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RECYCLED WASTE TIRES MANAGEMENT IN CONSTRUCTION

BY

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ABSTRACT

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Concrete is one of the most commonly used materials in construction worldwide. Yet the production of concrete from raw materials, such as cementitious materials, water, sand, and natural aggregate, leads to the release of significant amounts of CO_2 and greenhouse gases. Therefore, there is a growing interest in producing sustainable concrete using recycled materials. This study will focus on waste management considering the incorporation of recycled tires as a replacement for fine and coarse aggregate in structural concrete. These waste car and truck tires present serious environmental challenges when dumped into landfills as they consume large amounts of space, contaminate the air, soil, and water, and impact human health. The reuse of rubber is therefore inevitable.

This study conducts a life cycle cost analysis (LCCA) to compare the cost-effectiveness of a conventional concrete mix (RC1) with a rubberized concrete mix (RC2). Furthermore, to promote the use of eco-friendly materials in concrete mixes, this study suggests the use of seawater as a replacement for freshwater in both the conventional mix and the rubberized concrete mix in order to eliminate the cost and energy consumed during the desalination process. The LCCA results show that the rubberized concrete (RC2), obtained by replacing 5% of aggregate and mixing it with seawater, is more cost-effective than RC1, with a cost savings of 30%.

LCCA data were acquired by investigating thirteen concrete mixes (a control mix; 5%, 10%, and 20% rubber aggregate substitutions mixed with freshwater; and 0%, 5%, and 10% rubber aggregate substitutions mixed with seawater). Moreover, the impact of rubber and seawater was evaluated on fresh and hardened concrete characterizations. The results show that as the rubber and seawater contents were increased, the workability, density, and compressive strength were decreased; however, for durability in terms of Rapid Chloride Permeability (RCP) and water absorption, rubberized and seawater concrete mixes outperformed the control mix. Our selection of RC2 for LCCA is based on its good fresh and mechanical characterizations in comparison to the other rubberized concrete mixes. In its approach to its subject, this study is an example of multidisciplinary research, as it synergizes construction management through life cycle cost analysis with construction engineering materials area.

DEDICATION

I would like to dedicate this work to my family.

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GLOSSARY OF ABBREVIATIONS

1. United Nations Framework Convention on Climate Change (UNFCCC)
2. Life Cycle Cost Analysis (LCCA)
3. Life Cycle Cost (LCC)
4. Federal Highway Administration (FHWA)
5. Net Present Value (NPV)
6. Glass Fiber Reinforced Polymer (GFRP)
7. Fiber Reinforced Polymer (FRP)
8. Crumb Rubber Modified (CRM)
9. Qatar Statistics Authority (QSA)
10. Terminal Blend (TB)
11. Total Dissolved Solid (TDS)
12. American Society for Testing and Materials (ASTM)
13. British Standard (BS)
14. Qatar Construction Specifications (QCS)
15. Natural Aggregate (NA)
16. Modern Recycling Factory (MRF)
17. Rapid Chloride Permeability (RCP)
18. International Organization for Standardization (ISO)
19. Ordinary Portland Cement (OPC).
20. Portland Pozzolana Cement (PPC)
21. Sulphates Resisting Cement (SRC)
22. Micro Silica (MS)

CHAPTER 1: INTRODUCTION

1.1 Background

According to the United Nations' World Commission on Environment and Development, sustainability means "meeting the needs of the present without compromising the ability of the future generations to meet their own needs" UNFCCC COP9 Rep. 200 [1]. Due to population growth and urbanization, natural resources have become threatened within the last century [2]. As a result, there has been growing interest in reusing materials instead of disposing of them in landfills [3].

Concrete is the most common material used in the construction sector worldwide [4]; the prime components of concrete are cement, freshwater, sand, and aggregate. The massive production of concrete for the purpose of using in residential and commercial buildings and infrastructure projects exerts a negative impact on the environment because these prime components are generally extracted from natural resources [5]. Fortunately, new concrete can make use of most construction and demolition waste, such as aggregate [6], which can be treated and reused. Moreover, there is growing interest in using green cement, which is produced from recycled materials, to reduce the environmental impact of producing traditional cement [7].

Another material that could potentially be recycled for use in concrete is waste tires, which mainly come from cars and trucks [8]. Tire recycling also mitigates their disposal in landfills, which is causing serious environmental issues [9]. As tires remain in landfills for long periods and the micro-organisms take more than 100 year to biodegrade them [10] . In 2004, China generated 120 million waste tires, and this number is increasing by 12% each year. Moreover, the United States has about 300 million waste tires stockpiled, with an increase of 290 million waste tires generated each year [11]. Currently, there are different approaches to eliminating waste tires, including reuse, rethreading, recycling/mechanical recycling, landfill engineering, and energy recovery [12]. Waste rubber tires are already recycled and used a number of civil engineering applications, and this is considered to have many environmental and economic benefits, such as preserving natural resources, producing sustainable materials, and reducing harmful pollution resulting from landfill disposal. This study focuses on one specific civil application: the construction management of recycled waste tires as a replacement for fine and coarse aggregate.

Our work also suggests the use of seawater as an alternative to the commonly used freshwater for mixing concrete. This move is a response to the growing global concern regarding freshwater scarcity [13]. Studies show that about two-thirds of the world's population is likely to suffer from water scarcity for at least one month every year [14]. In light of this, it is concerning that global concrete production consumes more than two billion tons of freshwater every year [15]. Furthermore, the intensive desalinization treatment of seawater has a significant negative environmental impact, and in the Middle East two-thirds of the water produced from seawater desalination is based on fossil fuel-powered thermal desalination. The seawater desalination process is also costly [16,17].

1.2 Literature Review

1.2.1 Life Cycle Cost Analysis

Life cycle cost analysis (LCCA) is used for assessing the total cost of projects [18]. When used for a construction project, it takes into account all associated costs including investment, operations, and maintenance costs as well as eventual demolition and disposal costs [19]. LCCA is commonly used in construction projects and is highly effective, especially when there are many design alternatives [20]. For this reason, it is often used to compare the entire costs of various alternatives from the initial stage up to the demolition stage, enabling efficient decision-making in the early stages of the project and thus increasing project savings [21].

There are several benefits of conducting LCC analysis. For instance, it enables organizations to use the best alternatives and leads to the best long-term value [22]. Furthermore, while LCCA may lead to very high initial costs because it prompts decision-makers to choose high-quality materials, it also leads to a correspondingly lower risk of rework and maintenance costs [20]. Therefore, properly conducting LCCA can even increase a building's lifespan. In addition, LCCA enables the project team to control the project throughout all its stages [23], as conducting LCCA in the early project stage can determine the cost baseline that can be used to track the project, and corrective actions can then be taken should any risk arise.

LCCA also has environmental benefits: it is mandatory for many green building organizations, so using LCCA makes it easier for the project to obtain green building certification [23]. While the construction of green buildings does cost considerably more than the construction of conventional buildings [24] and this might deter contractors from adopting green construction techniques, conducting LCCA in the long-term analysis shows that green buildings yield savings in operation and maintenance costs [25]. Yet despite both the cost benefits and the environmental benefits, the many advantages of LCCA are still not fully exploited in the construction sector, primarily due to owners' lack of awareness of the benefits of LCCA, poor actual cost and performance data on buildings, and uncertainty related to LCCA assumptions [26–28].

Guidelines for using LCCA advise that it should be started as early as possible in project development. For construction projects, the appropriate time is during the design stage as soon as there are sufficient details for all design alternatives, allowing for cost estimations and analysis [29]. The LCCA should be comprehensive enough to cover all the long-term costs associated with the case study subject. For pavement construction, for example, the LCCA policy of the US Federal Highway Administration (FHWA) recommends using at least 35 years as the analysis period [30]. In high-rise buildings, the analysis period can be assumed to be up to 100 years [31].

The LCCA determines all the costs that can be incurred during the analysis period. Most likely, these include material costs, construction costs, and maintenance and repair costs. Based on the area where the LCCA is applied, the costs may also include demolition [31] and energy cost residual value [32].

Net present value (NPV) is the value of all future costs incurred at the end of each year discounted to the present value; it is widely used to simplify the determination of the NPV [33], as expressed by Equation (1).

$$NPV = A_t \times \frac{1}{(1+d)^t}$$

Equation 1: NPV

Where A_t is the cost at year (t), d is the discount rate, and t is the number of years [33]. The discount rate is used to express the costs predicted in the future as present costs [34]; it should reflect the historical economical trend over a long-term period and the inflation rate and vary according to the time and location where the LCCA is conducted [35].

Sensitivity analysis is an important tool in LCCA, showing how the variance of key input parameters influences the LCC value [36]. Based on the analysis inputs and assumptions, the major parameter can be the discount rate, labor cost, material cost or any other parameter [37]. The sensitivity analysis also allows a large number of inputs to vary simultaneously [29].

A number of tools have been employed to conduct LCCA, including MicroBENCOST, which was developed by the National Cooperative Highway Research Program in 1990 [38] and was used to conduct a cost-benefit analysis for seven project types. These types included capacity enhancement, bypass, intersection or interchange improvement, rehabilitation of pavements, bridge construction, safety, and highway-railroad grade crossing [39]. MicroBENCOST was used to compare the LCC of conventional and asphalt-rubber pavements [30]. However, the main disadvantages of MicroBENCOST are that the input must be entered before the file can be saved and that the input may not be automatically updated when the user changes it [40].

Another tool of conducting LCCA is by using the Fourth Highway Development and Management Model (HDM-4). This program, developed by the World Bank, can apply three LCCA tools, namely strategy analysis, program analysis, and project analysis. However, the main disadvantage of this program is that since it was designed for developing countries, users in other nations may have difficulty in conducting a high-quality evaluation of the user costs for different design alternatives [30].

One specific consideration for our study is the cost analysis for rubber. In the construction industry, modified rubber is often used in asphalt pavement mixes, more so than in concrete mixes. The typical cost of a crumb rubber modified (CRM) asphalt mix is between 1.5 to 2.0 times that of a conventional mix due to the rubber cost, use of special aggregate, risk of uncertainty to the contractors, and change in the construction operations [41]; however, this cost is only considered as an initial cost. However, LCCAs include all the relevant costs of the asphalt mix, such as the initial, construction, operation, and maintenance costs up to the demolition cost. Therefore LCCA allows CRM to be thoroughly compared to conventional asphalt mixes and shows the benefits of CRM; for example, it reduces the cracks in the hot asphalt mixes, reduces the maintenance frequency, and provides smooth riding pavement with good slip resistance [30].

Since the use of recycled rubber is more common in asphalt works than in building works, many studies have conducted LCCA to investigate the cost-effectiveness of using recycled rubber in an asphalt mix. J. Jung et al. [30] showed that rubberized pavement is more cost-effective than conventional concrete pavement in terms of initial cost and maintenance cost. In addition, rubberized pavement provides a longer service life. Thus, based on annual equivalent costs, capital costs, and layer equivalencies, an LCCA showed that a rubber modified asphalt mix is also more cost-effective than a traditional asphalt mix, according to J. O’Brien et al. [42].

