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Case study

Material performance and cost effectiveness of seawater-mixed rubberized concrete

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A R T I C L E I N F O

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A B S T R A C T

The combined use of seawater and recycled tire aggregate (RTA) in concrete is potentially a way forward towards sustainable construction. It can help control harvesting of natural aggregates, manage waste tires, mitigate freshwater consumption and desalination impacts. The current paper aims at investigating the material performance and cost effectiveness of concrete mixed with seawater and RTA. The paper consists of two parts. The first part studies the characteristics (fresh and hardened) of concrete mixed with seawater and RTA. Thirteen concrete mixtures, varying in mixing water (seawater/freshwater) as well as fine and coarse aggregates (at 0%, 5%, 10%, and 20% replacement levels), were investigated. An extensive experimental program was conducted to compare the thirteen mixtures in terms of physical properties, workability, strength, water absorption, and chloride permeability. The second part of the paper performs a life cycle cost analysis (LCCA) for a 20-story building over a 100-year analysis period to verify the cost effectiveness of a proposed sustainable concrete that combines seawater, RTA (at 5% replacement level), and glass fiber-reinforced polymer (GFRP) reinforcement. A sensitivity analysis was performed to investigate the effect of the discount rate on the LCCA results.

1. Introduction

Concrete is the most commonly used material in the global construction industry, which is primarily composed of cement, freshwater, and fine/coarse aggregates. The massive production of concrete exerts a negative impact on the environment as the mixing aggregates are generally extracted from natural resources. Recycled tires may represent a valid alternative to the natural aggregates in concrete, which can make a step forward towards mitigating the increasing global concerns of accumulated waste tires and continuous harvesting of natural aggregate resources. Indeed, disposing of tires to landfills might cause serious environmental issues, as tires remain for long periods, and the micro-organisms take more than 100 years to biodegrade them [1].

To further promote the use of eco-friendly materials in construction, this study also uses seawater as an alternative to freshwater for mixing concrete. This move is in response to the growing global concerns regarding freshwater scarcity. In effect, a recent survey showed that about two-thirds of the world's population are likely to suffer from water scarcity at least 1 month per year [2]. In light of this, there have been concerns that global concrete production consumes over two billion tons of drinking water every year [3].

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Furthermore, the intensive desalinization treatment of seawater has significant adverse environmental and economic impacts [4].

Generally, there is a common belief that seawater-mixed concrete should not be used in reinforced concrete structures; in case of a lack of freshwater, the use of seawater is recommended in plain concrete [5]. Since seawater contains a high amount of chlorides, mixing concrete with such water will lead to a considerable amount of free chloride ions coming into contact with steel reinforcement, thus promoting corrosion. To counter this issue, researchers have suggested using corrosion-resistant reinforcement in seawater concrete instead of traditional carbon steel to mitigate the corrosion process and therefore extend the service life of reinforced concrete elements [5]. Amongst the corrosion-resistant reinforcements proposed in the literature, glass fiber-reinforced polymer (GFRP) is deemed most popular given its light weight, high tensile strength, excellent non-magnetization properties, and low cost compared to the stainless steel or carbon-FRPs [6,7].

1.1. Recycled rubber in plain concrete

A significant amount of research has been devoted to understanding the effects of recycled tire aggregates on the fresh and hardened properties of concrete [1,8–13]. Most of the research on what is termed “rubberized concrete” (i.e. that incorporating recycled rubber from used tires in the mix) shows that the compressive strength is reduced when compared with the traditional concrete [12,14,15]. Therefore, the rubber aggregate should be used in structures where strength is not critical, and the recommended maximum replacement of the rubber aggregate ranges between 20% and 30% by volume [14,15]. For instance, Toutanji [16] investigated the effect of replacing 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 decrease in the compressive and flexural strengths, and the relationship between the strength loss and rubber content was not linearly proportional. Accordingly, some studies suggested the pre-treatment of recycled tires to improve the performance of rubberized concrete [8,12,17]. Sofi [18] evaluated the performance of rubberized concrete mix by replacing 5%, 7.5%, and 10% of fine aggregates with crumb rubber. The results showed that the rubber mix had lower compressive and flexural tensile strength, but higher permeability performance compared to those of the control mix. Accordingly, Sofi [18] recommended that rubber (up to 10% replacement of fine aggregate) could be used in pavements, floors, hydraulic structures, concrete highways, or any structure that may be prone to brittle failure. Likewise, Batayneh et al. [19] recommended using rubberized concrete only in non-structural elements such as pavements, partition walls, road barriers, and sidewalks. Yet, despite its reduced compressive strength, rubberized concrete may be potentially advantageous in high seismic zones as it provides good damping and energy absorption properties [11]. As far as fresh properties of rubberized concrete are concerned, Najim and Hall [10] indicated that increasing the rubber aggregate content reduces the workability performance, due to the increased porosity and hydrophobicity of recycled rubber compared to natural aggregates. However, as reported by Youssf et al. [12], the workability performance of rubberized concrete can be enhanced if the rubber is pre-mixed (dry or wet) with the other raw ingredients before adding water.

