Results in Engineering 20 (2023) 101565

Contents lists available at ScienceDirect

Results in Engineering

journal homepage: www.sciencedirect.com/journal/results-in-engineering

Life cycle cost analysis of sustainable reinforced concrete buildings with treated wastewater, recycled concrete aggregates, and fly ash

Abdelrahman Abushanab, Wael Alnahhal *

Department of Civil and Environmental Engineering, Qatar University, Doha, Qatar

A R T I C L E I N F O

Keywords:
Life cycle cost analysis
Discount rate
Treated wastewater
Recycled concrete aggregates
Fly ash
Cost savings

A B S T R A C T

The global excessive demand for concrete has resulted in a significant depletion of concrete natural resources and substantial release of carbon emissions in the environment. To tackle such challenges, treated wastewater (TWW), recycled concrete aggregates (RCA), and fly ash (FA) have recently been proposed as sustainable concrete constituents. From a management perspective, it is necessary to evaluate the cost-saving potential of incorporating TWW, RCA, and FA simultaneously in concrete applications. Accordingly, this study conducted a life cycle cost analysis over 60 years on 12 multi-story buildings with TWW, RCA, and FA. Various parameters were investigated, including the number of floors (20–70 floors), discount rate (0–10%), RCA-to-natural aggregate price ratio (50–200%), and construction-to-material price ratio (50–250%). Test results highlighted that buildings incorporating TWW, RCA, and FA showed 60.18% and 19.21% lower maintenance and life cycle costs compared to conventional buildings, respectively. Furthermore, the study showed that the highest cost savings are achieved with a discount rate of 2% or less. The achieved cost saving reveals the importance of utilizing eco-friendly alternatives to natural concrete ingredients. On the other hand, the number of floors, RCA-to-natural aggregate price ratio, and construction-to-material price ratio have negligible effects on the life cycle cost of the buildings.

1. Introduction

The worldwide increased demand for fresh water, driven by unprecedented global population growth, has jeopardized the sustainability of freshwater resources. Furthermore, the proportion of people living in water scarcity areas has significantly increased in recent years. Annually, more than 60% of the world's population faces water shortages for at least 1 month [1]. Accordingly, some countries have increased the capacity of their seawater desalination plants to secure the needed quantities of potable water. However, desalination is expensive, consumes a large amount of energy, and generates carbon dioxide emissions and desalination waste (i.e., brine). In particular, desalinating 1 m^3 of water costs between USD 0.50 and 1.20, with an equivalent energy consumption of 10.8–14.4 MJ and carbon dioxide emissions of 1.4–1.8 kg. Moreover, desalination is expected to generate a brine volume of 156 m^3 by 2050 [2].

Concrete manufacturing is considered a prominent non-human application that consumes large amounts of fresh water [3]. Particularly, the worldwide concrete industry utilizes approximately 2 billion tons of fresh water per year for mixing and curing of reinforced concrete (RC) elements and washing of concrete plants and trucks [4]. Therefore, the utilization of treated wastewater (TWW) in concrete applications contributes to measures for solving the global water crisis [4]. Employing TWW in the concrete industry not only reduces the overall demand for fresh water but also reduces the negative environmental and economic impact of wastewater disposal [3]. Numerous studies have already confirmed the feasibility of replacing fresh water with TWW for concrete applications [4–9]. Abushanab and Alnahhal [4] and Asadollahfardi et al. [6] demonstrated that TWW had an insignificant effect on the slump of concrete. In addition, Abushanab and Alnahhal [4] reported that TWW decreased concrete mechanical properties by 5% to 12%. Similarly, Arooj et al. [5] noticed that the compressive strength of concrete decreased by 15% when TWW was employed. In addition, Abushanab and Alnahhal [10] reported that the flexural capacity of RC beams with TWW was 14% lower than those with fresh water. On the durability effect of TWW in concrete, Abushanab and Alnahhal [4] revealed that concrete with TWW had 40% lower durability characteristics compared to conventional concrete. Similar observations were also found by Saxena and Tembhurkar [7] and Hassani et al. [11].

Meanwhile, the worldwide demand for natural aggregates has significantly increased in recent years to supply the enormous quantities

* Corresponding author.
E-mail address: wael.alnahhal@qu.edu.qa (W. Alnahhal).

https://doi.org/10.1016/j.rineng.2023.101565
Received 30 August 2023; Received in revised form 31 October 2023; Accepted 31 October 2023
Available online 2 November 2023

List of abbreviations

• RC	Reinforced Concrete
• TWW	Treated Wastewater
• RCA	Recycled Concrete Aggregates
• FA	Fly Ash
• OPC	Ordinary Portland Cement
• LCCA	Life Cycle Cost Analysis
• LCC	Life Cycle Cost
• FNC	Reference Concrete Mix with Fresh water, Natural Aggregates, and 100% Cement
• TRF	Proposed Concrete Mix with Treated Wastewater, Recycled Concrete Aggregates, and 20% Fly Ash
• r	Discount Rate
• C_t	Total Amounts Spent at a Specific Time t
• C_m	Material Cost
• C_c	Construction Cost
• C_r	Repair Cost
• C_e	End-of-life Cost

of concrete needed for urbanization and industrialization [12]. It has been estimated that the annual utilization of natural aggregates has reached approximately 48 billion tons [13]. On the other hand, urban renewal in countries results in massive amounts of construction and demolition waste. An estimated 3 billion tons of construction and demolition waste are generated every year across the globe, accounting for about 30% of total waste [2]. The recycling of such waste into recycled concrete aggregates (RCA) has recently been investigated for geopolymer and concrete applications as a means of reducing the production rate of natural aggregates, carbon emissions associated with natural aggregate production, manufacturing cost of concrete, and disposal cost of concrete waste [14–16]. Wang et al. [17] and Huda and Alam [18] showed that concrete with RCA had 10% to 25% lower workability than conventional concrete. Wang et al. [17] demonstrated that the mechanical properties of RCA concrete were 40% to 45% lower compared to reference concrete. Moreover, Abushanab and Alnahhal [3] pointed out that RCA concrete properties had inferior durability characteristics compared to natural aggregate concrete. In addition, Choi and Yun [19] and Al Mahmoud et al. [20] revealed that RCA decreased the flexural and shear capacities of RC beams by 20% and 11%, respectively. More recently, Abushanab and Alnahhal [3] investigated the combined effects of RCA and TWW. The authors showed that incorporating RCA with TWW yielded an average of 13% better mechanical and durability properties compared to mixes with RCA and fresh water. From the environmental perspective, Xing et al. [21] showed that at a similar concrete compressive strength, RCA decreased the carbon footprint, regardless of the RCA replacement ratio. Moreover, Khan et al. [22] demonstrated that utilizing construction waste decreased the global warming potential by 18%. Similar results were reported by Mahmoodi et al. [23] when recycled brick powder was used.