Seawater is another specific consideration in our study. It can be incorporated in a concrete mix, replacing freshwater and thus eliminating the cost and energy consumption resulting from water desalination [16]. In fact, the use of seawater in reinforced concrete is considered to be more cost-effective than using conventional reinforced concrete that uses freshwater [31]. However, seawater will cause corrosion in black steel, so many studies have suggested the use of corrosion-resistant reinforcement in lieu of black steel in seawater concrete [31,43]. Although corrosion-resistant reinforcement has a high cost, in the long term it extends the service life of seawater concrete and significantly reduces maintenance costs. Consequently, cost savings of over 40% can be achieved by using seawater concrete, associated with non-corrosive reinforcement, in place of conventional steel-reinforced concrete [31,44].

1.2.2 Applications of Recycled Tires in Construction

The recycling of waste materials is becoming inevitable in industrial sectors [45]. Recycling addresses one of the negative results of economic growth, which is the increasing generation of waste [46] that is usually disposed of in landfills, leading to soil, air and water contamination from toxic substances, such as chemicals, heavy metals, plastic materials, rubber, and asbestos [47]. Therefore, there is a growing awareness of the need to recycle to protect natural resources, save them for the next generation, and eliminate the harmful impact of waste on human health in the short- and long-term [45].

Rubber is one of the materials that cause major environmental issues when stored in landfills. It takes a long time to dissolve and emits toxic gases when burnt. The United States alone has about 300 million scrap tires in landfills, with an increase of 270 million tires generated per year [48]. However, there is a growing concern about recycling rubber, both in the United States and worldwide. Table 1 shows how around 170 million tons of rubber have been reused in different industries.

Table 1. Some Facts about Rubber Recycling in the United States [48]

Fact	Figure
Number of scrap tires generated annually	270 million
Approximate weight of scrap tires	3.6 million tons
Number of scrap tires in stockpiles	300 million
Number of tire processing facilities	498
Scrap tires used in civil engineering applications	30 million
Scrap tires processed into ground rubber	18 million
Scrap tires used for fuel	125 million
Number of states with scrap tire legislation/regulations	48
Number of states that ban whole tires from landfills	33
Number of states that ban all scrap tires from landfills	5
Number of states with no landfill restrictions	12

According to the Qatar Statistics Authority (QSA), Qatar imports 900,000 tires annually, more than 70% of them for cars. Meanwhile, 1.9 million worn tires are sent to landfills as scrap every two to four years, assuming an average tire lifespan of three years [49]. Based on the growing population in Qatar, these numbers are expected to increase in the near future [50]; therefore, the country has an ambitious plan, reflected in the Qatar National Vision 2030 (QNV2030), to promote tire recycling [51]. In 2010, the first recycling plant was established in Qatar, with an annual production of 6,000 tons of reclaimed tires [52]. This was followed in 2012 with the opening of a new tire recycling factory, producing 75 tons of crumbed rubber per hour for reuse in different sustainable applications, such as running tracks, playgrounds, building infrastructure and flooring [53].

Many studies have been conducted on the performance of asphalt mixes containing rubber [54]. In general, ground tire rubber (GTR) has been utilized to modify the asphalt binders used in hot-mix asphalt construction since the early 1960s [55]. There are two methods of incorporating crumb rubber in asphalt mixes. The first is the dry process, in which the crumb rubber is added to the mix as an aggregate portion. The second is the wet process, in which the crumb rubber is first incorporated into asphalt cement and then incorporated into the mix [56].

N. Hassan et al. [57] reviewed crumb rubber modification considering dry-mixed rubberized asphalt mixes. They concluded that generally, crumb rubber is often used in asphalt mixes to improve the performance of the mix and to benefit the environment. Also, rubber shows a greater elastic recovery characterization than conventional asphalt mixes. Rubber has also been shown to improve fatigue, cracking, resistance, and permanent deformation.

R. Salini [56] also conducted a study of the behavior of crumb rubber in an asphalt mix. They incorporated the crumb rubber into the mix using the dry process, but also followed up the structural development obtained with the wet process by keeping the mix in an oven at 160 °C. The study found that as a result of an increase in the rubber in the mix, the density of the mix decreased, the void content increased, and the tensile stress value decreased.

Using the wet process, L. Han et al. [58] investigated a terminal blend (TB) rubberized binder. Compared to the traditional mix, TB uses finer rubber particles to obtain a homogeneous mix. The study concluded that TB is a promising and environment-friendly bituminous material that resembles a polymer-modified binder in terms of manufacturing systems and performance properties as well as mix handling. The TB binder can be performance-graded and its application covers hot-mix asphalt overlay and surface treatment, such as chip seal.

In addition to studies of the applications of rubber in asphalt mixes, several studies have focused on the application of rubber in concrete mixes and its performance in fresh and in hardened concrete. Most of the research on incorporating rubber into concrete mixes as a replacement for aggregate shows that the compressive strength is reduced [59–61] therefore, rubber should be used in structures where strength is not critical, and the maximum replacement of the rubber aggregate should range between 20% and 30% by volume [11].

In one such study, H. Toutanji [62] conducted experiments to investigate the effect of replacing mineral coarse aggregate with rubber, using rubber contents of 25%, 50%, 75% and 100% as replacement ratios. The results showed that an increase in the rubber content led to a reduction in the compressive and flexural strength values. However, the relationship between strength losses and increasing rubber content was not linear. The toughness of rubberized concrete was higher in comparison to the conventional concrete mix.

A. Sofi [63] evaluated the performance of rubberized concrete mix by replacing 5%, 7.5% and 10% (by weight) of aggregate and cement with rubber. The results showed that the rubber mix had lower compressive strength, flexural tensile strength and depth of water penetration than the control mix, while the abrasion resistance and water absorption (up to 10% replacement) showed better results than the traditional mix concrete. Hence, A. Sofi [63] recommended that rubber (up to 12.5% replacement of fine aggregate) could be used in pavements, floors, hydraulic structures, concrete highways or any structure that may be prone to brittle failure. M. Batayneh et al. [64] also recommended using rubberized concrete in construction elements such as pavements, partition walls, road barriers, and sidewalks, since these elements do not require high compressive strength.

To improve the performance of ground rubber in concrete mixes, M.Balaha et al. [65] suggested adding polyvinyl acetate (PVA), silica fume (SF), and sodium hydroxide (NaOH) as a treatment. The treated rubber yielded better results than normal rubber in terms of compressive strength and tensile strength; in the case of treated rubber, the compressive strength reduction ranged from 14% to 17% compared to ordinary concrete, while the reduction in the case of untreated rubber was 27% at the same percentage of rubber aggregate replacement. On the other hand, there was an increase in the tensile strength in the rubberized concrete incorporating the treated rubber when compared to the untreated rubber counterpart.

The fresh properties of rubberized concrete were investigated by N. Deshpandeet al. [66], who observed that while performing the slump test, increasing the rubber aggregate content reduces the workability. However, the rubberized concrete mixes did not show any problems in terms of finishing, casting or placement. A good quality finish could be achieved, although additional effort was required to smooth the finished surface.

N. Al-Akhraset al. [67] studied the properties of tire-rubber ash (TRA) mortar. As the TRA content increased, the workability of the fresh mortar decreased, but both the initial and final setting times increased with an increase in TRA content.

1.2.3 Seawater in Structural Concrete

In the near future, the water crisis is highly likely to be exacerbated as freshwater is a limited natural resource and the amount of water generated by the hydrological cycle will not increase overall [68]. Rain, snow, groundwater, and rivers are the only sources of freshwater on the planet. Evaporation from land, bodies of water, and plants transfers the water to the atmosphere, from which it returns to the earth as snow or rain [69]. At present, there are major signs of water shortage with respect to some main sources of freshwater. For example, some rivers are running dry, including major rivers such as the Colorado River in North America, the Yellow River in China, the Teesta River in India and the Murray River in Australia [69]. Another sign of water shortage is the decline of water tables worldwide, including among the biggest producers, namely China, India, and the United States. A groundwater survey found that on the North China Plain, the water table has declined by about six to eight billion tons every year since 2002 due to the long-term irrational consumption of water and dry weather [70]. It is expected that within the next quarter of this century, freshwater will become scarce and very difficult to obtain. The UN and the World Meteorological Organization are predicting that 5 billion people will eventually face water shortages, even of drinking water [71].

Water is a key element in construction, where it is used in a variety of activities and products [72]; for example, the consumption of water in cement production ranges from 147 to 3,500 liters per ton of cement, and the production of a cubic meter of concrete consumes between 100 and 240 liters of water [73].

According to S. Kaushik et al. [74], the need to use seawater in concrete already arises in situations where there is no other source of water available or the transportation of freshwater is costly. As 80% of the Earth's surface is covered by oceans and seas, many coastal buildings are exposed to the seawater; as a result, many studies have examined the impact of seawater in construction as well as the durability of buildings exposed to seawater [75].

Yet the substitution of seawater for freshwater in concrete does pose some unique issues. This study, along with its focus on the use of recycled waste tires in construction, will discuss the economic impact and technical aspects of using seawater in concrete, and in so doing, it draws on a considerable body of existing work. The performance of seawater in concrete has actually been a focus of debate since 1840, when J. Smeaton and L. J. Vicat 1840 discussed this issue in a work titled "What is the trouble with concrete in sea water" [13]. Thereafter, many studies and investigations were carried out to test the performance of seawater in plain and reinforced concrete in terms of durability, compressive, tensile, and flexural strength, and many other characterizations in the short and long terms [13,71,76].

Generally, there is a common belief that seawater-mixed concrete should not be used in reinforced-concrete structures; in the case of a lack of freshwater, the use of seawater is recommended in plain concrete [13]. Since seawater contains a high amount of chlorides, mixing concrete with such water will lead to an appreciable amount of free chloride ions coming into contact with steel rebar within a short period. Along with carbonate, even a low concentration of chloride weakens the reinforcement steel in the concrete and causes corrosion [74]. As previously mentioned, to counter this corrosion problem, many studies have suggested using corrosion-resistant reinforcement in seawater concrete instead of black steel to extend the service life of reinforced concrete and delay the corrosion process [31,43]. For this reason, the use of fiber-reinforced polymer (FRP) reinforcement in concrete structures has rapidly increased due to its corrosion-resistance, light weight, high tensile strength, adequate corrosion resistance, and excellent non-magnetization properties [77].

