results

Concrete group	Absorption %	Apparent density (kg/m ³)	Voids %
TT	6.74	2.65	15.13
WT	6.51	2.65	14.72
WW	6.64	2.65	14.97

5.10 Half-Cell Potential

Considering Figure 20 corrosion potential increased when TWW is used in concrete production. According to the results presented in Table 17, with respect to the control sample; the WT group displayed a higher half-cell potential of 17.94% at 28 days, 20.51% at 56 days, and 7.10% at 120 days. While, the WW sample showed the highest

corrosion risk, with increments of 37.18% at 7 days, 39.31% at 56 days, and 21.30% at 120 days with respect to the control sample. Also, results showing higher corrosion potential in samples using TWW are in line with earlier studies [29], [86]. Even though, the results indicated a higher corrosion potential in samples using TWW; it is important to emphasize that, according to the ASTM category, the WT and WW samples exhibited less than 10% corrosion likelihood, with the exception of the WW group at 120 days, which exhibited uncertain corrosion conditions. The results highlight the fact that the half-cell potential test has its own limitation and cannot measure the corrosion rate directly, hence it cannot be a reliable indicator for the corrosion state in our study.

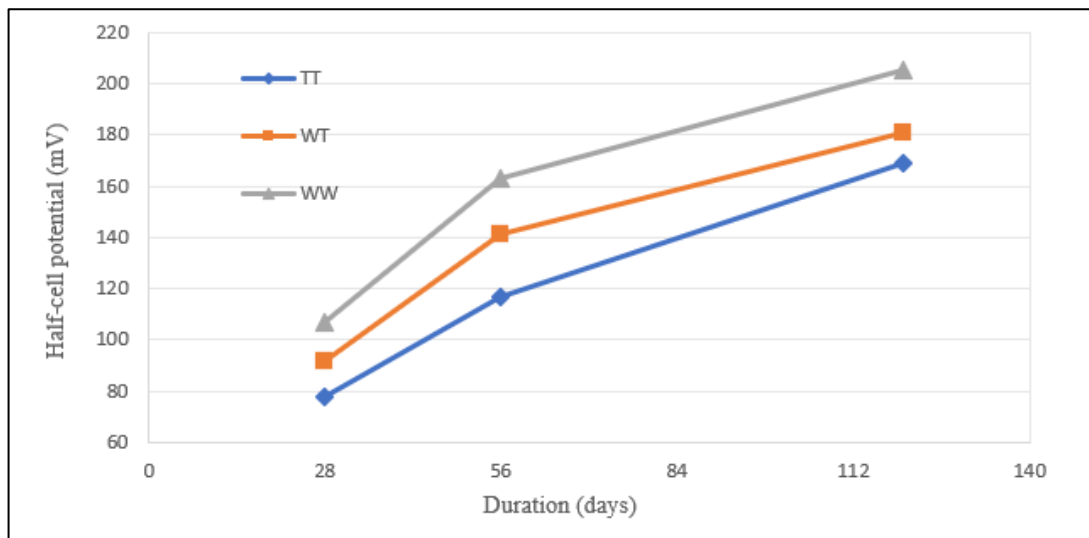


Figure 20: Half-cell potential test results

Table 17: Half-cell potential test result

Concrete group	Test periods		
	28 days	56 days	120 days
TT	78	117	169
WT	92	141	181
WW	107	163	205

5.11 pH Value of Hardened Concrete

The results shown in Table 18 indicate that the pH value for all concrete groups was almost the same around 12.93 to 12.95. This result suggests that the type of water sample used in concrete production either for mixing or curing, had a negligible effect on the pH level of the hardened concrete.

Table 18: Concrete groups pH value results

Concrete group	TT	WT	WW
pH Value	12.93	12.94	12.95

5.12 Accelerated Corrosion Test by Impressed Voltage Technique

The corrosion current versus time data from the accelerated corrosion test are illustrated in Figure 13, and it highlights the influence of concrete's conductivity on the electrochemical reaction process. This conductivity is primarily determined by the concrete's pore structure and the saturation level of the pore solution. As supported by other researchers the current/time curve typically undergoes three stages: Stage I, a descending phase; Stage II, a stable stage; and Stage III, an ascending phase [4], [87].

Stage I, accumulation of the corrosion products at the concrete-rebar interface causes the pore structure to fill up, thereby reducing porosity. This reduction interferes with the penetration of free electrons and oxygen atoms, thereby causing the current trend to descend. Nevertheless, the overall trend in all the concrete groups remained the same with various durations. It's worth noting that, conductivity of TW based on the result in Table 10 was lower than TWW, which probably explains the lower initial impressed current through the TT sample.

Stage II is characterized by the system achieving an equilibrium in the consumption and transportation of oxygen and free electrons, leading to a stabilization of the current. At this phase, the lower density with higher volume corrosion products lead to micro cracking at the interface. Given the lower tensile strength and higher amount of chloride content in samples produced with TWW, this phase was notably shorter for WT and WW samples compared to the TT sample.