Previous studies have revealed that the use of either TWW or RCA appears to have a negative impact on the mechanical and durability properties of concrete [3,9]. Thus, researchers have recently incorporated by-product fly ash (FA) as a partial replacement of ordinary Portland cement (OPC) to densify the concrete matrix and improve its mechanical and durability characteristics [24–27]. Kurda et al. [24] found that the slump of RCA concrete was improved with the incorporation of FA. In addition, Ilcan et al. [26] reported that geopolymer mixes with FA had the highest workability compared to mixes with blast furnace slag and silica fume. Lima et al. [25] demonstrated that concrete made with RCA and FA exhibited similar properties to reference concrete at later ages. Xing et al. [21] and Mir et al. [27] pointed out that incorporating supplementary cementitious materials with RCA decreased the carbon emissions in the environment. The effects of TWW, RCA, and FA combined were recently investigated by Abushanab and Alnahhal [3]. The authors showed that mixes with TWW, RCA, and FA combined achieved about 42% lower chloride permeability than the reference mix. Likewise, Abushanab and Alnahhal [10] reported that FA decreased the deflection of RC beams with RCA and TWW by 17.5% compared to the reference beam. More recently, Abushanab and Alnahhal [28] conducted a study to evaluate the influence of TWW, RCA, and FA on the bond strength between concrete and corroded steel bars. The authors revealed that the use of 20% FA in TWW-RCA concrete decreased the steel mass loss by 82% and 61% at corrosion levels of 2% and 10%, respectively. In addition, it was found that specimens without FA exhibited a bond strength degradation of 36% to 71% with corrosion, whereas TWW-RCA concrete specimens with FA showed a mere 3% drop in the bond strength at the same corrosion level.

Sustainable concrete products with TWW, RCA, and FA combined have been experimentally investigated in terms of their mechanical and durability properties [3,10,29]. Nonetheless, from a management perspective, it is necessary to measure the cost performance of such a combination throughout the life cycle of RC structures. The cost-effectiveness of concrete can be assessed using several methods; one of which is the life cycle cost analysis (LCCA) [30]. According to ISO 15686–5:2017 [30], the LCCA is defined as a tool for evaluating the economic feasibility of a certain product over an operating period. In principle, LCCA is composed of four main cost categories: construction, operation, maintenance and rehabilitation, and end-of-life. Previous studies have analyzed the cost-effectiveness of using RCA and FA in concrete applications [31–33]. Makul [31] showed that the addition of FA to high-performance RCA concrete mixes could have a higher initial cost. However, a favorable cost-benefit is achieved through the improved durability properties of FA-RCA concrete mixes. Ohemeng and Ekolu [34] pointed out that the production cost of RCA is 40% lower than that of natural aggregates. Kurda et al. [32] reported that the cost-benefit of utilizing RCA in concrete applications can be achieved by incorporating FA. Reiner and Rens [33] revealed life cycle cost (LCC) savings of 20% when FA was utilized in concrete.

Even though much research has been conducted to evaluate the cost-saving of individual use of RCA and FA in concrete applications, a research gap remains on the LCC of RC structures with TWW, RCA, and FA combined. Hence, from a novelty perspective, this study fills this research gap by conducting LCCA on 12 high-rise buildings made simultaneously with TWW, RCA, and FA. The parameters considered in this study are the number of floors, discount rate (r), RCA-to-natural aggregate price ratio, and construction-to-material price ratio. The results of this study are expected to illustrate the economic efficiencies associated with using TWW, RCA, and FA combined in concrete applications.

1.1. Practical implications

As presented in the above literature, the concrete industry extensively utilizes fresh water, natural aggregates, and OPC to meet the worldwide extreme demand for concrete applications. Consequently, concrete natural resources are extremely exploited, and more carbon footprint is released into the atmosphere, raising concerns about the sustainability of concrete. Therefore, the proposed combination of TWW, RCA, and FA in the concrete industry serves as a sustainable option to alleviate the strains on the natural resources of concrete and decrease the costs and carbon emissions associated with concrete manufacturing, desalination of seawater, and production and transportation of natural aggregate and OPC. The results of this study are expected to promote the practical use of concrete mixes with recyclable products. This study is also anticipated to be useful in establishing guidelines on the use of recyclable products in concrete applications.

2. Materials and methods

2.1. Overview

The LCCA in this study was performed in five consecutive steps. A conventional multi-story building and its alternative with TWW, RCA, and FA were identified in the first step. The second step includes a structural design scenario for a multi-story building with a different number of floors and gross areas. Details of the concrete mix proportions with the convention and alternative buildings were presented in the third part. The fourth step provides the calculations of the LCC of the alternatives based on the material, construction, maintenance, and end-of-life costs. Sensitivity analysis was done using different parameters in the fifth step. A summary of the methodology adopted is illustrated in Fig. 1.

2.2. Design alternatives

The LCCA of the multi-story buildings was conducted using two design alternatives. The alternatives follow a three-letter designation according to the material used. The first letter (F and T) belongs to 100% fresh water and 100% TWW, respectively. The second letter (N and R) is