However, these beneficial properties are no substitute for compressive strength, which is the major characteristic tested in any concrete mix. P. Tiwari et al. [78] investigated the impact of saltwater on the compressive strength of concrete by comparing the compressive strength of ordinary concrete cubes cast and cured in freshwater with that of other cubes cast and cured in seawater. The study found that there was some increase in the strength when saltwater used for casting and curing concrete cubes. F. Wegian [79] found that there was an appreciable increase in the strength of concrete specimens mixed and cured in seawater compared with specimens mixed and cured in freshwater; however, the rate of the strength increase was faster in the second specimen than in the first specimen. The same result was obtained by M. Islam et al. [80], whereby the seawater negatively affected the rate at which the concrete gained strength when it was used for mixing. F. Wegian [79] conducted the split tensile test in concrete for two specimens of concrete that were mixed and cured in seawater and another specimen mixed and cured in freshwater. The study found that when the concrete was mixed and cured with seawater as opposed to the conventional concrete mix, there was a decrease in the tensile strength.

In terms of the impact of seawater on fresh concrete characterizations, seawater decreases the setting time of cement by 30-75% as the concentration of the mixing seawater increases, according to S. Kaushik et al. [74].

1.3 Research Objectives

The main objectives of this research can be summarized as follows:

- Introduce the recycled waste tires as an alternative to produce green concrete by reducing the consumption of natural resources in concrete production and decreasing the growing volume of scrape tires in the landfills. Also suggest the use of seawater as mixing water in rubberized concrete as a sustainable material that eliminate the cost and energy consumed during the desalination process.
- Conduct life cycle cost analysis to evaluate the cost-effectiveness of using recycled tire waste and seawater as a replacement for aggregate and freshwater, respectively, in a concrete mix, in comparison with the conventional concrete mix.
- Ensure the validity of incorporating recycled rubber into the concrete mix from the technical perspective (before conducting the LCCA) by investigating the fresh and hardened concrete characterizations of thirteen concrete mixes, including a conventional mix, rubberized concrete mixes, and seawater mixes.

1.4 Thesis Outline

This study consists of five chapters:

1. Chapter 1 is the introduction, discussing the factors that have led to the growing concern about using recycled materials in concrete and outlining the potential benefits of using recycled rubber and seawater in the concrete mix. The chapter also provides an extensive literature review of LCCA, the application of recycled rubber in construction, and the use of seawater in plain concrete.

2. Chapter 2 provides the technical data that will be used as an input for the

LCCA. The chapter also discusses the properties of the materials, like water, cementitious material, aggregate, and rubber that constitute the conventional concrete mix, rubberized mix, and seawater mix.

3. Chapter 3 discusses the performance of recycled rubber and seawater in the concrete mix to ensure the validity of using these materials as a replacement for aggregate and freshwater, respectively, before conducting the LCCA.

4. Chapter 4 presents the LCCA, the tools and techniques that were used to conduct the LCCA, and the main principles and assumptions that were adopted to evaluate the cost-effectiveness of using recycled rubber and seawater in concrete.

5. Chapter 5 is a conclusion of the results obtained from LCCA and the investigation of the materials. The chapter also lists recommendations for future research.

CHAPTER 2: SOLUTION FOR ACCOMMODATING RECYCLED TIRES IN CONCRETE

2.1 Materials

2.1.1 Water

The amount of water in a concrete mix significantly influences all the fresh concrete and hard concrete properties, such as workability, compressive strength, durability, shrinkage and cracking potential [81]. Therefore, controlling the amount of water in the concrete mix is crucial during the construction stage and the operation of the structure [82]. Generally, a low water to cement (W/C) ratio improves hardened concrete proprieties by increasing the compressive strength of concrete, reducing permeability, improving durability and increasing concrete density [83]. On the other hand, a high W/C ratio is required to provide concrete with suitable workability during mixing, transporting and casting.

In this study, among the thirteen concrete mixes, two types of water were used. Seven mixes were mixed using freshwater, which is the common type of water used in construction, and six mixes were mixed using seawater which is most likely used where there is a lack of freshwater.

In Qatar, the freshwater used by the concrete plant was obtained from the normal household water supply, which is originally seawater that was desalinated to become drinking water. The seawater was pumped from the Gulf, from Al-Khor in the northern coast of Qatar to a portable tank. The seawater was then pumped into 10-liter water containers and stored at the concrete plant to be used for mixing. Chemical characterization tests were conducted for both types of water to determine the chloride and sulfate contents, alkalinity, total dissolved solids, and pH.

Table 2 shows the maximum limitation of the chemical contents as per Qatar Construction Specifications (QCS 2014) [84], which is in line with ASTM D512, BS

1377 and BS 6068-2.51 standards [85–88]. The chloride (CL) content of seawater is significantly high, as expected, and it is higher than the maximum limit allowable in the standards; the chloride content in the seawater is responsible for the corrosion commonly observed in reinforcement steel. The seawater also has extremely high sulfate content and total dissolved solids (TDS) that exceed the maximum limits according to the standards. However, the alkalinity and pH are comparable to freshwater and are within allowable limits in both types of mixing water, with a slight increase in seawater.

Table 2. Chemical Characterizations of Freshwater and Seawater

Test	Unit	Method/Standard	Maximum Unit	Result	
				Freshwater	Seawater
Chloride (Cl^-)	mg/L	BS 1377 PART 3[85]	1000	14.09	18,600
Sulfate (SO_4^{-2})	mg/L	BS 1377 PART 3[85]	2000	20.93	2359
Total alkalinity	mg/L	BS 6068-2.51[87]	500	69.51	149
Total dissolved solids (TDS)	mg/L	BS 1377 PART 2[86]	2000	62.00	30,300
pH (at 25 C)	-	BS 6068-2.50[89]	6.5–9.0	8.06	8.20

2.1.2 Aggregate

Aggregate constitutes as much as 60% to 80% of the volume and 70% to 80% of the weight of a typical concrete mix, and it provides concrete with its compressive strength [90]. Therefore, aggregate must be properly selected to ensure desirable gradation and to confer other desirable characteristics such as, strength, workability, and durability.

In terms of size, aggregate is classified into two types [91]:

1. Fine aggregate, usually referring to sand and crushed stone with particles less than 9.55 mm in diameter.
2. Coarse aggregate, which refers to particulates ranging between 9.55 mm and 37.5 mm in diameter.

However, in terms of origin, aggregate is classified into two types [92]:

1. Natural aggregate (NA), which has not exposed to any process and is taken from natural resources, such as sand, gravel, riverbeds, quarries, and mines.
2. Artificial aggregate, which is commonly taken from engineering waste and then treated to be suitable for construction activities. Sources of artificial aggregate include recycled aggregate from demolished structures, industrial slag, and burnt clay.

Three sizes of aggregate were used in this research: washed sand, 10 mm NA and 20 mm NA. The washed sand was mixed using water to remove any salt and clay and then it was placed in the oven for about 24 hours – more or less, depending on the quantity – until it returned to a dry condition.

According to Table 3, the physical and mechanical properties of the aggregate fulfill QCS 2014 [84], which is in accordance with BS/EN and ASTM standards.

Table 3. Physical and Mechanical Properties of Aggregate

Requirement	Standard	Permissible Limits		Result	
		Fine	Coarse	Fine	Coarse
Grading	BS 933 – 1[93]	Standard	Standard	Standard	Standard
Natural: materials finer than 0.063 mm	BS 933 - 1[93]	3% max	2% max	0.5%	0.3%
Crushed rock: materials finer than 0.063 mm	BS 933 - 1[93]	7% max	2% max	1%	0.3%
Fine quality: Structural concrete sand equivalent %	BS 933 – 8[94]	60% min[2]	--	30% min[2]	--
Fine quality: non-structural concrete methylene blue adsorption value (0/2 mm)	BS 933 - 9[95]	1.0 (g/kg)	--	0.7 (g/kg)	---
Clay lumps and friable particles	ASTM: C142[96]	2% max	2% max	0.0%	0.0%
Water absorption	BS 1097 – 6[97]	2.3% max	2% max	0.6%	0.5%
Flakiness index	BS 933 – 3[98]		35% max		5%

We performed a sieve analysis, which is a common test conducted on aggregate to verify their size. The sieve analysis for sand and the two sizes of aggregate were done in accordance with BS EN 932-1 standard, as shown in Table 4. More than 90% of the three sampled aggregates passed through the sieve sizes of 2.00 mm, 10 mm and 20 mm for sand, 10 mm aggregate and 20 mm aggregate samples, respectively; these results confirm the three aggregate sizes.

Table 4: Sieve Analysis for Sand, 10 mm and 20 mm Aggregate

Sieve size (mm)	Sand		10 mm aggregate		20 mm aggregate	
	Retained (gm)	Passing (%)	Retained (gm)	Passing (%)	Retained (gm)	Passing (%)
Pan	2.8	--	12.6	--	10.4	--
.063	14.5	0.5	1.8	0.5	1.3	,2
0.125	13.1	3	1.0	1	0.0	0
.150	86.8	5	1.0	1	0.0	0
.250	245.6	20	0.0	1	0.0	0
.500	134.5	61	0.0	1	0.0	0
1.000	49.5	84	2.6	1	0.0	0
2.000	29.3	92	42.9	1	0.0	0
4.00	17.2	97	690.6	2	2.5	0
6.30	0.0	100	848.5	29	30.9	0
8.00			830.8	63	234.2	1
10.00			124.8	95	971.9	5
12.50			0.0	100	879.1	24
14.00					879.4	41
16.0					1955.6	59
20.0					176.1	97
31.5					0.0	100

For the rubberized concrete, three sizes of recycled rubber replaced the sand, 10 mm aggregate and 20 mm aggregate. The recycled rubber was collected from Modern Recycling Factory (MRF) in Messaied City in Qatar; this factory specializes in transforming recycled waste tires into flooring products and other products for construction applications. The tires were a mixture of car and truck tires collected from landfills. Prior to the recycling process, the inner tubes, debris or any other material that may prevent or obstruct the grinding process were removed from the tires. The grinding process was done using different types of grinding machines based on the type of the final product and the size of the shredded tire required.

The fine rubber size is free of steel since it was processed through a machine that attracts and extracts magnetic metals, but the non-magnetic content was 2% of the sample. The fiber content was less than 0.5%. However, due to the greater complexity of producing shredded rubber with a size of more than 9 mm, the fiber and steel could not be extracted from the larger sizes of rubber, as can be observed in Figure 1.

a. Fine rubber replacing sand

b. Rubber replacing 10 mm aggregate

c. Rubber replacing 20 mm aggregate

Figure 1: The Three Sizes of Rubber

The specific gravity of the fine rubber was 1200 kg/m^3, determined as per the BS 932-2 [99] and BS 1097-6 [97] standards. As shown in Table 5, the sieve analysis as per BS 932-2 [99] and BS 933-1 [93] shows that 96% of the fine rubber particles passed through the 1 mm sieve size, similar to the normal sand size used in the control mix.