1.2. Seawater in plain concrete

The performance of seawater concrete (the terms “seawater concrete” and “seawater-mixed concrete” are interchangeable here) has been a focus of debate since 1840 when Smeaton and Vicat raised this issue in their work titled "What is the trouble with concrete in seawater" [20]. After that, many studies were carried out to investigate the performance of seawater in plain and reinforced concrete in terms of compressive, tensile, and flexural strength, as well as several other characterizations in the long and short terms [5,21–24]. Shi et al. [25] reported a slight increase in the compressive strength with the use of salt water. In contrast, other researchers indicated that seawater negatively affects the concrete strength gain by 5–15% on average [21]. As far as fresh concrete properties are concerned, seawater mixing generally decreases the slump (by 15–30%) and setting time (by 30–70%) of the resulted concrete [26], which is mostly attributed to the accelerating effects of salt ions. However, this can be addressed with the use of suitable admixtures to improve the workability of seawater concrete [27].

1.3. Life cycle cost analysis

To assess the sustainability of a construction project, the environmental and economic impacts associated with it are quantified on a life-cycle basis (i.e., cradle to grave), accounting for raw materials extraction and procurement, construction, operation, maintenance, and eventual demolition and disposal [28]. With more focus on the economic aspect of sustainability for construction, life cycle cost analysis (LCCA) is often used to financially compare various design alternatives of the same project from the initial stage up to the end of its service life. Consequently, LCCA helps achieve efficient decision-making in the early stages of the project and augment project savings [28].

Since the use of recycled rubber is more common in asphalt works than in concrete structures, the majority of LCCA studies focused on the cost effectiveness of using recycled rubber in asphalt mixes. In this context, Jung et al. [29] showed that rubberized pavement is more cost-effective than conventional concrete pavement and provides a longer service life. As for seawater, when used instead of freshwater the cost and energy consumption resulting from seawater desalination may be eliminated [30]. Since seawater ions potentially lead to steel corrosion, the use of corrosion-resistant reinforcement (e.g., GFRP) in place of traditional steel in seawater concrete is commonly suggested. Although corrosion-resistant reinforcement has a relatively higher initial cost, it extends the service life of seawater concrete and significantly reduces maintenance costs in the long term. In this context, Younis et al. [31] reported cost savings of 40–50% using seawater concrete associated with GFRP reinforcement as compared to conventional concrete.

1.4. Research scope and significance

In view of the aforementioned literature survey, this study considers (arguably for the first time) combining seawater and recycled tire aggregates (RTA) to achieve sustainable concrete. While several specifics of such sustainable concretes need to be understood prior to general implementation, the current paper is focused on quantifying the material-characterization and economic impacts of the combined use of seawater and RTA in structural concrete. The work is, therefore, carried out with a two-fold objective: (a) to assess the effects on fresh and hardened concrete characteristics due to the combined use of seawater and RTA, and (b) to evaluate the cost impacts of the use of seawater, RTA, and non-corrosive glass FRP reinforcement in concrete. Consequently, the paper consists of two parts: the first part reports on an extensive experimental study on the fresh and hardened properties of thirteen concrete mixtures. The test parameters include mixing water (seawater/freshwater) and the replacement level of natural aggregates by RTA (0%, 5%, 10%, and 20%). In the second part of the paper, we present a 100-year LCCA study for a 20-story building to compare the cost performance between a conventional concrete (RC1, with natural aggregates, freshwater, and traditional carbon steel reinforcement) and a proposed sustainable concrete (RC2) that combines RTA (at 5% replacement level), seawater, and GFRP reinforcement.

2. Materials and methods

2.1. Concrete raw ingredients

Two types of mixing water were considered, namely, freshwater and seawater. The freshwater used was obtained from the normal household water supply, which (in Qatar) is originally desalinated seawater. The seawater was pumped from the Arabian Gulf, from Al-Khor coast in Qatar, and then stored to be used for mixing. Despite having no significant difference between both water types in terms of pH (8.2 for seawater and 8.06 for freshwater), the relatively high contents of sulfate and chloride ions measured in seawater (2.36 and 18.6 g/L, respectively) would ultimately make the difference between seawater- and freshwater-mixed concretes. For more details, the chemical characterization results for both water types can be found in Ref. [32], in which work the same mixing waters were used.