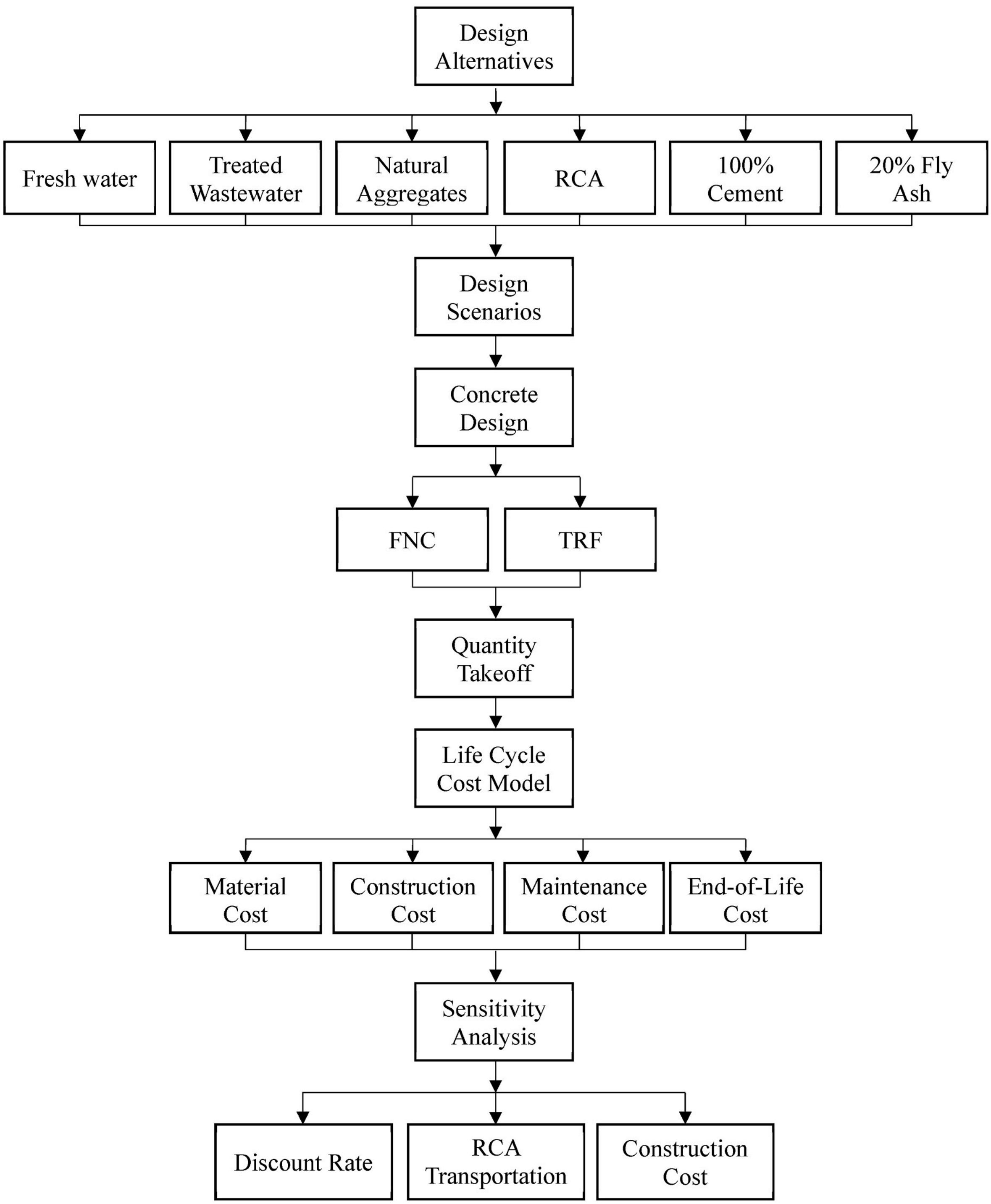

Fig. 1. A flowchart summarizing the life cycle cost methodology. Note: FNC: conventional concrete mix and TRF: proposed concrete mix with treated wastewater, RCA, and fly ash.

for 100% natural coarse aggregates and 100% RCA, respectively. The third letter corresponds to the cementitious binder (C for a binder of 100% OPC and F for a mixture of 80% OPC and 20% FA). Alternative FNC is the reference option for the multi-story building constructed with conventional concrete ingredients, whereas alternative TRF is the proposed option that combines 100% TWW, 100% RCA, and 20% FA.

It is to be emphasized that the simultaneous utilization of TWW, RCA, and FA in concrete was first introduced and examined by Abushanab and Alnahhal [3,10]. The TWW used by Abushanab and Alnahhal [3,10] was provided by a local plant in Qatar after the tertiary treatment stage. It is characterized by a chloride, sulfate, zinc, phosphate, and total dissolved solid concentration of 511, 490, 0.11, 9.19, and 1690 mg/L, respectively. All TWW characteristics were in accordance with the permissible limits of ASTM C1602/C1602M − 18 provisions [35] for plain concrete and RC members. In addition, the RCA incorporated were utilized from demolished concrete buildings. The RCAs' dry specific gravity, Los Angeles abrasion, and water absorption were 2.47, 17.6%, and 3.51%, respectively. Furthermore, the FA utilized was of class F and characterized by a specific gravity of 2.18, moisture content of 0.5%, and particle distribution between 3 and 55 μm. The authors [3,10] designed the concrete mixes as per ASTM C192/C192 M−19 [36]. RCA replaced natural aggregates using the volume replacement method, whilst TWW and FA were incorporated using the mass replacement method. The mechanical and durability properties and the flexural performance of alternative TRF are presented in detail in Abushanab and Alnahhal [3,10].

2.3. Reinforced concrete scenarios

The grades and amounts of reinforcement and concrete should be carefully selected in the design of RC structures due to their enormous influence on the overall performance, safety, and cost of the buildings [37]. In this study, the design scenario and quantity takeoff of a multi-story building were obtained from Foraboschi et al. [38] and utilized for the LCCA of alternatives FNC and TRF. The structural system of the selected building is composed of slabs, beams, columns, and central cores. The analysis includes six different stories (20, 30, 40, 50, 60, and 70 floors) and six different gross floor areas (8000, 17250, 36000, 57800, 105840, and 189280 m^2). A higher number of floors has been selected to evaluate the effect of the floor number on the LCC of the buildings. The buildings' design was performed using finite element methods in order to analyze their embodied energy. The non-bearing members are assumed to have a uniformly distributed dead load of 2.5 kN/m^2 over the entire floor area. In addition, a facade dead load of 4 kN/m was accounted on the perimeter beams. Moreover, a uniformly distributed live load of 3 kN/m^2 was considered over the entire floor area. A wind load in accordance with Eurocode [39] was included in the analysis. Furthermore, the analyses showed that the seismic action has marginal influence on the buildings compared to the wind load, and hence the seismic effect was neglected. Additionally, all buildings were designed to be displaced horizontally due to the wind load by a maximum of 1/400 of the buildings' height. As well, the maximum vertical displacement due to the live load was limited to 1/400 of the floor span.

The required amounts of concrete and reinforcement needed for all RC multi-story buildings investigated by Foraboschi et al. [38] are presented in Table 1. The amounts of concrete and reinforcement were divided by the gross floor area for each building to illustrate the needed quantities per floor area. Moreover, the amounts of concrete and reinforcement weight per unit area were averaged for the purpose of the sensitivity analysis.

2.4. Concrete mix design

The adopted high-rise buildings in this study were structurally analyzed by Foraboschi et al. [38] assuming concrete compressive strength of 40 MPa, which is an appropriate strength for tall RC buildings. The concrete ingredient quantities of a 40-MPa compressive strength were selected as 186, 463, 1150, and 530 kg/m^3 of water, OPC, coarse aggregates, and fine aggregates, respectively, for the conventional alternative FNC. However, for alternative TRF, fresh water and natural coarse aggregates were completely substituted with TWW and RCA, respectively. In addition, the binder was replaced with a mixture of 80% OPC and 20% FA. TWW and FA were considered using the weight replacement method, while RCA were incorporated using the volume replacement method. The difference in the density between the natural aggregates and RCA were considered in calculating the coarse aggregate quantities and cost for alternative TRF.