The 10 mm and 20 mm sizes of shredded rubber are not often produced in the factory; therefore, a specific gravity test and sieve analysis test could not be done as per the normal standard; however, as the same source of rubber and the same recycling conditions were used, the specific gravity was considered to be the same as the fine rubber in this research.

Table 5. Fine Rubber Sieve Analysis

BS sieve size (mm)	% passed by weight
0.63	0.3
0.125	2
0.250	10
0.500	44
1.0	96
2.0	0.3

2.1.3 Cementitious Materials

Cement is a crucial substance used in construction, where it serves as an adhesive to bind sand and aggregate together in the concrete mix [100]. Cement is mixed with sand to obtain mortar or is mixed with sand and gravel to obtain concrete [101]. The most common raw materials used to produce cement are limestone, shells, clay, slate, blast furnace slag, silica sand, and iron ore; these materials are combined and heated at high temperatures to become a rock-like substance, which is ground to a fine grey powder, commonly known as cement [102].

Cement is the most widely used material worldwide, and it has widespread acceptance as a construction material [103]. This is due to many reasons, including but not limited to the fact that cement is a strong binding material that gives sufficient strength in a short period of fewer than two days, meaning it speeds up the construction progress. Also, cement can be produced, packed and transported in large volumes under controlled conditions [61]. In addition, cement can be used for at least four months if stored properly, and it is more economical than other alternatives [104].

There are various types of cement, including ordinary Portland cement (OPC), Portland Pozzolana cement (PPC), rapid hardening cement, quick setting cement and sulfate resisting cement (SRC) [105]. OPC is the most widely used type of cement globally as it is suitable for all types of structural concrete [106]. SRC is used in concrete structures that are exposed to sulfates from the surrounding soil or groundwater, such as coastal structures, pile foundations and sewage lines [107].

In this research, the cement used was OPC and was produced locally by Qatar National Cement Company. As shown in Table 6, we tested many of the chemical and physical properties of cement. These include its magnesium oxide (MgO) content, which, in accordance with BS 4027 [108], should be below 5% as a higher amount of MgO slightly decreases the strength and extends the setting time [109]. Furthermore, an excess amount of sulfur trioxide (SO_3) can make cement unsound, while tricalcium silicate (C_3S) and calcium aluminoferrite (CaO/SiO_2) cause hardening and an early gaining of strength and initial setting [105]. Loss on ignition (LOI) determines the water content in cement, and a high LOI value is usually due to poor storage conditions [110]. The insoluble residue (IR) refers to the content of non-cementing material that affects the cement's properties, especially its compressive strength [111]. As reported in Table 6, all chemical properties of the concrete in this study were within the limits required by the BS 4027 [108] standard.

We also investigated the physical properties of the cement as per BS 4027 [108]. The soundness test determines the ability of the cement to avoid shrinkage upon hardening [112]. Compressive strength is the most commonly tested property of cement [113], and this test was performed to ensure that the strength of the cement at compression at an age of 2 days and 28 days is equal to or more than 10 and 45.5 MPa, respectively, as per the BS 4027[62] standard. The initial setting time indicates the time in which the cement paste starts to harden and loses plasticity [105]. As with the chemical properties, the physical properties of the cement used in this study were all within the BS 4027 [108] standard's requirements.

Table 6. Physical and Chemical Properties of the Cement.

Description	Requirement	Result	Unit
1. Chemical composition			
Magnesium oxide MgO	5.0 max	4.31	%
Sulfur trioxide SO_3	3.5 max	2.96	%
Tricalcium silicate + dicalcium silicate (C_3S+C_2S)	66.7 min	70.86	%
Tracalcium aluminoferrite (CaO/SiO_2)	2.0 min	3.1	%
Loss on ignition (LOI)	5.0 max	1.86	%
Insoluble residue (IR)	5.0 max	0.76	%
2. Physical prosperities			
Soundness (le Chatelier expansion)	10 max	0.5	mm
Compressive strength – 2 days	10 min	22.75	MPa
Compressive strength – 28 days	42.5 min	46.65	MPa
Initial setting time	60 min	135	minutes

According to the concrete mixes applied in this research, 7% of the cement was replaced by micro silica (MS). MS is a fine light grey powder extracted when filtering the dust resulting from silicon and ferrosilicon manufacture [114]. It is widely used in concrete mixes as it is a good filler, based on its fine particular size; this combination of MS and concrete leads to an increase in resistance to chloride, acid, and sulfate, and it also improves strength [115].

Another admix added to the concrete was a superplasticizer known as Hyperplastic PC 350. This is based on polycarboxylate polymers, which are added to the concrete mix to enable the water content to perform effectively and to improve the mix’s workability while at the same time maintaining the strength [116]. As per Table 7, the physical and chemical properties in terms of appearance, specific gravity and solid content were tested for PC350, and all the results were within the limits specified by the ASTM C494 standard [117].

Table 7. Physical and Chemical Properties for PC 350

Test	ASTM C494[117] limits	Results	Remarks
Appearance	Very light yellowish liquid	Very light yellowish liquid	Accepted
Specific gravity (gm/cm^3)	1.050 - 1.060	1.053	Accepted
Solid content %	17.5 – 22.5	19.47	Accepted
PH @ 25°C	5 – 8	6.34	Accepted

According to the ASTM C494 [117] standard, the range of PC350 should be between 0.5 to 2.5 liters per 100 kg of cementitious materials in the mix, including the MS. Overdosing would cause a significant increase in retardation and workability.

2.1.4 Concrete Mixture Proportions

In order to conduct a proper LCCA for rubberized concrete, we must first ensure that using rubber as a replacement for aggregate in the conventional mix is valid. Therefore, conducting experimental work to investigate the performance of rubber and seawater in concrete was essential before conducting the LCCA. The thirteen concrete mixes, as described in Table 8, were produced at the Hassanesco concrete plant under laboratory conditions. The volume of each mix was 80 m^3 to allow us to perform all the fresh concrete tests and still have a sufficient amount of concrete cubes left for the hardened concrete tests. The mix grade for all concrete mixes was 45 MPa OPC + 7% MS, which means that the compressive strength at the age of 28 days should not be less than 45 MPa. The cement used in the mixes was OPC and 7% of the cement weight was replaced by MS. According to Table 8, M1 refers to the conventional concrete mix that is prepared regularly in the concrete plant. In addition to the concrete grade specifications, 250 grams of superplasticizer (PC 350) was added to M1 to improve the workability without increasing the W/C ratio. M2 is similar to M1, but the freshwater used for mixing in M1 was replaced by seawater in M2.

M3, M4, and M5 were rubberized concrete, whereby 5%, 10%, and 20%, respectively, of the sand of the control mix was replaced with the equivalent volume of fine rubber similar to the size of the sand. These mixes were classified into a & b according to the type of mixing water, as shown in Table 8; (a) refers to freshwater (FW), while (b) refers to seawater (SW). M6, M7, and M8 are additional rubberized mixes in which 5%, 10% and 20% of aggregate (10 mm and 20 mm), respectively, were replaced by the equivalent volume of two types of rubber, similar to the size of the aggregate (10 mm and 20 mm); these rubberized concretes were also classified into (a) and (b) according to the type of mixing water, the same as with the sand rubberized concrete mixes. However, in all mixes, the curing water was freshwater.

The superplasticizer (PC 350) volume used in all concrete mixes was not the same, and the dose of PC 350 was increased as a result of increasing the rubber volume in the mix or due to the use of seawater. As we observed during the experimental work, the rubber and seawater decreased the slump; however, we needed to maintain the same W/C ratio for all mixes. Therefore, additional doses of PC350 were added to achieve a desirable slump measurement (according to common practice in Qatar, the slump result for fresh concrete, which is done immediately after the mixing process, should be at least 200 mm).

Table 8. Concrete Mixes

Sr. no.	Mix ref	Mix sub. ref	Remarks
1	M1	M1	Control mix – conventional mix
2	M2	M2	Conventional mix, mixed with seawater
Sand Replacement			
3	M3	M3.a	5% of sand replaced by rubber (FW)
4		M3.b	5% of sand replaced by rubber (SW)
5	M4	M4.a	10% of sand replaced by rubber (FW)
6		M4.b	10% of sand replaced by rubber (SW)
7	M5	M5.a	20% of sand replaced by rubber (FW)
8		M5.b	20% of sand replaced by rubber (SW)
Aggregate Replacement			
9	M6	M6.a	5% of aggregate replaced by rubber (FW)
10		M6.b	5% of aggregate replaced by rubber (SW)
11	M7	M7.a	10% of aggregate replaced by rubber (FW)
12		M7.b	10% of aggregate replaced by rubber (SW)
13	M8	M8.a	20% of aggregate replaced by rubber (FW)

2.2 Assessment Methods for Concrete

2.2.1 Fresh Concrete

Workability is a common fresh concrete characteristic. It indicates how easily concrete can be mixed, transported to the site, and laid while the concrete is in a plastic state and with a minimal loss to homogeneity [118]. Workability has a direct impact on concrete strength, shape and even the cost of labor during the laying and finishing process.

The concrete mix design has a major impact on workability; for example, the W/C ratio has a significant impact on workability, a higher amount of water usually allows the concrete mix to consolidate and increase the workability, and a higher portion of cementitious materials means an increase in the strength [119]. Therefore, the W/C ratio should be carefully determined to balance the concrete workability and the required strength. Moreover, the shape and surface of the aggregate also influence the workability as a large surface area requires more cement paste to cover it; thus, a smaller aggregate size provides less workability in comparison with a larger aggregate size.

Flaky, elongated and angular aggregate shapes are more difficult to mix and place, so they lead to low workability [120]. Beyond the W/C ratio and aggregate shape, the concrete admix, such as superplasticizers, decreases the attraction between the cement and the aggregate and makes the mix more flow-able without reducing the strength [118].

The most common test to determine the workability of fresh concrete is the slump test. In this study, the slump test was conducted in accordance with the BS EN 12350-2 standard [121], using a slump cone (300 mm height, 200 mm bottom diameter, 100 mm top diameter) placed on a smooth and even surface. The cone was filled with fresh concrete in three layers, with each layer being compacted manually using a rod 25 times from a suitable height to ensure proper compaction and reduce the air content of the sample. Then, the cone was lifted carefully and, as a result, the concrete settled down. The slump value was determined by measuring the differences between the cone height and the concrete height. As a result of lifting the slump cone, the fresh concrete takes three forms [122], as shown in Figure 2. The true slump is the most desirable form, whereby the concrete subsides briefly and maintains the cone shape. The shear slump is when one side of concrete slides on an inclined plane, and the collapse slump is when concrete collapses completely due to a high W/C ratio.

Figure 2: Three Slump Forms [118]

According to BS EN 12350-2 [121], workability falls into four categories based on the slump value, namely very low, low, medium and high, as described in Table 9.

Table 9: Workability Categorization According to the Slump Value [121].