For natural-aggregate concrete, locally available washed sand was used as natural fine aggregates. The natural coarse aggregates used were local crushed rock (Gabbro) of 10 and 20-mm nominal sizes. The densities of the natural aggregates, measured as per BS EN 1097-6 [33], were 2980, 2930, and 2620 kg/m^3 for 20-mm Gabbro, 10-mm Gabbro, and washed sand, respectively. The water absorption was also measured (in accordance with BS EN 1097-6 [33]) as 0.4% for 20-mm Gabbro, 0.6% for 10-mm Gabbro, and 0.6% for washed sand. For more details, the chemical, physical, and mechanical characteristics of the natural aggregates can be found in Ref. [34], in which work the same aggregate resources were adopted.

For the rubberized concrete, three sizes of recycled rubber replaced the fine aggregates (as shown in Fig. 1-a) as well as the 10-mm Gabbro and 20-mm Gabbro as shown in Fig. 1-b and -c, respectively. The recycled rubber was collected from the Modern Recycling

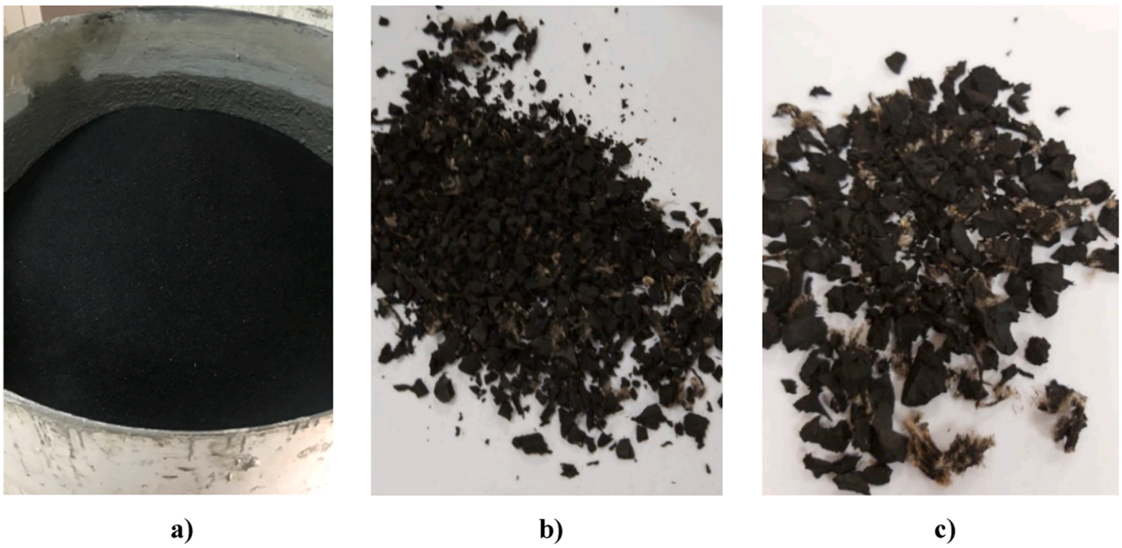

Fig. 1. Recycled tire aggregates — (a) fine rubber replacing sand; (b) coarse rubber replacing 10 mm Gabbro; (c) coarse rubber replacing 20 mm Gabbro.

Factory located in Messaied City, Qatar [35]. The parent rubber was a mixture of car and truck tires collected from landfills [35]. Prior to recycling, the inner tubes, debris, and any other material that may prevent or obstruct the grinding process were removed. The specific gravity of the rubber aggregates was 1200 kg/m^3, determined as per BS 1097-6 [33]. The fine rubber aggregate was free of steel (since it was processed through a machine that attracts and extracts magnetic metals), with a fiber content $\leq$ 0.5%. On the other hand, due to the high complexity of producing shredded rubber with greater sizes, the fiber and steel impurities were not extracted from the coarse shredded rubber.

Ordinary Portland cement (OPC) was used, for which the chemical characterization results can be found in Ref. [32], in which work the same cementitious materials were considered. Silica fume (or micro silica) was used at 7% wt. OPC replacement level in all mixtures of concrete, as it is known to enhance the durability performance of rubberized concrete [36]. A commercial superplasticizer (Hyperplast PC350 [37]) conforming with ASTM C494 [38] was used. A minimum initial slump of 200 mm was targeted in all concrete mixtures, as per common practice in Qatar [39], while maintaining the same w/c ratio by means of superplasticizer addition.

2.2. Concrete mixtures

A total of 13 concrete mixtures were prepared for this investigation as shown in Table 1. Ready-mix concrete with a 28-day design compressive strength of 45 MPa was considered. Table 1 presents the mix proportions (per cubic meter) as per BS EN 206 [40] for each mixture. Mixes M1 and M2 represent natural aggregate concretes mixed with freshwater and seawater, respectively. Mixes M3, M4, and M5 were rubberized concrete, where 5%, 10%, and 20%, respectively, of the sand was replaced with an equivalent volume of fine shredded rubber (Fig. 1-a). Mixes M6, M7, and M8 were also rubberized concretes in which 5%, 10%, and 20% of coarse aggregates (10 mm and 20 mm), were replaced by an equivalent volume of two types of rubber with comparable sizes (Fig. 1-b and -c, respectively). Rubberized concretes were additionally labeled as "a" or "b" according to the type of mixing water (indicating freshwater and seawater, respectively). It is to be noted that slight variations in the mixing water were needed to achieve the same water-to-cement ratio among the concrete mixtures, accounting for the differences (in density and moisture content) between natural aggregates and RTA.