Table 1
Quantity takeoff of the investigated RC buildings [38].

Number of floors	Floor area (m^2)	Concrete volume (m^3)	Steel weight (kg)	Concrete volume per floor area (m^3/m^2)	Steel weight per floor area (kg/m^2)
20	8000	2185	341547	0.27	42.69
30	17280	4883	764123	0.28	44.22
40	36000	11222	1764518	0.31	49.01
50	57800	20772	3275740	0.36	56.67
60	105840	36371	5772557	0.34	54.54
70	189280	66345	10515272	0.35	55.55
Average	–	–	–	0.32	50.45

According to Abushanab and Alnahhal [3,10], the combined incorporation of TWW, RCA, and FA in concrete reduces the mechanical properties and flexural performance of RC beams. This deficiency contradicts the base of the LCCA, which requires that all alternatives should perform the same. In this regard, Marinković et al. [40] pointed out that a slight increase in OPC content (∼%5) can compensate for the compressive strength drop in RCA concrete elements. Therefore, an addition of 5% of OPC was considered for alternative TRF to compensate for the shortcomings of the proposed materials in terms of strength. Likewise, the presence of 20% FA in alternative TRF is expected to compensate for the drop in the concrete slump due to the residual mortar of RCA. Therefore, the concrete ingredient quantities for alternative TRF are 186, 389, 93, 983, and 530 kg/m^3 of TWW, OPC, FA, coarse aggregates, and fine aggregates, respectively.

2.5. Life cycle costs

2.5.1. Overview

The economical aspect of TWW, RCA, and FA was evaluated in this study by calculating the LCC of all scenarios (Table 1) for design alternatives FNC and TRF. The LCC calculation was made according to the costs of buildings' materials, construction, repair/maintenance, and end-of-life. It should be mentioned that the operational costs required to run the buildings, such as housekeeping, energy and water fees, and IT services were excluded from the LCCA, as both alternatives are expected to operate the same for all scenarios. The components of the life cycle expenses are demonstrated in Fig. 2. As per ISO 15686–5:2017 [30], the study period in the buildings' LCCA should be long enough to effectively analyze the maintenance cost of the alternatives. Previous research studies have performed LCCA on RC buildings using study periods between 40 and 75 years [41,42]. Accordingly, a 60-year study period was adopted in this study. It has been assumed that both alternatives will be demolished after 60 years.

2.5.2. Material cost

The materials' costs in the LCCA cover the expenses and delivery costs of concrete, water, gravel, steel reinforcement, OPC, and FA. These are considered the most influential elements in this analysis to differentiate alternatives FNC and TRF. Steel reinforcement with a yield strength of 420 MPa and density of 7860 kg/m^3 was considered for the

Material Cost
- Concrete
- Water
- Aggregates
- Binders
- Steel reinforcement
- Transportation of materials

Construction Cost
- Transportation of staff and equipment
- Equipment rental
- Formwork erection
- Concrete pouring
- Reinforcement assembly
- Waste disposal

Maintenance Cost
- Periodic inspections
- All types of repairs

End-of-Life Cost
- Demolition of the building
- Landfill of demolished products
- Management of scrap items

Fig. 2. Description of the life cycle expenses.

buildings. Even though both alternatives have similar reinforcement, the cost of steel bars was incorporated into the LCCA to perform a complete and systematic LCC model. The prices of the materials were obtained from different sources and adjusted to account for the inflation rate of the United States for the year 2022 [43]. The unit rates of all materials are listed in Table 2. The total cost of each design scenario for both alternatives was estimated using these unit costs. As shown in Table 2, the cost of conventional concrete is 215 USD/m^3. However, the estimated cost of concrete for alternative TRF was calculated using the difference in prices of water, aggregates, and binders and by adding the cost of the additional OPC content that is required to achieve a similar compressive strength to the reference building FNC. It was assumed that the sources of fresh water and TWW are equidistant, and both have the same infrastructure and pipeline networks. Hence, the only factor affecting the cost of water in this analysis is the difference in cost between seawater desalination and wastewater treatment. This assumption was made because of the lack of data on the transportation cost of TWW to construction projects. However, this assumption can only be applicable if TWW is considered a common practice for concrete works worldwide. On the other hand, previous research studies on RCA demonstrated that the transportation costs of natural aggregates and RCA are not similar [2,44]. Paranhos et al. [44] showed that the transportation cost of trucks has a linear relationship with the mileage traveled. This principle could be applied to calculate the transportation cost difference between natural aggregates and RCA. In this regard, four RCA-to-natural aggregate (R-to-N) price ratios of 50%, 100%, 150%, and 200% were included in the sensitivity analysis to account for the aggregate transportation cost difference. Furthermore, the transportation costs of OPC and FA are assumed to be similar.

Table 2
Unit rates considered in this study.

Item	Cost	Unit	Reference
Concrete	215	USD/m^3	RSMeans [45]
Steel Reinforcement	0.8	USD/kg	RSMeans [45]
Coarse Natural Aggregates	17.47	USD/ton	Younis et al. [2]
Coarse RCA	13.17	USD/ton	Younis et al. [2]
OPC	117.48	USD/ton	Shwekat and Wu [46]
FA	61.83	USD/ton	Shwekat and Wu [46]
Seawater Desalination	1.3	USD/m^3	Shannak [47]
Wastewater Treatment	0.62	USD/m^3	Shannak [47]
Building Demolition	147.73	USD/m^3 of concrete	RSMeans [45]
Demolition Landfill	0.11	USD/kg	RSMeans [45]
Steel Reinforcement Scrap	0.16	USD/kg	Capital Scrap Metal LLC [48]

2.5.3. Construction cost

The construction cost of the buildings is the expenditures allocated to staff hiring and transportation, equipment rental, formwork erection, steel bars assembly, concrete pouring, and waste disposal. It is common practice to estimate the construction cost in LCCA from the material costs [2,49]. In this study, the construction process and technology are expected to be the same for both alternatives. Thus, the construction costs of all buildings were estimated equally as 150% of the materials' costs of the conventional alternatives. Furthermore, a sensitivity analysis covering five construction-to-material (C-to-M) cost ratios of 50%, 100%, 150%, 200%, and 250% was performed to investigate the influence of C-to-M on the overall costs of the buildings. It should be noted that the construction costs of buildings rarely exceed 250% of the buildings' materials [45].