Workability	Slump value	Remarks
Very low	0 – 25 mm	Use dry mix concrete design
Low	25 – 50 mm	Low workability mix design
Medium	50 – 100 mm	Medium workability mix design
High	100 – 175 mm	High workability mix design

According to common practice in Qatar, the slump measured directly after mixing should be 200 mm or more.

Flow table test of concrete also determines the workability, according to BS 1881-105:1984 standard [123] the flow is calculated by measuring the spread of concrete (after lifting up the slump cone) in diameter vertically and horizontally. The average of two measurements represents the flow.

Density is another fresh concrete property, simply it is a mass to volume ratio, measured by weighting the concrete filled into container with known volume and weight [124]. Generally, the a higher value of density of the hardened concrete provides a higher compressive strength due to less a lower number amount of voids [125].

2.2.2 Hardened Concrete

Several properties can be measured for hardened concrete, including compressive strength, tensile strength, shrinkage, durability, creep, and density [126]. In this study, we conducted a compressive strength test, a rapid chloride permeability test (RCP), and a water absorption test.

Concrete is strong in compression but weak in tension, and its compressive strength is about ten times higher than its tensile strength [127]**.** The compressive strength is defined as the resistance of concrete to failure under the action of compressive force; it is an important parameter to determine the performance of structural concrete during the operation stage of any structure [128]. Based on the structural design of the concrete structure and the predicted loads, the designing engineer determines the strength required for each structural element, then proportions the concrete mixes according to the compressive strength required [129].

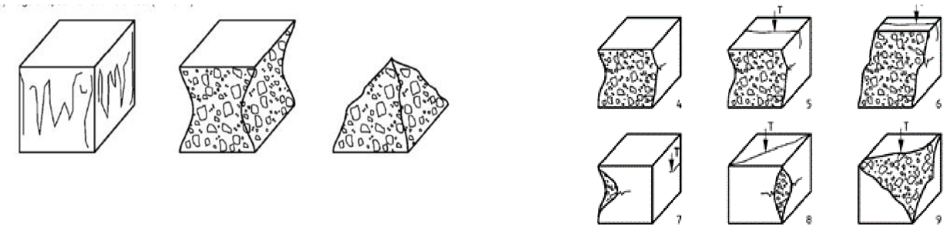
We measured compressive strength of the concrete at the ages of 7 days, 28 days and 56 days. In line with BS EN 12390-1[130], three cubes (150 × 150 ×150 mm) were tested for each age. Each cube was filled in three layers and each layer was compacted manually by a rod to reduce the air content and voids; each cube was prepared carefully as any damaged cube not complying with the standard should not be tested.

Subsequently, the cubes were cured in freshwater for two or three days to obtain the hardened form before sending them to the laboratory for testing. In the laboratory, the cubes remain cured until the testing date. In accordance with BS EN 12390-3 [131], the cubes were exposed to continuous load by a compression testing machine, with the load increasing at a constant rate of 10% until the failure load. Upon the failure of the cube, the failure load was recorded to determine the compressive strength. The compressive strength (f), as shown in Equation (2), is given by dividing the maximum failure load (F) in Newton (N) by the surface area of the cube in mm.

$$f = \frac{F}{A}$$

Equation 2: Compressive Strength

The type of fracture was also recorded; Figure 3 shows examples of the satisfactory and unsatisfactory failure forms of concrete cubes.



a. Satisfactory failures

b. Unsatisfactory failures

Figure 3: Types of Cube Failure [131]

Three cubes were tested for each concrete age (7, 28 and 56 days); the same procedures were done for all the cubes. At the end, the average of the compressive strengths of the cubes of a given age was taken as the compressive strength for that age.

We also tested the concrete's resistance to chloride, since the corrosion of reinforcement steel due to chloride is a common problem affecting structures and is attracting growing attention because it occurs frequently and the repair cost is very high [132]. Chloride attacks can occur from inside the concrete if seawater is used to mix the concrete or the concrete mix ingredients include chloride; also, the chloride can penetrate the concrete from the external environment [133]. Therefore, the determination of chloride permeability is an important indicator of concrete durability.

In this research, the RCP test was used to determine the resistance of concrete to the penetration of chloride ions. This test was conducted in accordance with ASTM C1202-19 [134], whereby the chloride penetration was determined by monitoring the electrical current passing through a concrete specimen cylinder (100 mm of diameter, 50 mm thickness) over 6 hours. A 60-volt current was applied to one end of the cylinder, and during the 6 hours there were differences in the electrical current at the other side of the cylinder. According to ASTM C1202-19 [134], there is a relationship between the charge passing through the specimen and the chloride penetration. Table 10 provides a quantitative relationship between the charge pass and the chloride permeability of the concrete specimen.

Table 10. Chloride Ions Penetration Based on Charge Passed (coulombs) [132]

Charge passed (coulombs)	Chloride ion penetration
>4000	High
2000 - 4000	Moderate
1000 - 2000	Low
100 - 1000	Very low
<100	Negligible

The concrete specimens were sent to the laboratory as cubes (150 ×150 × 150 mm), similar to compressive strength cubes, and these RCP cubes were also cured in freshwater until the testing age (28 days). Before the testing, the concrete cubes were cored into a cylinder shape (100 mm diameter, 50 mm thickness) to become suitable for the test as per ASTM C1202-19 [134]. For each mix, three cubes were tested at the age of 28 days and the average was taken to present the chloride penetration resistance for the mix.

Water that penetrates an unsaturated concrete surface is considered to be a harmful agent because it has a major negative impact on concrete durability [135]. Therefore, measuring the concrete's ability to absorb water is very important. The preparation of the cubes for the water absorption test is similar to the case of the compressive strength test and RCP test, in line with BS EN 12390-1[130]. Three cubes from each mix were prepared for the water absorption test concrete at the age of 28 days. In accordance with BS 1881-122[136], however, the drying of the cubes started at the age of 24 days. The cubes were cored by a coring machine with a diamond edge into a cylinder (75 mm diameter, 150 mm thickness). As per the BS 1881-122 [136] standard, the three cylinder specimens were placed in a ventilated drying oven for about 72 hours at 105 °C. Then, the specimens were cooled in a dry, airtight vessel for 24 hours; immediately after cooling, the weight of each specimen was recorded (W1). After that, the specimens were completely immersed in a curing tank (at least 125 mm depth) at 20 °C for 30 minutes. Then, the free water on the specimen surface was removed with a cloth, and the weight of each specimen was recorded (W2).

The water absorption value was determined as the percentage increase in the specimen weight after immersing (W2 – W1) compared to the dry weight (W1) as per Equation (3)

$$Water\ Absorption\ (\%)\ = \frac{(W2 - W1)}{W1}$$

Equation 3: Water Absorption (%)

However, a correction factor based on the size of the specimen was applied to the percentage of water observed to obtain the water absorption parameter; the correction factor is given by Equation (4)

$$Correction\ factor = \frac{Volume\ (mm3)}{Surface\ area\ (mm2) \times 12.5}$$

Equation 4: Correction Factor

According to the dimensions of our specimens, the correction factor in this study was 1.2. The final water absorption test value of the concrete mix was obtained by taking the average value of the results of the three specimens.

CHAPTER 3: MATERIALS PERFORMANCE OF RUBBERTIZED CONCRETE

3.1 Fresh Concrete

The fresh concrete test results for slump, temperature, and density are given in Table 11; the slump test was conducted to indicate the workability of the concrete mix.

Table 11: Fresh Concrete Test Results.

Sr. no.	Mix Ref	Mix Sub. Ref.	Superplasticizer (gm.)	Temperature (°C)	Density (kg/m^3)	Slump (mm)	Flow (mm)
1	M1	M1	6.3	27.8	2566	200	470
2	M2	M2	7.5	28.5	2560	200	480
Sand replacement							
3	M3	M3.a	7.19	27.1	2318	190	310
4		M3.b	7.81	26.8	2441	185	310
5	M4	M4.a	7.50	30.4	2165	170	300
6		M4.b	8.44	26.5	2416	195	320
7	M5	M5.a	8.44	27	2214	210	400
8		M5.b	10.36	27.4	2004	180	310
Aggregate replacement							
9	M6	M6.a	8.44	29.4	2531	170	365
10		M6.b	10.36	29.4	2516	170	365
11	M7	M7.a	8.82	27.2	2304	150	270
12		M7.b	11.34	29.4	2214	170	320
13	M8	M7.8	10.39	28.9	2344	180	300

During the experimental work, it was noticed that, as a result of increasing the volume of rubber in the mix and using seawater, the workability decreased, although the W/C ratio was constant for all mixes. According to common practice in Qatar, the slump measurement for fresh concrete measured directly after mixing should be equal to or more than 200 mm; this is due to the very hot weather in the county, which may reach up to 50 °C in the summer season. The same practice was considered in this study, however, instead of increasing the W/C ratio, an additional dose of superplasticizer was added to reach the desirable slump. That explains why the result of slump after 45 min (shown in Table 11) is high (> 150 mm), despite the negative impact of rubber and seawater in workability.

The relationship between the volume of superplasticizer (PC 350) and rubber content is not linear; therefore, we could not precisely specify the additional dose of PC 350 required for rubberized concrete. The highest slump for rubberized concrete was recorded for M5.a; this might indicate that the PC 350 dose was slightly higher than the ideal dose. Also, the lowest slump value, obtained for M7.a, might be related to the PC 350 dose as it could be slightly less than the ideal dose.

The flow of concrete also indicates the workability and influenced by the PC 350 volume. Similar to the slump measurements the highest flow was recorded for M2, M1 & M5.a and the lowest flow was obtained for M7.a.

Regarding the density of the fresh concrete, the highest density was found in the control mix and the second-highest in M2; this indicates that increasing the percentage of sand/aggregate replacement with rubber decreases the density, as the sand/aggregate density is higher the rubber density. However, the densities of the aggregate replacement mixes are higher than the corresponding sand replacement mixes.

It is important to note that all the mixes were prepared under lab conditions; therefore, the temperature of the mix was changed slightly from one mix to another.

3.2 Hardened Concrete

3.2.1 Compressive Strength

Table 12 presents the compressive strength test results for the thirteen mixes at the ages of 7, 28 and 56 days. Generally, the results indicate a reduction in compressive strength in rubberized concrete. This reduction is increased as the percentage of replacing sand or aggregate by rubber increases. The highest loss of strength is 64% of the control mix strength, which was recorded for M5.b (20% rubber sand replacement and seawater used for mixing); however, there was a slight strength increase in M6.a and M6.b, which may be related to the low percentage of the replacement of aggregate by rubber and the higher volume of the superplasticizer in the two mixes compared to the corresponding volume in the control mix. Generally, the aggregate/rubberized concrete mix provides better results than the sand/rubberized mixes in terms of compressive strength.