Table 1
Concrete mixture proportions (kg/m^3).

Mix No.	Mix ID	Description	Cement	Micro silica	Total water	Washed sand	Rubber fine particles	Gabbro 20 mm	Rubber 20 mm	Gabbro 10 mm	Rubber 10 mm
I. Natural aggregate concretes											
1	M1	Control/conventional mix with freshwater and natural aggregates	391	29	148	796	–	741	–	395	–
2	M2	Seawater-mixed natural-aggregate concrete	391	29	148	796	–	741	–	395	–
II. Sand replacement by rubber											
3	M3.a	Freshwater-mixed; 5% of sand replaced by rubber	391	29	148	756	19	741	–	395	–
4	M3.b	Seawater-mixed; 5% of sand replaced by rubber	391	29	148	756	19	741	–	395	–
5	M4.a	Freshwater-mixed; 10% of sand replaced by rubber	391	29	147	716	37	741	–	395	–
6	M4.b	Seawater-mixed; 10% of sand replaced by rubber	391	29	147	716	37	741	–	395	–
7	M5.a	Freshwater-mixed; 20% of sand replaced by rubber	391	29	146	636	74	741	–	395	–
8	M5.b	Seawater-mixed; 20% of sand replaced by rubber	391	29	146	636	74	741	–	395	–
III. Gabbro replacement by rubber											
9	M6.a	Freshwater-mixed; 5% of aggregate replaced by rubber	391	29	148	796	–	704	15	375	8
10	M6.b	Seawater-mixed; 5% of aggregate replaced by rubber	391	29	147	796	–	704	15	375	8
11	M7.a	Freshwater-mixed; 10% of aggregate replaced by rubber	391	29	148	796	–	667	31	356	17
12	M7.b	Seawater-mixed; 10% of aggregate replaced by rubber	391	29	148	796	–	667	31	356	17
13	M8.a	Freshwater-mixed; 20% of aggregate replaced by rubber	391	29	147	796	–	593	62	316	33

2.3. Concrete testing

The slump test was conducted in accordance with the BS EN 12350-2 [41] provisions for measuring the workability performance of fresh concrete. Also, the density was measured as per BS EN 12350-6 [42] standard. As for hardened concrete, the compressive strength was measured for each mixture at Ages 7, 28, and 56 days. In accordance with BS EN 12390-1 [43] provisions, three cubes (150 × 150 × 150 mm) were tested and averaged for each test specimen. Concerning durability performance, rapid chloride permeability (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 [44] at Day 28 following casting. Furthermore, the water absorption test was carried out as per BS 1881-122 [45] at Day 28 following casting. Since seawater concrete is not originally intended to be used with reinforcing steel, chloride permeability is not important per se; however, it provides a general indicator for concrete quality.

2.4. Life cycle cost model

In accordance with the ISO 15686-5 standard [46], the life cycle cost model accounts for four main components as shown in Fig. 2, namely, material cost, construction cost, repair/maintenance cost, and end-of-life cost. Two design alternatives were compared for a 20-story building in Doha, Qatar: (a) RC1 which represents the traditional concrete with freshwater, natural aggregates, and carbon steel reinforcement, and (b) RC2 which represents a proposed sustainable concrete combining seawater, recycled tires (at 5% coarse aggregate replacement level), and GFRP reinforcement. Among the tested concrete mixtures, the 5% coarse-aggregate replacement level (i.e. Mix M 6.b) was selected to represent RC2 concrete mixture since it provided relatively acceptable fresh and hardened concrete properties (as to be explained in Section 3.1).

All costs were allocated for a functional unit of 1 m^2 of the floor area. As per the structural design details of the building, the concrete volume per one square meter of the floor area was 0.27 m^3, and the reinforcement ratio was 2%. The LCCA solely considered the structural component of the building (i.e., the mechanical, electrical, and finishing components were neglected as the cost of these elements would not differ between the design alternatives). Although the life cycle for such buildings falls between 40 and 75 years, a 100-year study period was selected to account for the expected long-term durability performance of RC2 reinforcement. The unit costs were obtained from local suppliers [35,39,47,48], previous publications [49], and the *RSMeans* dataset [50], as listed in Table 2.