2.5.4. Maintenance cost

The maintenance cost is the amount of money spent on a regular basis to maintain the structural components of the buildings during their operational periods. The maintenance cost includes periodic inspections, preventative measures, redecoration, and replacement or repair of damaged components. Since the buildings are assumed to operate for 60 years only, the costs for a complete renovation were disregarded in this study for all design scenarios. The only repair opted for in this study is the repair due to steel corrosion.

The determination of the maintenance cost in LCCA is usually regarded as a percentage of the material and construction costs [2,49]. Such costs cover the transportation of the new components and materials, replacement and repair of the defective parts of the buildings, and disposal of the old components. In the current study, the maintenance process and technology are expected to be the same for both alternatives. In particular, it was assumed that the repair would take place in 10% of the buildings' gross areas. In this area, 50% of the materials are expected to be replaced with repair costs of 200% of the construction cost [49].

The service life of the conventional buildings was estimated using Life-365 software [50] assuming that the buildings are exposed to chloride environments. The service period in Life-365 software [50] is the period during which the buildings undergo structural deficits and demand maintenance. The buildings are assumed to be constructed 800 m away from the sea. In addition, the buildings were considered to have a 0.6% surface chloride concentration within 15 years. The concrete cover of the structural elements was 40 mm. The analysis of Life-365 software revealed that conventional buildings should have regular repairs against corrosion every 10 years. On the other hand, as demonstrated by Cabrera [51], the incorporation of FA in concrete delays the initiation time of corrosion by three times compared to conventional concrete. In addition, as per Abushanab and Alnahhal [28], incorporating FA in concrete mixes with TWW and RCA decreased the mass loss of corroded steel bars by 82% and 61% at corrosion levels of 2% and 10%, respectively. Therefore, corrosion repairing work for buildings with alternative TRF is scheduled every 20 years in the analysis.

2.5.5. End-of-life cost

The end-of-life cost is related to the costs of the building demolition, construction waste disposal and landfill, and steel scrap management. The unit rates of these operations are listed in Table 2. The scrap value of steel reinforcement is considered in this stage because a high proportion of steel bars could be utilized to fabricate new steel reinforcement with the same or higher grades [52]. In this study, it is assumed that 90% of the steel bars' weight will be sold as scrap and the remaining 10% will be disposed to landfills by the end of the buildings' life periods.

2.5.6. Calculation of life cycle cost

LCC is defined according to ISO 15686–5:2017 [30] as the total amount of money spent on a product and discounted to present value over the operating period. LCC can be calculated as per Eq. (1):

$$LCC = \sum_{t=0}^{T} \frac{C_t}{(1+r)^t} \tag{1}$$

Where t is the time when the money is spent, T is the total operating period, C_t is the total amounts spent at time t, and r is the discount rate.

The total amounts spent in a certain year can be calculated as per Eq. (2):

$$C_t = C_m + C_c + C_r + C_e \tag{2}$$

Where $C_m, C_c, C_r, and\ C_e$ are the total costs in a certain year for materials, construction, repair, and end-of-life, respectively.

The r is incorporated to calculate the time value of the money in the future. It means that the future money is discounted to today's rate. In the present study, r was taken as 0.5% in accordance with the White House Office of Management and Budget in the United States for 30-year investments for the year 2022 [53]. However, it should be emphasized that r differs with different places and time of projects. Moreover, private sectors consider high values of r, whereas public organizations take into consideration low values of r. Therefore, to investigate the impact of r on the LCC of both alternatives, six values of r (0%, 2%, 4%, 6%, 8%, and 10%) were considered in the sensitivity analysis. The selected range of r is in line with the previous studies [54,55].

3. Results and discussion

3.1. Cost savings from concrete mixes

The costs incurred for all buildings and alternatives over the study period were summed up and demonstrated in Table 3. The costs in Table 3 were calculated in USD/m^2 for a C-to-M cost ratio of 150% without considering the future discount rates. The designation used for the buildings included a combination of the design alternative and the number of floors. For instance, building FNC-20 is a 20-floor building made with the design alternative FNC. The results show that the total costs of the buildings increase with increasing the number of stories for both alternatives. This is due to the design concept of the buildings. As presented in Table 1, increasing the number of floors increases the buildings' areas and the needed quantities of concrete and reinforcement, which, in turn, increases the overall cost of the buildings. The results also reveal that the cost savings in materials and construction (year 0 in Table 3) achieved by utilizing concrete mix TRF ranged between 0.82% and 1.08% for all design scenarios. Minimal savings were obtained despite the reduced prices of TWW, RCA, and FA compared to fresh water, natural aggregates, and OPC (see Table 2), respectively. This has occurred because 5% of OPC, which is the most expensive ingredient in concrete, was added in mix TRF to overcome the strength shortage due to TWW, RCA, and FA. This observation is in accordance with Younis et al. [2], who also showed that utilizing different sources of aggregates and fresh water negligibly reduced the cost of concrete. On the other hand, the maximum cost saving in all buildings with alternative TRF was achieved during the maintenance periods (years 10–50). For instance, building FNC-20 has regular annual expenses of 32.5 USD/m^2 for corrosion-damage repairs from years 10–50, whereas building TRF-20 has only a repair cost of 32.4 USD/m^2 in years 20 and 40. Consequently, the overall cost of building TRF-20 was reduced by 20.02%. Similarly, Younis et al. [2] and Alqahtani et al. [56] pointed out that the saving achieved from the utilization of green concrete products in RC elements is limited due to the remedial measures taken to achieve the target strength.

3.2. Life cycle cost analysis

Table 4 presents the LCC of all design scenarios with a C-to-M cost ratio of 150% and r of 0.5%. It can be seen that the cost savings associated with the material costs make an insignificant contribution to the LCC of all buildings. This could be exemplified in the LCC results (column 2 in Table 4), where the LCC savings ranged between 2.04% and 2.69%. Martínez-Lage et al. [57] also emphasized replacing conventional concrete ingredients with recyclable products might not have a saving in the initial cost. Additionally, Alqahtani et al. [56] and Majhi and Nayak [58] reported that concrete with recycled aggregates had higher cost than conventional concrete. Moreover, it is apparent that the LCC of the buildings with alternative TRF outperformed those with FNC in the maintenance costs. On average, buildings with alternative TRF achieved maintenance cost of 60.18% compared to those with FNC. This is mainly attributed to the chloride binding capacity and small size distribution of FA, which resulted in increasing the service life of the buildings and reducing the periodic repair costs of corrosion. Furthermore, the LCC results indicate that replacing the conventional mix FNC with mix TRF decreased the LCC of the 20, 30, 40, 50, 60, and 70-story buildings by 19.28%, 19.27%, 19.21%, 19.15%, 19.18%, and 19.16%, respectively. This implies that the number of floors has no correlation with the cost savings associated with the use of concrete mix TRF. These findings are supported by Makul [31] and Kurda et al. [32], who demonstrated that FA enhanced the long-term durability of RCA concrete, and, in turn, improved its cost-saving potential. Several recent studies have also shown the cost-effectiveness of FA-RCA mixes [59,60].