Table 12. Compressive Strength Test Results

Sr. No.	Mix Ref	Mix sub. ref.	Compressive strength (MPa)		
			7 days	28 days	56 days
1	M1	M1	53.93	66.80	76.20
2	M2	M2	53.53	66.87	74.97
		Sand replacement			
3	M3	M3.a	50.67	62.47	74.87
4		M3.b	45.90	58.50	72.57
5	M4	M4.a	38.70	48.10	57.93
6		M4.b	45.87	57.63	64.07
7	M5	M5.a	23.33	27.50	36.40
8		M5.b	16.87	23.93	32.63
		Aggregate replacement			
9	M6	M6.a	59.67	72.70	80.87
10		M6.b	57.50	71.77	79.93
11	M7	M7.a	33.83	48.23	56.43
12		M7.b	43.97	56.13	64.23
13	M8	M7.8	38.93	50.90	60.20

Figure 4 shows the compressive strength for the seawater mixes in comparison with their corresponding freshwater mixes or control mix. For the control mix (M1) and the 5% rubberized mix (sand and aggregate), the results indicate a reduction in the compressive strength of the seawater mixes, ranging from 1.5% to 3%; however, for the 10% and 20% rubberized mixes (sand and aggregate replacement), the differences between the seawater mixes and their corresponding freshwater mixes are more than +/-10%.

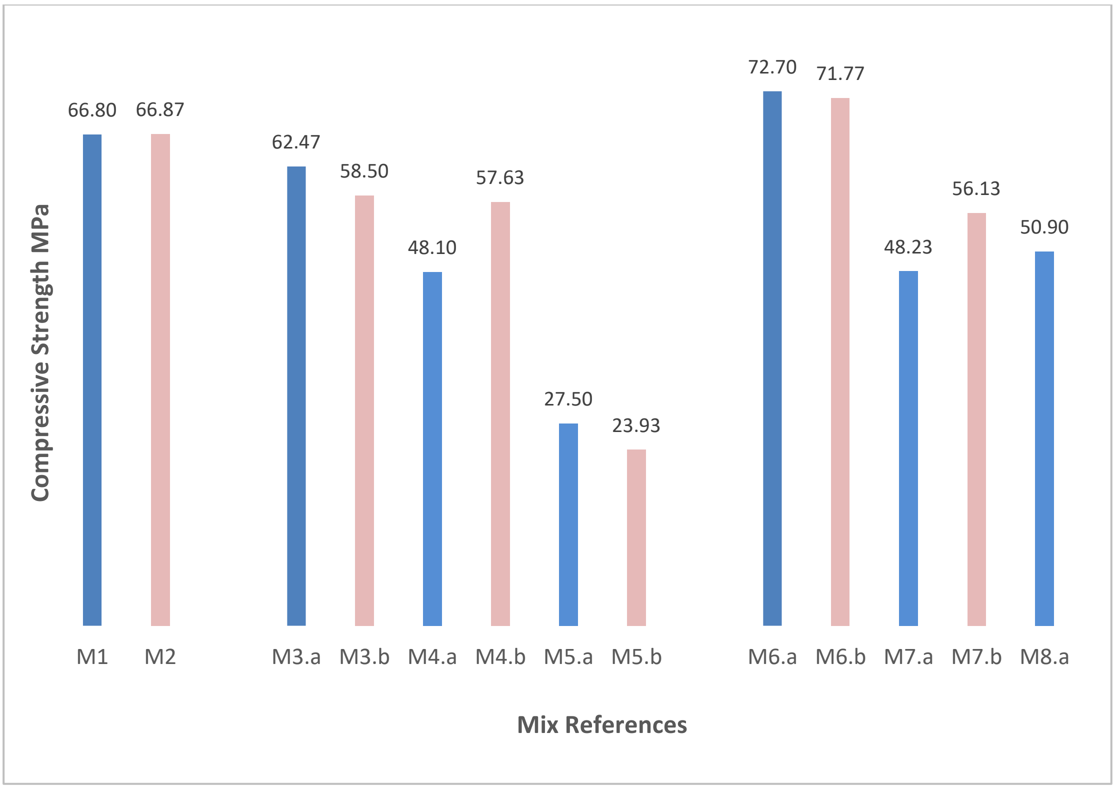


Figure 4: Compressive Strength Test Results at 28 days

According to the results the all the mixes gained more than 65% of their final strength (at 56 days) at the age of 7 days and more than 80% at the age of 28 days, except for the M5.a and M5.b (mixes with the lowest compressive strength), where the gaining of strength was 64% and 52% at age of 7 days, and 76% and 73% at age of 28 days respectively.

3.2.2 Rapid Chloride Permeability

Table 13 presents the RCP test results, and all the results range from 100 to 1000. According to Table 10, this measurement is considered a very low chloride penetration rate. The highest RCP value was reported for un-rubberized mixes (M1 & M2), and the RCP measurements of the other rubberized mixes are all below 500. Although there is no regular relationship between the volumes of rubber in concrete mixes and the RCP measurements, the performance of rubber in the concrete mix has a positive impact on chloride penetration since the penetration is lower in the rubberized mixes than in M1 and M2.

Table 13. RCP Test Results

Sr. No	Mix Ref	Mix sub. ref	RCP
1	M1	M1	739
2	M2	M2	846
		Sand replacement	
3	M3	M3.a	278
4		M3.b	275
5	M4	M4.a	408
6		M4.b	295
7	M5	M5.a	354
8		M5.b	449
		Aggregate replacement	
9	M6	M6.a	348
10		M6.b	438
11	M7	M7.a	463
12		M7.b	457
13	M8	M7.8	488

3.2.3 Water Absorption

Similar to the RCP results, all the water absorption results fall into the low category according to BS 1881 – 122 [136] for all the thirteen mixes, as shown in Table 13. The measurements differ slightly from mix to mix. The highest result was reported for the un-rubberized mixes (M1 and M2). The positive performance of rubber in terms of water absorption can be related to the low ability of the rubber itself to absorb water in comparison to sand and aggregate.

The seawater effect in terms of water absorption is not considerable, since the results for M3.b, M4.b, and M6.b are slightly less than their corresponding freshwater mixes, while the results for the remaining seawater results are similar to their corresponding freshwater mixes.

Table 14. Water Absorption Test Results

Sr. No	Mix Ref	Mix sub. ref	Water absorption
1	M1	M1	1.3
2	M2	M2	1.3
	Sand replacement		
3	M3	M3.a	1.0
4		M3.b	0.8
5	M4	M4.a	1.1
6		M4.b	0.8
7	M5	M5.a	0.8
8		M5.b	0.8
	Aggregate replacement		
9	M6	M6.a	1.1
10		M6.b	1.0
11	M7	M7.a	1.0
12		M7.b	1.0
13	M8	M7.8	1.0

CHAPTER 4: LIFE CYCLE COST ANALYSIS OF USING RECYCLED TIRE AND SEAWATER IN CONCRETE

4.1 Life Cycle Cost Model

A life cycle cost analysis (LCCA) is conducted here to compare the cost-effectiveness of using recycled tires and seawater in a structural concrete mix. The analysis considers two concrete mixes, namely the conventional mix M1 (RC1) and the M6.b (RC2) mix, in which 5% of coarse aggregate is replaced by rubber and seawater is used in the mix.

The structural design for both alternatives is assumed to be the same, but the influence of seawater on steel must be considered. Previous studies [31,44,137] suggested the replacement of black steel, which is used in conventional reinforced concrete, with glass fiber reinforced polymer (GFRP) to avoid the potential corrosion the may occur due to seawater as GFRP is a corrosion-free material [138].

In addition to the previous assumption, LCCA is also based on the following assumptions:

- The proposed structure is a high-rise building consisting of 20 floors and located in Doha, the capital of the State of Qatar.
- According to the building design details described in Table 15, the concrete volume in one square meter of the building is 0.27 m^3 and the concrete reinforcement ratio is 1.99%.
- The LCCA considers the owner's perspective.
- The cost analysis will not include the mechanical, electrical and finishing components of the building as the cost of these elements will not be affected by the change to the structural concrete mix.
- The study period is assumed to be 100 years. Commonly, the life cycle for such

buildings falls between 40 to 75 years [32,139]; however, a 100-year period is selected due to the long-term durability of RC2 reinforcement [31].

Table 15: Summary of The Structural Design of Conventional Steel-reinforced Concrete.

No. of floors	Gross floor area (m2)	Total concrete volume (m3)	Total steel weight (kg)	Volume of concrete per unit area (m3=m2)	Steel weight per unit area (kg/m2)	Reinforcement Ratio (%)
20	8000	2185	341,547	.27	4269	1.99

LCCA considers all the costs associated with the projects, from the investment and design stages up to the demolition and disposal stages [19]. Based on these stages, the LCCA in this study will be based on four components, namely material cost, construction cost, maintenance/repair cost, and end of life cost, as explained in Figure 5.

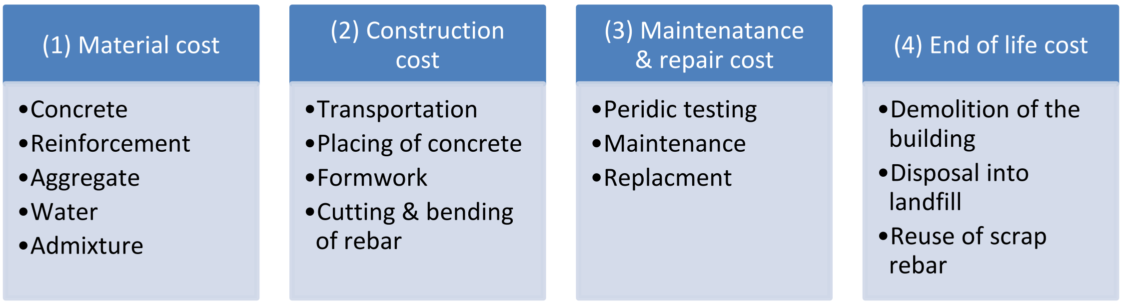


Figure 5: Life Cycle Cost Analysis Module

4.1.1 Material Cost

Material cost includes all the costs incurred by the owner in order to purchase materials, including concrete, aggregate, water, and shredded rubber, from the suppliers. The unit costs are obtained from local suppliers in Qatar, previous publications, and RSMeans [140], as shown in Table 16.