To determine the unit cost of RC2 concrete mixture, the difference in price due to changing the mixing water (i.e., seawater versus freshwater in RC1) was accounted for by deducting the desalination cost. This consideration is deemed valid only assuming that the establishment of seawater is similar to that of freshwater in terms of the current water supply infrastructure such as pipeline networks, water tanks, etc. The price of 5% of the natural coarse aggregates was deducted from the conventional concrete unit rate, and the price of the equivalent volume of rubber was correspondingly added. Although the unit price of (processed) rubber was higher than that of Gabbro aggregate (Table 2), incorporating rubber in the mix had only a slight effect on the ultimate unit cost of rubberized concrete because of the low replacement percentage used. The additional superplasticizer volume added to RC2 was also considered.

The construction cost was considered to be 1.5 times the material cost, consistent with previous LCCA studies [31]. However, the installation of GFRP reinforcement resulted in lower construction costs (by ∼20%) compared to conventional steel due to its light weight and pre-shaped profiles. The maintenance and repair costs including general inspection, detailed inspection, and routine maintenance were taken as 0.5%, 2.5%, and 1.5% of the initial cost, respectively. General and routine inspections were assumed at 5-year regular periods, whereas the detailed inspection was considered just before major repairs. It was assumed that the building would be demolished in 100 years following initial construction, for which the end-of-life cost accounts for the demolition and disposal activities minus the earned value of the reinforcement scrap. Further details regarding the assumptions and methods followed to obtain construction, repair/maintenance, and end-of-life costs can be found in the M.Sc. Thesis [51]. Finally, to calculate the LCC, the costs incurred through the service life of the structure were discounted to present value as per Eq. (1): [46]

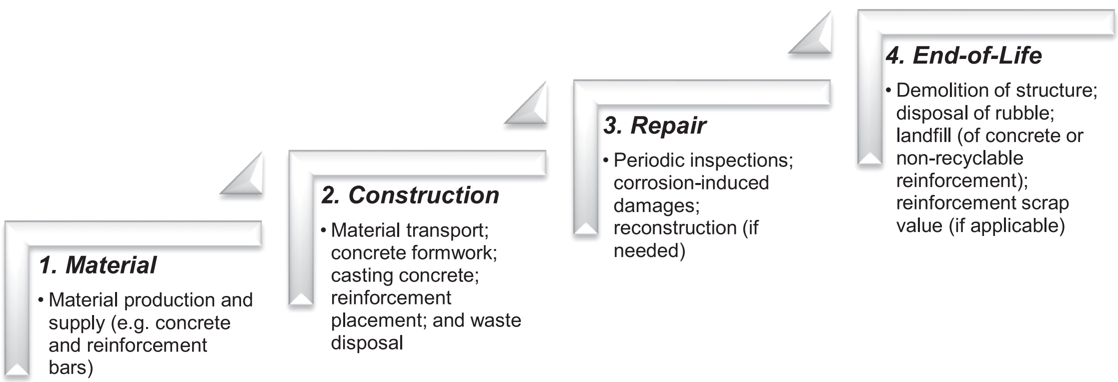

Fig. 2. Components of the LCC model.

Table 2
Unit costs (taking 1 QAR = 0.27 USD).

Material	Unit	Rate	Source
Concrete	QAR/m^3	330.00	Local supplier (Hassanesco Group [39])
Sand	QAR/ton	22.00	Local supplier (Hassanesco Group [39])
Gabbro aggregate - 10 mm	QAR/ton	77.00	Local supplier (Hassanesco Group [39])
Gabbro aggregate - 20 mm	QAR/ton	77.00	Local supplier (Hassanesco Group [39])
Reinforcement steel (all grades > 8 mm)	QAR/kg	2.09	Public Work Authority (Ashghal), Qatar [47]
GFRP	QAR/kg	34.22	RSMeans [50]
Rubber - 10 mm	QAR/ton	1200.00	Local supplier (Modern Recycling Factory [35])
Rubber - 20 mm	QAR/ton	1200.00	Local supplier (Modern Recycling Factory [35])
Water	QAR/m^3	8.20	Local supplier (Hassanesco Group [39])
Seawater (desalination)	QAR/m^3	1.64	Previous publication (Darwish et al. [49])
Superplasticizer	QAR/liter	2.00	Local supplier (Hassanesco Group [39])
Demolition (concrete)	QAR/m^3	455.00	RSMeans [50]
Landfill rate	QAR/Kg	0.33	RSMeans [50]
Reinforcement scrap	QAR/ton	400.00	Local supplier (JMCI Qatar [48])

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

where C (t) is the summation of all costs experienced at Year t, and r is the 'real' discount rate. In this study, 0.7% was used as the discount rate based on the recommendation from the office of Management and Budget [52] for long-term investments. A sensitivity analysis was performed for r values ranging from 0% to 15%, given that the discount rate is highly sensitive to changes in industrial economics, and it is a key parameter in LCC calculations.