The cumulative LCC of all buildings throughout the study period is illustrated in Fig. 3. It can be seen that all buildings have approximately similar initial costs, regardless of the concrete mix used. Fig. 3 also reveals that the LCC is primarily influenced by the maintenance costs of

Table 3
Cost incurred for all design scenarios over the study period. Costs are in USD/m^2.

Building ID	Year							Sum
	0	10.0	20.0	30.0	40.0	50.0	60.0	
FNC-20	232.2	32.5	32.5	32.5	32.5	32.5	106.3	501.0
FNC-30	240.3	33.6	33.6	33.6	33.6	33.6	110.0	518.3
FNC-40	265.6	37.2	37.2	37.2	37.2	37.2	121.3	572.9
FNC-50	306.5	42.9	42.9	42.9	42.9	42.9	139.8	660.8
FNC-60	293.8	41.1	41.1	41.1	41.1	41.1	133.6	632.9
FNC-70	299.5	41.9	41.9	41.9	41.9	41.9	136.3	645.3
TRF-20	229.7	0	32.4	0	32.4	0	106.3	400.7
TRF-30	237.8	0	33.5	0	33.5	0	110.0	414.8
TRF-40	263.1	0	37.1	0	37.1	0	121.3	458.5
TRF-50	304.0	0	42.8	0	42.8	0	139.8	529.4
TRF-60	291.3	0	41.0	0	41.0	0	133.6	506.9
TRF-70	297.0	0	41.8	0	41.8	0	136.3	516.9

Table 4
The LCC of the investigated buildings.

Building ID	Present costs				LCC
	Material	Construction	Maintenance	End-of-life	
FNC-20	92.9	139.3	140.3	78.8	451.3
FNC-30	96.1	144.2	145.2	81.5	467.1
FNC-40	106.2	159.3	160.5	89.9	516.0
FNC-50	122.6	183.9	185.2	103.6	595.4
FNC-60	117.5	176.3	177.5	99.1	570.4
FNC-70	119.8	179.7	181.0	101.1	581.5
TRF-20	90.4	139.3	55.8	78.8	364.3
TRF-30	93.6	144.2	57.8	81.5	377.1
TRF-40	103.7	159.3	63.9	89.9	416.9
TRF-50	120.1	183.9	73.8	103.6	481.4
TRF-60	115.0	176.3	70.7	99.1	461.0
TRF-70	117.3	179.7	72.1	101.1	470.1

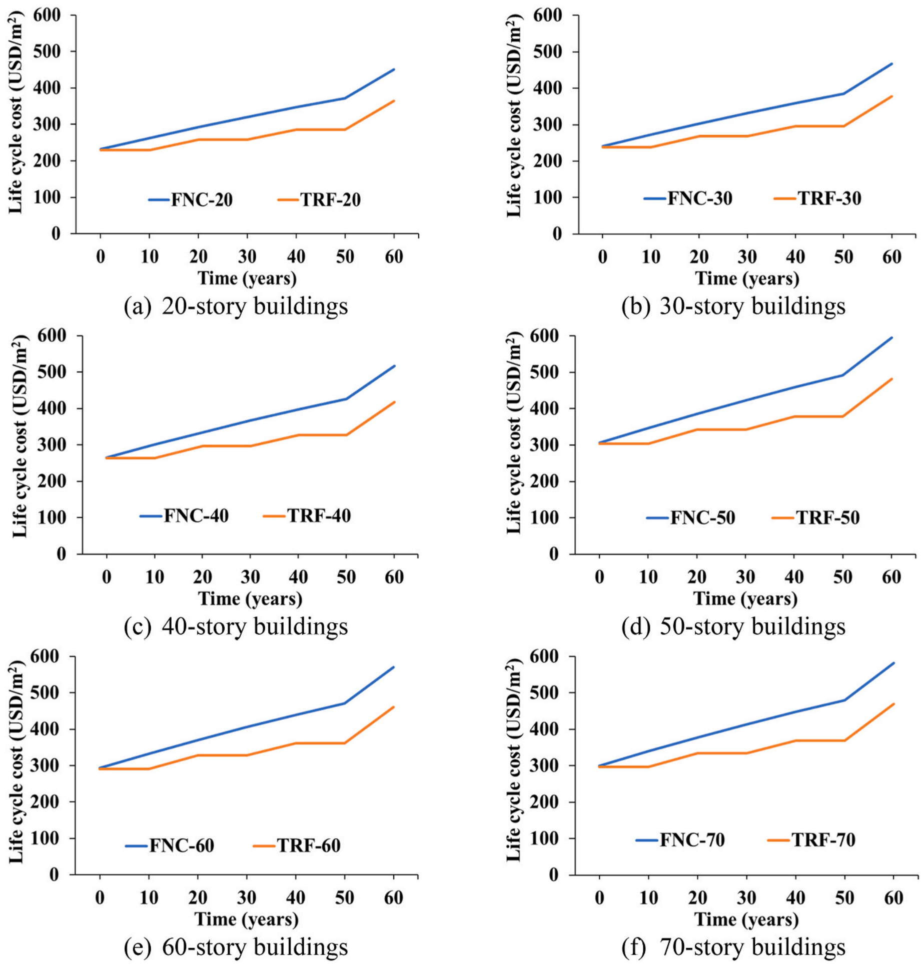

Fig. 3. Cumulative life cycle cost of all buildings.

the buildings. Buildings with FNC and TRF have regular repairs due to corrosion every 10 and 20 years, respectively. Within the operating periods of each building, no repair costs are assigned to the buildings.

3.3. Sensitivity analysis

A sensitivity analysis was performed to evaluate the impact of *r* and the costs of materials and construction on the LCC of the buildings with alternatives FNC and TRF. Since the previous discussion depicted that the number of floors and the gross floor areas have no effect on the total savings of the buildings, the sensitivity analysis was conducted using the average rates of the concrete and reinforcement. As such, the concrete volume and steel weight per unit area were considered as 0.32 m^3/m^2 and 50.45 kg/m^2, respectively.