Stage III, expansion of microcracks at the concrete-rebar interface results in an increased entry of oxygen and electrons. With the passage of time, as these cracks extend in width, the penetration of both electrons and oxygen continues. This continuous ingress causes further expansion of the cracks, leading to a simultaneous increase in the current as time progresses. This phase signifies the critical stage in the corrosion process where the rate of corrosion accelerates rapidly due to the enhanced availability of reactants.

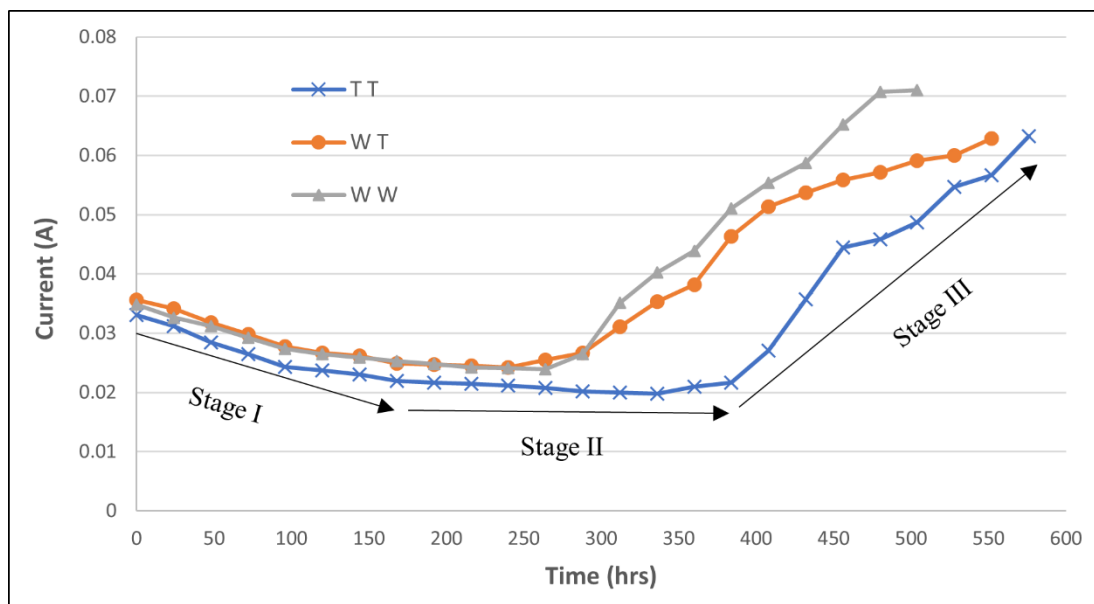


Figure 21: Corrosion current versus time

Thereby, based on the results presented in Figure 21 and explained mechanisms, it can be observed that the WT and WW samples exhibited almost a similar trend during stage I and stage II of the test. The time taken for the first crack to appear (t_{ini}) for the WT sample was 264 hours, and for the WW sample was 288 hours, which was 26.67% and 20.00% sooner than the control sample at 360 hours, respectively. As explained earlier, corrosion products during early stages generally fill the pore structure of the concrete sample prior to crack formation. As a result, the WT sample, which had the lowest void content, took less time for the formation of the first crack [87]. In contrast, when it came to the expansion of the crack to a width of 1 mm (t_{cr}), the WT sample took 552 hours, whereas the WW sample took 504 hours. These durations were 4.17% and 12.50% shorter than the control sample with 576 hours, respectively. The shorter durations of t_{cr} values for the WW sample might be attributed to the higher chloride content within the concrete sample due to curing condition, and also lower splitting tensile strength.

The average mass loss for all samples by applying equation 4 was determined and presented in Table 19. The mass losses for the TT, WT, and WW samples were 18.19 gr, 21.60 gr, and 19.86 gr, respectively. The lower mass loss in the WW sample compared to the WT sample is because of the shorter test duration with 504 hr compared to 552 hr. Hence, the results indicate that the WT sample experienced 18.75% higher mass loss, while the WW sample had a 9.18% higher mass loss compared to the control sample.

Table 19: Corrosion characteristics of concrete groups

Concrete group	Time to first crack, t_{ini} (hr)	Time to 1 mm crack, t_{cr} (hr)	Mass loss at t_{cr} , (gr)	Corrosion rate at t_{cr} , (mm/y)
TT	360	576	18.19	6.00
WT	264	552	21.6	7.43
WW	288	504	19.86	7.48

Lastly, by using equation 5, the corrosion rate of TT, WT, and WW samples were determined to be 6 mm/yr., 7.43 mm/yr., and 7.48 mm/yr., respectively. In comparison to the control sample, the corrosion rate of WT and WW samples were 23.83% and 24.66% higher, respectively. Indicating the impact of TWW on the corrosion resistance of concrete specimens.

Although the TWW satisfied the ASTM requirements for an acceptable water source, including water characteristics, setting time, and compressive strength, the corrosion test results underline the necessity of further research on the effects of using TWW in concrete production, particularly regarding the durability of reinforced concrete.