3. Results and discussions

3.1. Concrete characterization results

3.1.1. Fresh concrete

Table 3 presents fresh concrete characterization results including slump, slump flow temperature, density, and superplasticizer dosage for each concrete mixture. Provided that all mixtures were prepared under lab conditions, the concrete temperature showed little-to-no difference from one mix to another. As shown in Table 3, the measured concrete density varied across all 13 mixtures, since the rubber replacement % was made on a volume basis, and the density was different among natural aggregates and rubber. The density of M1 and M2 concretes was higher than that of their rubberized counterparts: this is perhaps unsurprising as the sand/gravel density is higher than that of the rubber. However, the densities of the coarse-rubber mixtures were slightly higher (within 10%) than those of their fine-rubber counterparts (with similar replacement levels). Provided that the replacements were volume-based, this can be attributed to the differences in density among fine and coarse aggregates in the mix.

It was observed that the workability has decreased as a result of using seawater and recycled tire aggregates in the mix, conforming with previous studies on seawater-mixed [26] and rubberized [8] concretes. The reduction in workability of seawater-mixed rubberized concrete can be attributed to the accelerating effects induced by seawater ions (this was also explained in Ref. [26]) as well as the increased porosity, air adhesion, and hydrophobicity of rubber compared to natural aggregates (as also indicated by Siddika et al. [8]). In such cases, an additional dose of superplasticizer is sufficient to achieve the desired slump as demonstrated in Table 3. It is to be noted that the required dose of PC 350 increased with both increasing rubber volume and the use of seawater; however, the relationship between the superplasticizer dose and rubber content did not follow a linear trend.

Table 3
Fresh concrete characterization.

Mix ID	Superplasticizer dose (kg/m^3 concrete)	Temperature (°C)	Density (kg/m^3)	Slump (45 min, mm)	Slump flow (45 min, mm)
M1	6.30	27.8	2566	200	470
M2	7.2	28.5	2560	200	480
M3.a	7.2	27.1	2318	190	310
M3.b	7.8	26.8	2441	185	310
M4.a	7.5	30.4	2165	170	300
M4.b	8.4	26.5	2416	195	320
M5.a	8.4	27	2214	210	400
M5.b	10.4	27.4	2004	180	310
M6.a	8.4	29.4	2531	170	365
M6.b	10.4	29.4	2516	170	365
M7.a	8.8	27.2	2304	150	270
M7.b	11.3	29.4	2214	170	320
M8.a	10.4	28.9	2344	180	300

3.1.2. Hardened concrete

Table 4 summarizes the hardened concrete characterization results including the compressive strength, RCP, and water absorption. Generally, the results indicate a reduction in the compressive strength of rubberized concrete; with the strength loss increasing with the percentage of the aggregate replacement. These observations agree with previous research studies on rubberized concrete [1,8], which indicate approximate strength reductions of 4–70% with 5–50% rubber replacements. The reduced strength of rubberized concrete is attributable to the inferior mechanical and physical characteristics of rubber compared to natural aggregates. Another explanation for this decreasing trend, as suggested by Aslani [53], is the very low adhesion between the rubber and the cement paste in concrete, which leads the rubber to act as a void that disrupts the integrity of the concrete matrix. An exception to this rule was M 8.a, which showed slightly higher compressive strength (compared to Mix 7.a) despite its higher rubber-replacement level (likewise comparing M6 with M1). A possible explanation for this observation is that the retarder was excessively used in this particular mix (i.e. M 8.a) to achieve the desired slump, which somehow led to extra strength gains. In this context, previous research contributions [54, 55] showed that chemical admixtures may have such effects on the compressive strength of the resulted concrete. The highest loss of strength (as compared to the control mix) was 64%, recorded for M5.b (with 20% fine rubber and 100% seawater). Remarkably, minor strength increases in Mixes M6.a and M6.b were observed, which (again) can be attributed to the low percentage of aggregate replacement as well as the relatively high dosage of retarder/superplasticizer. Generally, the coarse-rubber concrete mixtures showed higher strength than that of corresponding fine-rubber mixtures with similar replacement levels.

Fig. 3 compares the 28-day compressive strength among the 13 concrete mixtures. For the control mix (M1) and the 5% rubberized mixes (coarse and fine), the results indicate a slight reduction in the compressive strength (1.5–3%) with the use of seawater, conforming with previous studies on seawater concrete [5,21,22]. However, for the 10% and 20% rubberized mixes (coarse/fine), the differences between the seawater concretes and their freshwater-mixed counterparts were more than 10%. This means that the adverse effects of seawater on concrete strength were more pronounced in the case of incorporating recycled tires in the mix.