Table 16: Unit Costs

Material	Unit	Rate	Resource
Concrete	QAR/m^3	330.00	Local supplier [141]
Sand	QAR/ton	22.00	Local supplier [141]
Gabro aggregate - 10 mm	QAR/ton	77.00	Local supplier [141]
Gabro aggregate - 20 mm	QAR/ton	77.00	Local supplier [141]
Reinforcement steel (all grades> 8 mm)	QAR/kg	2.09	Local supplier [142]
GFRP	QAR/kg	34.22	RSMeans [140]
Rubber - 10 mm	QAR/ton	1,200.00	Local supplier [143]
Rubber - 20 mm	QAR/ton	1,200.00	Local supplier [143]
Water	QAR/m3	8.20	Local supplier [141]
Seawater (desalination)	QAR/m3	1.64	Previous publication [144]
Superplasticizer	QAR/liter	2.00	Local supplier [141]
Demolition (concrete)	QAR/m3	455.00	RSMeans [140]
Landfill rate	QAR/Kg	0.33	RSMeans [140]
Reinforcement scrap	QAR/ton	400.00	Local supplier [145]

The unit cost of concrete (grade 45 MPa) is considered as the basic cost to determine the total unit cost for the two mixes. For example, for RC2, 5% of coarse aggregate cost is deducted from the conventional concrete unit rate and the cost of the corresponding volume of rubber is added accordingly. Although the capital cost of rubber is more than 15 times the cost of raw coarse aggregate, the replacement by rubber slightly affects the total unit cost of rubberized concrete in comparison with the conventional concrete mix due to the low percentage of replacement. As well as rubber, the additional superplasticizer volume added to RC2 is also considered.

The desalination cost is considered as the only additional cost for the mixing water of RC2. This consideration is valid assuming that the establishment of seawater is similar to freshwater in terms of the current water supply infrastructure, such as pipeline networks, water tanks, etc.

4.1.2 Construction Cost

The construction costs include the cost of transportation of materials, placing of concrete, formwork, cutting and bending of reinforcement steel and all the labor and equipment costs incurred during the construction stage. The construction cost is considered to be 150% of the material cost, as per previous studies [31]. However, the installation of GFRP is considered to be 80% of the material cost due to the lighter weight of GFRP compared to conventional black steel [146,147].

4.1.3*Maintenance and Repair Cost*

The maintenance and repair cost refers to all the costs incurred during the operation stage of the structure to ensure that the building is performing according to the design and stakeholders' requirements. This includes general and detailed periodic inspection in addition to routine maintenance. General inspections are usually performed every 5 years [44] after the construction has finished to investigate any major damage in the structure that could lead to safety issues. The detailed inspections are conducted directly before the repair actions to identify the damaged items that may require repair. Routine maintenance is conducted regularly, is similar to the general inspections, and includes repainting, checking the drainage system, fixing visual concrete cracks, and repairing the electrical and mechanical systems.

According to a previous study [148], the costs of general inspection, detailed inspection, and routine maintenance are taken as 0.5% (M +C), 2.5% (M +C), and 1.5% (M +C), respectively, where M is the material cost and C is the construction cost.

In this study, only the repair and reconstruction of reinforcement due to corrosion actions are considered. As with the construction cost, the repair and reconstruction cost is determined as a percentage of the material cost, assuming that at the time of repair, 10% of the structure will be affected and 50% of the material will require replacement [149]. The cost of manpower and equipment is assumed to be 200% of the material cost; however, the purchasing cost of raw materials remains the same.

The corrosion of reinforcement steel usually happens due to chloride attack, as discussed in previous publications [31,44,149]. Life-365 software was used to predict the repair scheduling of both traditional black steel and GFRP, taking into consideration the location of the building in relation to seawater and the concrete cover assumed in the design. Life-365 indicated the following:

- Black steel requires repairs every 10 years during the life of the structure.
- The end of service life for RC1 reinforcement is 50 years; thereafter, reconstruction is required to maintain the same performance of the structure.
- Since GFRP is unaffected by corrosion, no repair is conducted on RC2 throughout the life service of the building (100 years). Also, GFRP is thought to maintain about 70% of its tensile strength, which is sufficient to avoid any repair or reconstruction work until the demolition of the building.

  The repair is assumed to be conducted with the same materials used in the construction stage.

4.1.4 End of Life Cost

It is assumed that the building will be demolished at the age of 100 years regardless of whether its performance is as per the requirements. The end of life cost includes all the expenses incurred during the demolition stage, including demolition and disposal, in addition to the value earned from the reuse of traditional black steel scrap for RC1. According to local practice in Qatar, 100% of steel scrap can be reused;

however, due to its anisotropic characteristics, GFRP is difficult to reuse [44]. The unit rates of demolition cost and reinforcement steel scrap were obtained from RSMeans [140].

4.1.5 Determination of LCCA

The LCCA module consists of four components: material cost, construction cost, maintenance and repair cost, and end of life cost. The total cost at any time of the life of the building is given by Equation (5)

$$C(t) = M(t) + C(t) + R(t) + E(t)$$

Equation 5: Sum of the LCC Module

Where C (t) is the summation of materials costs (M), construction costs (C), repair/maintenance costs (R), and end of life costs (E) at year (t). However, in order to express the LCC, all the costs incurred through the life service of the structure need to be discounted to present value [150] as Equation (6).

$$LCC = \sum_{t=1}^{T} \frac{C(t)}{(1+r)^t}$$

Equation 6: Present Value of LCC

The discount rate (r) is used to express the future costs in the present; the value of (r) depends on economic parameters, such as inflation rates, purchasing power, and interest rates [34]. In this study, 0.7% was used as the discounting rate based on work by the White House Management and Budget Office [151]. Furthermore, a sensitivity analysis is conducted for (r) values ranging from 0% to 15%, since the discount rate is sensitive to changes in the economical parameters and it is a key variable in LCC calculation.

4.2 LCCA Results

The changes to the materials in concrete mixes of the two design alternatives RC1 and RC2 seem to have a negligible impact on the unit cost. Although the cost of shredded rubber is significantly higher than the cost of aggregate, due to the low percentage of replacement (5%), the high cost of rubber does not affect the unit cost of RC2 in comparison with the traditional mix (RC1). The unit cost of the design alternatives is highly influenced by the type of reinforcement selected. Figure 6 illustrates the LCC cash flow throughout the study period before applying the discounting for the future costs; it shows that the high purchasing cost of GFRP makes RC2 about two times more costly than RC1 at the construction stage. However, the regular repair and reconstruction cost (at year 50) due to the use of black steel makes the overall LCC of RC1 higher than RC2.

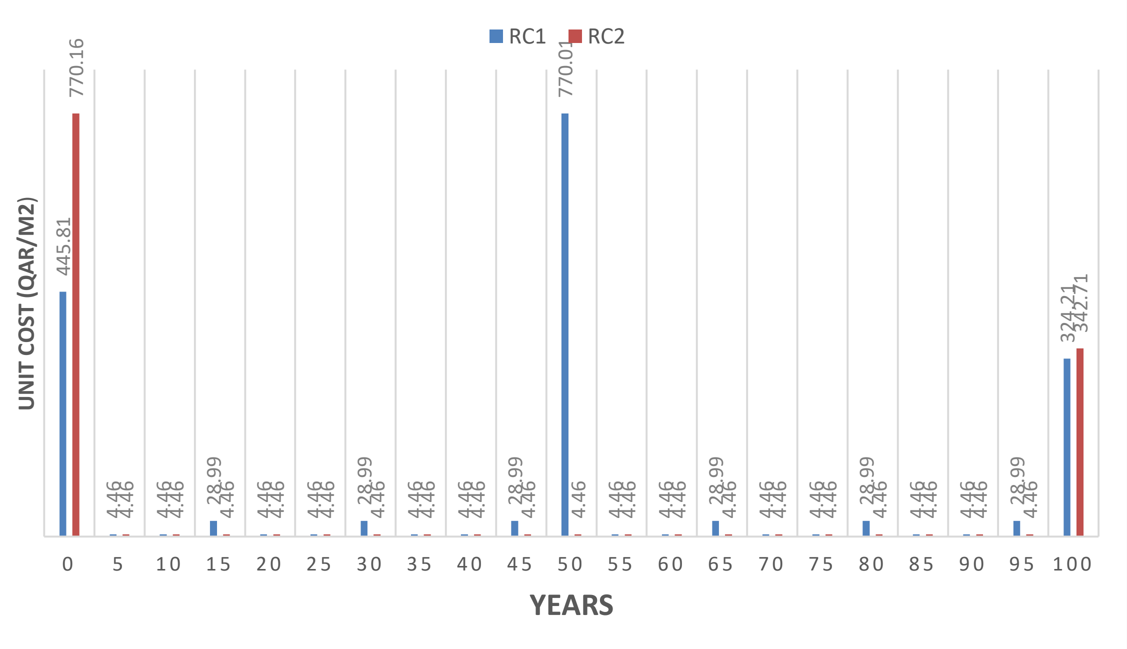


Figure 6: Cash Flow Diagram for Design Alternatives (future costs are not discounted)

The present value of the materials cost, construction cost, repair cost, reconstruction cost, and end of life cost is reflected in Table 16, using the discounting rate of 0.7% and assuming that the C to M ratio is 150%. RC2 can be considered to be more cost-effective than RC1at the end of the study period. The cost incurred in the construction stage of RC2 represents more than 65% of the LCC, while the repair and end of life costs represent only 7% and 26% of the total LCC of RC2. On the other hand, the material and construction costs of RC1 are only responsible for 27% of the total cost and the majority of the cost (43%) is incurred in year 50 (see figure 7), when the whole building needs to be reconstructed. The reconstruction cost involves the demolition and disposal costs of the existing building in addition to the material and construction costs required for reconstruction. Assuming that the building is reconstructed with the same specifications, the requirements for repair and maintenance will be similar to the previous requirements assumed for RC1 from age 5 to 50 years.

Table 17. Summary of LCC Results (using r = .7%)

Design alternative	Unit costs QAR/m^2					LCC QAR/m^2
	Material	Construction	Repair	Reconstruction	End life	
RC1	178.32	267.48	211.28	718.13	281.99	1,657.20
RC2	388.08	382.08	79.00	0.00	298.08	1,147.24

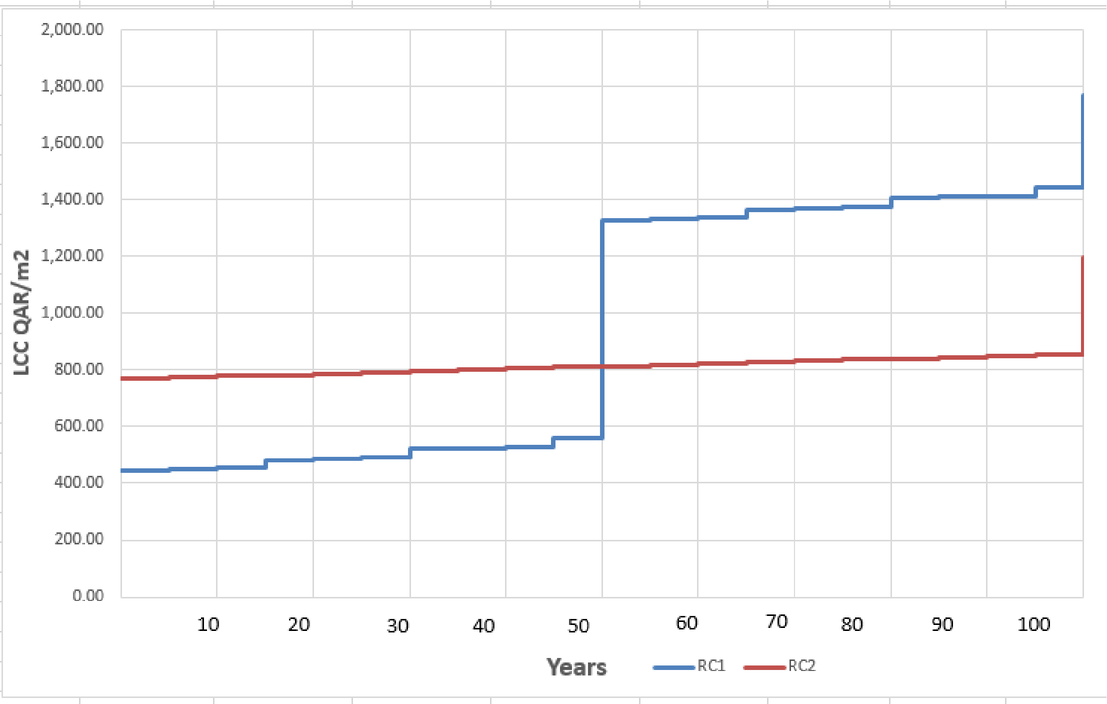


Figure 7: Life cycle Cost Results (where r = 0.7% and C is 150% of M).