Chapter 6

CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

This experimental study examined the effects of utilizing TWW as a source of mixing and curing water on the mechanical properties, durability, and corrosion resistance of reinforced concrete. Based on the results, the following conclusions can be drawn:

1. The chemical and physical properties of TWW satisfied the ASTM C1602 requirements.
2. The workability of fresh concrete was slightly affected when mixed with TWW, resulting in a minor reduction. However, this reduction remained within the acceptable range of concrete mix design.
3. Although the use of TWW marginally increased the initial and final setting times of cement paste, this retardation was very small and met the ASTM C1602 requirements, indicating suitability of TWW in concrete.
4. The WT and WW groups showed a reduction of less than 10% in compressive strength compared to the control sample, meeting the ASTM C1602 requirements, and confirming the suitability of using treated wastewater in concrete production. Notably, the compressive strength improved over a 6-month curing period, nearly reached the strength of the control sample, indicating the retardation effect of TWW. Interestingly, this effect was more noticeable when TWW was used for curing.

5. The results of splitting tensile strength exhibited a similar trend to the compressive strength, showing lower strength in the WT and WW samples compared to the control sample, with improvement observed over an extended period of time. Indicating retardation impact of utilizing TWW in concrete production with higher impact in case of using TWW for both mixing and curing procedure.
6. The ultra pulse velocity test results showed an excellent quality for all types of concrete samples indicating that TWW does not affect the compactness and homogeneity of the concrete.
7. Using TWW in concrete had minimal effects on absorption, density, and porosity. It slightly reduced water absorption and void content but did not alter the apparent density.
8. Using the half-cell potential test, revealed that samples using TWW displayed higher potential differences than the control sample, where the WW sample showing the highest after 120 days. However, according to the ASTM category, the majority of samples had less than 10% corrosion likelihood.
9. Utilizing TWW with higher pH value did not change the pH level of hardened concrete.
10. The corrosion test revealed that using TWW in concrete production increases the corrosion rate by 23.8% in WT samples and by 24.7% in WW samples. Furthermore, it significantly reduces the required time for microcracks to develop and expand.

According to this study, TWW met the ASTM requirement, demonstrating its suitability for both mixing and curing purposes in the concrete industry. However, caution should be exercised in aggressive environments, as indicated by the results of

corrosion tests that reinforced concrete using TWW has lower corrosion resistance. Precautionary measures such as using corrosion inhibitors or ensuring adequate concrete cover should be considered in such cases.

6.2 Recommendations

- The inclusion of other durability tests, such as the rapid chloride permeability test and accelerated carbonation test, would significantly broaden our understanding of how treated wastewater (TWW) impacts the durability properties of concrete specimens. Incorporating these additional tests in future research endeavors would provide valuable insights into the extent to which TWW influences concrete durability.
- Although this study examined a 100% replacement of tap water (TW) with TWW in concrete production, it would be beneficial to investigate other replacement ranges, such as 50% or 75% TWW, to mitigate potential impacts on corrosion resistance in the produced concrete. Exploring different replacement ratios would offer a more comprehensive understanding of how TWW affects the overall performance and durability of the concrete mix.
- To further enhance the understanding of the concrete's resistance to corrosion, conducting additional experimental tests with varying chloride concentrations in the mixing water can help establish critical thresholds that maintain suitable concrete production with minimal adverse effects. This would contribute to identifying the optimal conditions for utilizing TWW in concrete production while ensuring the concrete's long-term durability and performance.

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APPENDIX

Concrete Mix Design Table

stage	item		Reference or calculation	Values
1	1.1	Characteristic strength	Specified	40 N/mm ² at 28 days Proportion defective 10%
	1.2	Standard deviation	Fig. 3	8 N/mm ²
	1.3	Margin	C1	(k = 1.28) 8*1.28 = 10.24 N/mm ²
	1.4	Target mean strength	C2	40 + 10.24 = 50.5 N/mm ²
	1.5	Cement strength class	Specified	42.5
	1.6	Coarse and fine aggregate type		Crushed
	1.7	Free w/c ratio	Table 2, Fig. 4	0.5
2	2.1	Slump	Specified	Slump 130 mm
	2.2	Max. Aggregate size	Specified	20 mm
	2.3	Free-water content	Table 3	225 kg/m ³
3	3.1	Cement content	C3	225 / 0.5 = 450 kg/m ³
4	4.1	Relative density of aggregate (SSD)		2.72
	4.2	Concrete density	Fig. 5	2400 kg/m ³
	4.3	Total aggregate content	C4	2400 - 450 - 225 = 1725 kg/m ³
5	5.1	Grading of fine aggregate	Percentage passing from 600 μm sieve 38%	
	5.2	Proportion of fine aggregate	Fig. 6	45%
	5.3	Fine aggregate content	C5	1725 * 45% = 780 kg/m ³
	5.4	Coarse aggregate content		1725 - 780 = 945 kg/m ³