Regarding permeability performance, the RCP test results (expressed in terms of the electric charge passed) ranged from 100 to 1000 Coulombs for all concrete mixtures (Table 4), overall indicating a low chloride penetration rate (thus acceptable permeability performance) as per ASTM C1202 [44] provisions. Nonetheless, the chloride penetration of rubberized mixes was somewhat lower compared with the natural-aggregate benchmarks (i.e., M1 and M2). While there is no specific relationship between the volume of rubber and the RCP measurement, the use of rubber in concrete appears to have a positive impact on its chloride penetration resistance. This, as suggested by Li et al. [13], can be related to the higher electrical insulation/resistance of rubber compared to natural aggregates. Similarly, the water absorption results generally lied within the acceptable limits according to BS 1881 – 122 [45] for all mixes (Table 4), and the rubberized concretes had lower water absorption (thus higher permeability performance) compared to their natural-aggregate counterparts. The improved permeability performance of rubberized concrete can be attributed to the inherent hydrophobicity of the rubber. In conformity with previous studies [32], the seawater effect on water absorption was insignificant.

3.2. LCCA results

The changes in materials between RC1 and RC2 concrete mixes showed insignificant impacts on the final concrete's unit cost. Although the price of shredded rubber is higher than that of the natural aggregates (Table 2), the low percentage of rubber replacement (5%) ultimately results in a little-to-no effect on the unit cost of RC2 concrete. Therefore, the LCC of the design options is more influenced by the reinforcement material used.

Table 5 summarizes the LCCA outcomes for the baseline scenario of $r = 0.7\%$. RC2 is more cost-effective than RC1, with approximately 30% lower LCC. These results agree with previous LCCA studies on GFRP-reinforced concrete [56,57], which indicate approximately 20–50% long-term cost savings in GFRP-RC structures compared to conventional design. The initial cost of RC2 represents over 65% while the repair cost makes only 7% of the total LCC. On the other hand, the material and construction costs of RC1 are responsible for only 27% of the total cost, and most of the cost (43%) is incurred due to repair/reconstruction (Table 5). Therefore,

Table 4
Hardened concrete properties.

Mix ID	Compressive strength (MPa)			RCP (Coulombs of passed charges)	Water absorption (%)
	7 days	28 days	56 days		
M1	53.93 (1.1)	66.80 (1.5)	76.20 (1.4)	739 (8.7)	1.3 (4.4)
M2	53.53 (0.6)	66.87 (1.6)	74.97 (1.2)	869 (2.3)	1.3 (-)
M3.a	50.67 (1.0)	62.47 (1.6)	74.87 (1.5)	278 (4.4)	1.0 (-)
M3.b	45.90 (0.9)	58.50 (1.2)	72.57 (1.3)	275 (15.3)	0.8 (6.9)
M4.a	38.70 (1.3)	48.10 (1.5)	57.93 (1.5)	408 (3.6)	1.1 (5.6)
M4.b	45.87 (1.1)	57.63 (1.5)	64.07 (1.0)	295 (8.4)	0.8 (7.2)
M5.a	23.33 (5.8)	27.50 (4.2)	36.40 (2.3)	354 (13.1)	0.8 (7.2)
M5.b	16.87 (15.6)	23.93 (9.5)	32.63 (3.4)	449 (27.9)	0.8 (30.1)
M6.a	59.67 (0.8)	72.70 (1.4)	80.87 (1.2)	348 (20.3)	1.1 (-)
M6.b	57.50 (1.2)	71.77 (1.7)	79.93 (0.8)	438 (15.7)	1.0 (-)
M7.a	33.83 (2.5)	48.23 (0.8)	56.43 (0.8)	463 (3.0)	1.2 (8.3)
M7.b	43.97 (3.9)	56.13 (1.6)	64.23 (0.9)	457 (5.3)	1.0 (-)
M8.a	38.93 (0.6)	50.90 (2.4)	60.20 (0.6)	488 (7.5)	1.0 (-)

Coefficients of variation (%) are provided between parentheses.

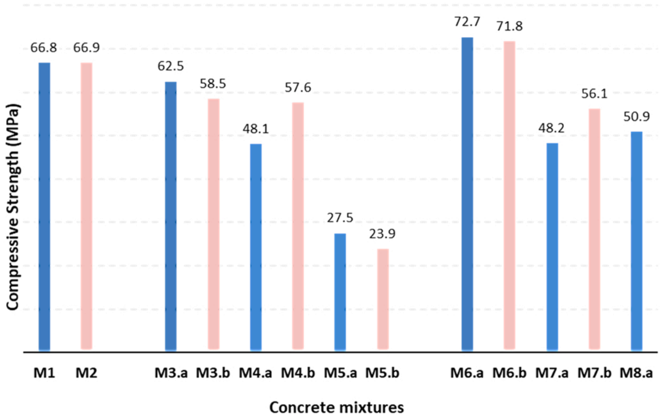

Fig. 3. Comparison among concrete mixtures in terms of 28-day compressive strength.

Table 5
Summary of the results of the LCCA (considering $r = 0.7\%$).