The first sensitivity analysis presents the influence of *r* on the LCC of the buildings. As appeared in Eq. (1), there is an exponential relationship between *r* and the LCC, implying that the value of *r* is highly sensitive to the LCC of the buildings. In addition, the value of *r* is widely fluctuated with different countries, organizations, and investment durations. In the LCC of RC buildings, the value of *r* typically ranged between 0% and 10% [2,54,55]. Accordingly, the selected values of *r* in this analysis are from 0% to 10% with an increment of 2%. The costs of the materials and operations were kept constant in the analysis as per the unit prices in Table 2. Moreover, a C-to-M cost ratio of 150% was assumed to calculate the construction cost. Fig. 4 illustrates the impact of *r* on the LCC of the buildings made with alternatives FNC and TRF. It can be seen that the building with alternative TRF outperformed its counterpart with FNC in all values of *r*. Moreover, the results show that as *r* increased, the

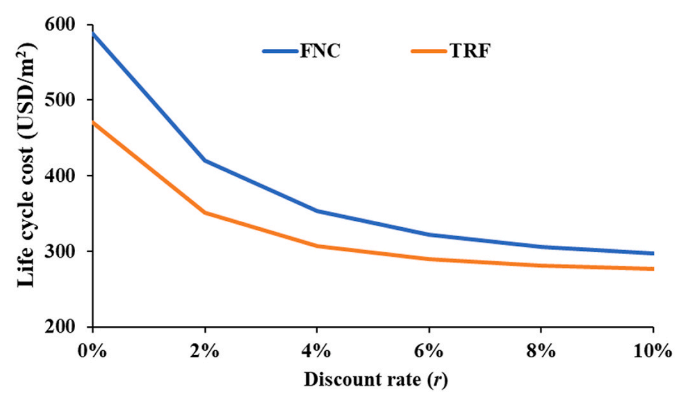

Fig. 4. Impact of the discount rate on the LCC.

difference in LCC of alternatives FNC and TRF became smaller. That is because the regular repair costs assigned for the conventional building decreased their values with higher values of *r*. On the basis of these results, buildings with TRF can achieve the highest cost saving when *r* is 2% or less. A similar response on the effect of *r* on the LCC was also reported by Alqahtani et al. [56].

The second sensitivity analysis was performed to investigate the influence of transportation cost variation of RCA, represented by four R-to-N price ratios (50%, 100%, 150%, and 200%). The analysis was conducted using the average quantities of the buildings, *r* of 0.5%, and C-to-M cost ratio of 150%. As shown in Fig. 5, the R-to-N price ratios have no

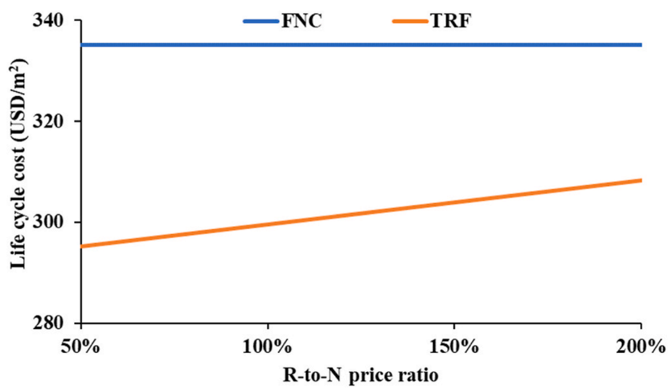

Fig. 5. Impact of R-to-N price ratio on the LCC.

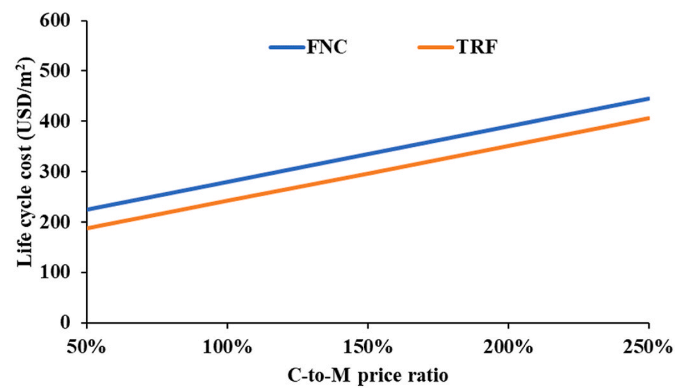

Fig. 6. Impact of C-to-M ratio on the LCC.

effect on the LCC of the buildings. This confirms the results of the LCCA, which revealed that the cost of different concrete mixes had an insignificant effect on the LCC of the buildings.

The third sensitivity analysis illustrates the influence of using C-to-M ratios of 50%, 100%, 150%, 200%, and 250% on the LCC of the buildings. The analysis was made based on an *r* value of 0.5% and constant costs of materials and construction. As depicted in Fig. 6, the LCC of both options increased with increasing the C-to-M ratio. Moreover, it can be seen that alternative TRF is more cost-effective than the conventional option in all C-to-M price ratios. It can also be observed that even when the construction cost increased by 250%, alternative TRF remains better than alternative FNC. This implies that the C-to-M price ratio had no influence on the LCC and cost saving of alternative TRF. Younis et al. [2] also reported that the LCC of sustainable RC buildings remained lower than conventional buildings even with increasing the R-to-N and C-to-M price ratios.

4. Conclusions and prospects

The cost performance of incorporating TWW, RCA, and FA in high-rise buildings was evaluated in this study through LCCA for two design alternatives: (a) FNC, conventional buildings made with fresh water, natural aggregates, and 100% OPC and (b) TRF, sustainable buildings prepared with TWW, RCA, and a mixture of 80% OPC and 20% FA. The following points summarize the main results of this study.

1 The utilization of TWW, RCA, and FA in concrete had negligible savings in the initial cost. Nevertheless, the cost savings from TWW, RCA, and FA are achieved by reducing the maintenance cost of alternative TRF.
2 The incorporation of FA in alternative TRF has improved the long-term durability of the structures. Throughout the assumed life span of the structures, alternative FNC was assumed to have regular maintenance against corrosion every 10 years. However, the corrosion-repair work for alternative TRF was scheduled every 20 years.
3 The maintenance cost of buildings with alternative TRF had an average saving of 60.18% compared to that of alternative FNC.
4 Alternative TRF achieved an average LCC saving of 19.21% compared to alternative FNC based on a study period of 60 years, discount rate of 0.5%, and C-to-M ratio of 150%.
5 The LCCA demonstrated that the buildings' number of floors had a negligible effect on the saving of alternative TRF.
6 The sensitivity analysis revealed that the highest cost saving of alternative TRF can be achieved when the discount rate is 2% or less. Furthermore, R-to-N and C-to-M price ratios appeared to have no effect on the LCC of all buildings.