4.2.1 Sensitivity Analysis

A sensitivity analysis is a financial module that determines how target values are influenced by a change of other relevant variables [152]. In this study, the basic assumption of determining the LCC is the value of the discounting rate, which is assumed to be 0.7%. Since the value of *r* is predicted based on the changing financial parameters in the future, changes to these parameters have an influence on LCC as well. A sensitivity analysis was conducted for *r* considering the range from 0% to 15%, as per Figure 8.

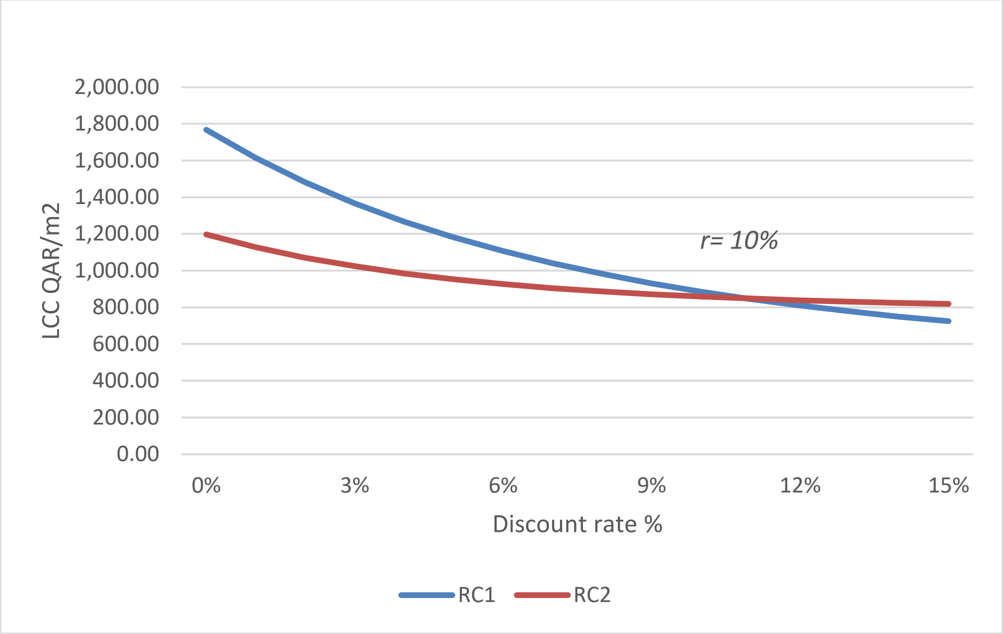


Figure 8: Sensitivity of the LCC Results to the Discount Rate (C= 1.5M)

Figure 8 shows that increasing r results in a decrease in LCC for both design alternatives. The RC1 costs remain higher than RC2 for all values of r less than 10%. Since there is a large range between the values of r assumed in this study (0.7% to 15%), it is most likely that RC2 will be more cost-effective throughout the study period.

Similar to the discount rate, the LCC value is also influenced by the C/M ratio. The basic assumption in this study is that the C/M ratio is 150%, but a sensitivity analysis is also conducted to determine the LCC amount for C/M ratios ranging from 0% to 250%. The analysis shows that the cost of RC1 remains higher than the RC2 cost for all the different C/M ratios, as presented in Figure 9.

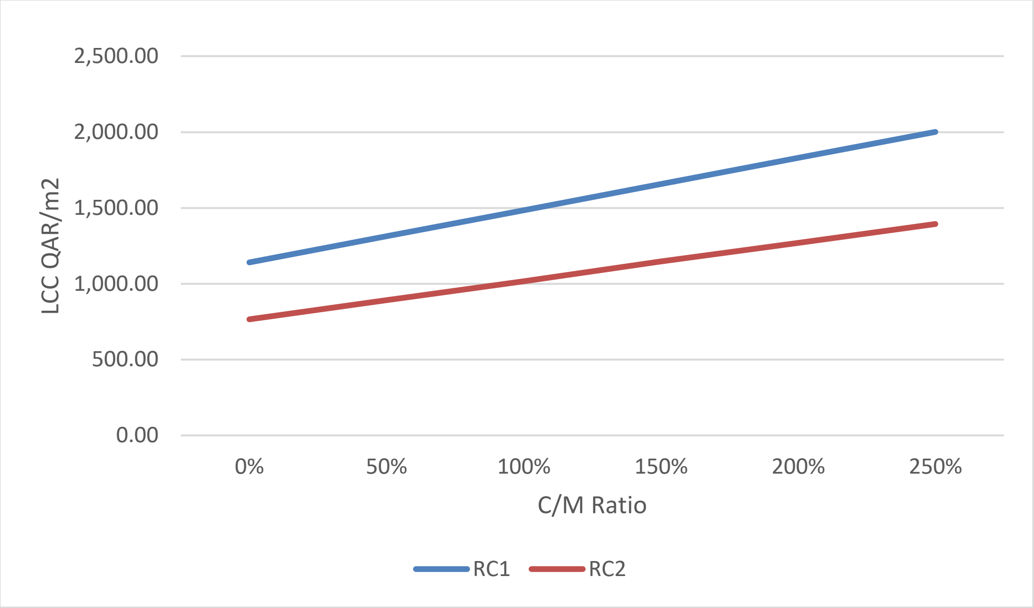


Figure 9: Sensitivity of the LCC results to the construction cost, C (r = 0.7%)

CHAPTER 5: CONCLUSION AND FUTURE RECOMMENDATIONS

5.1 Conclusion

This study contributes to the management area body of knowledge in general and in particular the construction and engineering management with an investigation of the use rubberized RC in building construction and its sustainability. Life cycle cost analysis has been conducted to compare between the rubberized and traditional structural concrete. The economic and technical impact of using recycled tires as a replacement for aggregate in structural concrete was investigated, as the use of recycled materials could help reduce the construction industry's consumption of natural resources and also decrease the growing volume of tires in landfills. The performance of rubber in fresh and hardened concrete was examined through twelve rubberized concrete mixes with different volumes of shredded tires. Then, both fresh and hardened characterizations of rubberized concrete mixes were made and compared with control mix characterizations. Based on the assumptions made and the test results, we conclude the following:

- The compressive strength of concrete is decreased by increasing the volume of rubber in concrete; the negative impact of rubber on concrete strength means that the use of rubber in structural concrete is not recommended since compressive strength is a key parameter in concrete structural design. However, based on the results obtained from the rapid chloride penetration and water absorption tests, we find that rubberized concrete is slightly more durable than conventional concrete.
- The fresh concrete characteristic of workability was investigated as well. The slump measurements immediately after concrete mixing showed that as the rubber volume in concrete increased, the workability was reduced. Therefore,

to achieve desirable slump results, the volume of superplasticizer in rubberized concrete mixes should increase as the rubber volume increases.

- Based on the technical data obtained from the experimental work, in the economic analysis we conducted an LCCA for RC1 and RC2. RC1 represented a traditional concrete mix. In RC2, 5% of aggregate was replaced by rubber, and seawater was used for mixing; this provided good fresh and hardened concrete characterizations for the rubberized concrete mixes.
- The LCCA showed that RC2 is more cost-effective (30% cost savings) than RC1, mainly due to its use of GFRP reinforcement instead of the traditional black steel used in RC1. GFRP reinforcement was chosen because seawater can cause corrosion in traditional reinforcement.
- The cost of shredded rubber is considerably higher than sand and aggregate, yet due to the low percentage of rubber/aggregate replacement in RC2, this had no effect on the material cost of RC2 in comparison with RC1.
- Despite the higher purchasing cost of GFRP, its durability and lower maintenance cost of GFRP made RC2 more cost-effective than RC1 in the long-term analysis.
- A sensitivity analysis was conducted for two variables, namely the discount rate and the material to construction cost ratio. The analysis showed that RC2 remains more cost-effective than RC1 for all discount rate values less than 10%; thereafter, RC1 became more cost-effective. However, the RC2 costs remain lower than RC1 for all C/M values ranging from 0% to 250%.

5.2 Future Recommendations

According to the materials used as well as the data, assumptions, and the approach followed, we recommend the following possible paths for future studies in relevant areas of research:

- The long-term cost-effectiveness of using rubber and seawater in concrete mixes may induce owners to adopt both materials in concrete manufacturing; however, to build on our work and create a more substantial practical foundation, more research is required using different assumptions and approaches.
- In addition to the technical and cost analyses for rubberized concrete, future studies could also conduct an extensive environmental assessment to evaluate the benefits obtained from using eco-friendly materials. The environmental advantages of using recycled tires in concrete may include reducing landfill volume, decreasing the use of natural resources in construction, and reducing the CO_2 emissions resulting from concrete production.
- Due to the lower compressive strength of rubberized concrete, the use of rubber may not be recommended in structural concrete, unless the shredded tires are specially treated. The pre-treatment of rubber with magnesium oxychloride [48] can improve the adhesion between rubber particles and other materials and can significantly improve the performance of rubberized concrete by improving the bonding characterizations of rubber.
- Moreover, rubberized concrete can be used in structural elements where compressive strength is not a key factor that is critical to structural performance, such as wall partitions, crash barriers, roads, and highways.

- To aid in legislation regarding the use of rubber and to suggest further potential applications of rubberized concrete in construction, further research is needed to investigate the split tensile strength, toughness, impact of resistance, shrinkage, and other properties of rubberized mixes.

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