Design alternative	Present values (QAR/m^2)					LCC (QAR/m^2)
	Construction	Material	Repair	Reconstruction	End-of-life	
RC1	267.5	178.3	211.3	718.1	282.0	1657.2
RC2	382.1	388.1	79.0	–	298.1	1147.2

it can be said that the higher initial cost of GFRP was recompensed in the long term by the savings obtained owing to its higher corrosion resistance. As a demonstration of this point, reconstruction at Year 50 is the key activity that represents the breakeven point between RC1 and RC2 (as shown in Fig. 4).

A sensitivity analysis was conducted for r considering a range from 0% to 15%, as shown in Fig. 5. Indeed, increasing r results in a decrease in LCC for both design alternatives (see the exponential relationship in Eq. (1)). Fig. 5 shows that RC2 remains more cost-effective than RC1 for $r \leq 10\%$.

4. Conclusions

In this paper, the technical and economic impacts of combining recycled tires (as a replacement for natural aggregates) and seawater (in lieu of freshwater) in structural concrete were investigated. At first, fresh and hardened properties of thirteen concrete mixtures were compared to assess the technical effects (i.e. in terms of material-characterization) of mixing concrete with seawater and RTA. After that, an LCCA study was conducted to evaluate the cost impact of combining seawater, RTA (at 5% replacement level), and GFRP rebars in concrete structures. Based on the assumptions made and the test results, the following conclusions are drawn:

- Slump measurements showed that when the rubber and seawater volume in the concrete mix increases, the workability performance is reduced. Yet, the slump loss can be controlled with proper compensation by chemical admixtures (i.e., superplasticizers) in the concrete mixture.
- In general, the compressive strength decreased with the combined use of recycled tires and seawater in concrete. Compared with the conventional mix (i.e. using freshwater and natural aggregates), a reduction of up to 65% was reported with the use of 100% seawater and 20% recycled-rubber fine aggregate in the concrete mixture.
- Results from RCP and water absorption tests showed a slight positive effect of recycled-tire aggregates on the permeability performance of the concrete.
- The LCCA showed that RC2 is more cost-effective (with 30% lower LCC) than RC1: this is mainly attributed to the use of GFRP instead of carbon steel to counter possible corrosion. A sensitivity analysis of the discount rate (r) for the LCCA showed that RC2 remains more cost-effective than RC1 for all r values less than 10%.

The above conclusions are exclusively based on the hypotheses made and the materials used in the current study. Future research is encouraged to include a wider range of concrete characteristics such as tensile strength, shrinkage, microstructure, Young's modulus, shear strength, etc. Other mix design methods may also be considered to achieve the same density among rubberized and conventional concretes, in order to (more accurately) research the relationship between the volume of rubber and the concrete's compressive strength. The pre-treatment of shredded rubber (e.g., with magnesium oxychloride) can also be considered as suggested in previous efforts [17]. Furthermore, provided that the use of rubberized concrete may not be associated with direct cost benefits, studies to assess the environmental impact of combining seawater and recycled rubber in concrete are critical.

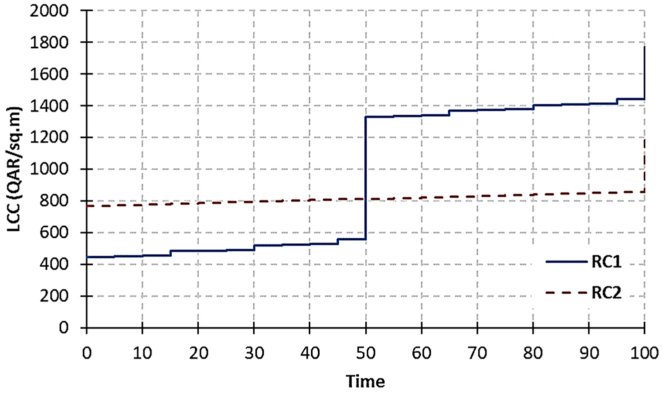

Fig. 4. Cumulative LCC up to Year 100 for the design alternatives.

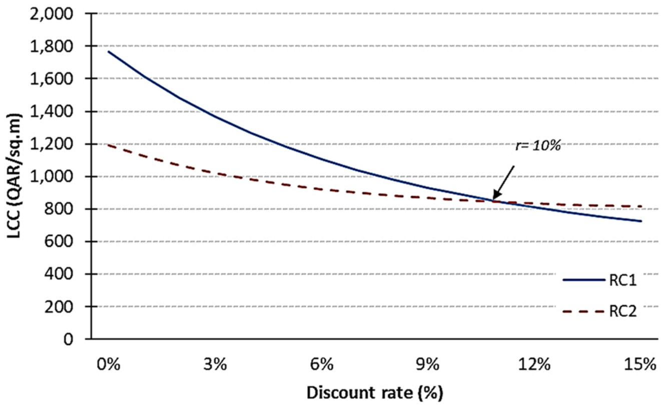

Fig. 5. Sensitivity of the LCC results to the assumed discount rate.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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