The findings of this study proved the cost-effectiveness of employing TWW, RCA, and FA simultaneously in RC applications. However, it should be emphasized that, similar to all sustainability measuring tools, the potential of cost savings achieved by the LCCA in this study has several challenges and limitations in terms of the materials' origin and costs, building's location and geometry, and assumptions made. Therefore, it is recommended to perform further studies with different assumptions and scenarios to validate the cost-effectiveness of employing concrete with TWW, RCA, and FA simultaneously in RC structures. In addition, studies should be conducted on the transportation cost of TWW to constriction projects. Furthermore, future studies are recommended to combine the LCC adopted in this study with more advanced sustainability measurement tools, such as life cycle impact assessment and integrated exergy-based approaches, to evaluate the exergoenvironmental and exergoeconomic of employing TWW, RCA, and FA in RC applications.

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.

Data availability

Data will be made available on request.

Acknowledgment

Qatar National Research Fund provided funding for this publication via GSRA grant GSRA6-1-0509–19022 and UREP award no. UREP28–242-2-066. Additionally acknowledged is Qatar University's financial support through grant # QUST-1-CENG-2021-20. Open Access funding is provided by the Qatar National Library. The results presented here are completely the authors' responsibility.

References

[1] M.M. Mekonnen, A.Y. Hoekstra, Four billion people facing severe water scarcity, Sci. Adv. 2 (2016), https://doi.org/10.1126/sciadv.1500323.
[2] A. Younis, U. Ebead, S. Judd, Life cycle cost analysis of structural concrete using seawater, recycled concrete aggregate, and GFRP reinforcement, Construct. Build. Mater. 175 (2018) 152–160, https://doi.org/10.1016/j.conbuildmat.2018.04.183.
[3] A. Abushanab, W. Alnahhal, Performance of sustainable concrete incorporating treated domestic wastewater, RCA, and fly ash, Construct. Build. Mater. 329 (2022), 127118, https://doi.org/10.1016/j.conbuildmat.2022.127118.
[4] A. Abushanab, W. Alnahhal, Combined effects of treated domestic wastewater, fly ash, and calcium nitrite toward concrete sustainability, J. Build. Eng. 44 (2021), 103240, https://doi.org/10.1016/j.jobe.2021.103240.
[5] M.F. Arooj, F. Haseeb, A.I. Butt, D.M. Irfan-Ul-Hassan, H. Batool, S. Kibria, Z. Javed, H. Nawaz, S. Asif, A sustainable approach to reuse of treated domestic wastewater in construction incorporating admixtures, J. Build. Eng. 33 (2021), 101616, https://doi.org/10.1016/j.jobe.2020.101616.

[6] G. Asadollahfardi, M. Delnavaz, V. Rashnoiee, N. Ghonabadi, Use of treated domestic wastewater before chlorination to produce and cure concrete, Construct. Build. Mater. 105 (2016) 253–261, https://doi.org/10.1016/j.conbuildmat.2015.12.039.
[7] S. Saxena, A.R. Tembhurkar, Impact of use of steel slag as coarse aggregate and wastewater on fresh and hardened properties of concrete, Construct. Build. Mater. 165 (2018) 126–137, https://doi.org/10.1016/j.conbuildmat.2018.01.030.
[8] A. Abushanab, W. Alnahhal, in: T. Kang, Y. Lee (Eds.), Characteristics of Concrete Made with Treated Domestic Wastewater, Springer Singapore, Singapore, 2022, pp. 231–235, https://doi.org/10.1007/978-981-16-6932-3_20.
[9] A. Abushanab, W. Alnahhal, Mechanical characteristics and durability of concrete made with treated domestic wastewater and recycled concrete aggregates, in: Twelfth Int. Conf, . Constr. 21st Century, 2022, pp. 650–654.
[10] A. Abushanab, W. Alnahhal, Flexural behavior of reinforced concrete beams prepared with treated wastewater, recycled concrete aggregates, and fly ash, Structures 45 (2022) 2067–2079, https://doi.org/10.1016/j.istruc.2022.10.029.
[11] M.S. Hassani, G. Asadollahfardi, S.F. Saghravani, S. Jafari, F.S. Peighambarzadeh, The difference in chloride ion diffusion coefficient of concrete made with drinking water and wastewater, Construct. Build. Mater. 231 (2020), 117182, https://doi.org/10.1016/j.conbuildmat.2019.117182.
[12] W. Alnahhal, A. Abushanab, N. Alnuaimi, R. Kahraman, M.G. Sohail, N. Altayeh, Mechanical Characteristics of Ultra-high Performance Steel FRC Made with Recycled Concrete Aggregates, 2023, 040009, https://doi.org/10.1063/5.0143845.
[13] A. Abushanab, W. Alnahhal, M.G. Sohail, N. Alnuaimi, R. Kahraman, N. Altayeh, Mechanical and durability properties of ultra-high performance steel FRC made with discarded materials, J. Build. Eng. 44 (2021), 103264, https://doi.org/10.1016/j.jobe.2021.103264.
[14] K. Chaiyasarn, N. Poovarodom, A. Ejaz, A.W.M. Ng, Q. Hussain, P. Saingam, H. Mohamad, P. Joyklad, Influence of natural fiber rope wrapping techniques on the compressive response of recycled aggregate concrete circular columns, Results Eng 19 (2023), 101291, https://doi.org/10.1016/j.rineng.2023.101291.
[15] A. Kul, B.F. Ozel, E. Ozcelikci, M.F. Gunal, H. Ulugol, G. Yildirim, M. Sahmaran, Characterization and life cycle assessment of geopolymer mortars with masonry units and recycled concrete aggregates assorted from construction and demolition waste, J. Build. Eng. 78 (2023), 107546, https://doi.org/10.1016/j.jobe.2023.107546.
[16] A. Abushanab, Experimental investigation on the flexural capacity of reinforced concrete beams with treated wastewater and recycled concrete aggregates, Int. Conf. Civ. Infrastruct. Constr. (2023) 5–8.
[17] Y. Wang, P. Hughes, H. Niu, Y. Fan, A new method to improve the properties of recycled aggregate concrete: composite addition of basalt fiber and nano-silica, J. Clean. Prod. 236 (2019), 117602, https://doi.org/10.1016/j.jclepro.2019.07.077.
[18] S.B. Huda, M. Shahria Alam, Mechanical and freeze-thaw durability properties of recycled aggregate concrete made with recycled coarse aggregate, J. Mater. Civ. Eng. 27 (2015), 04015003, https://doi.org/10.1061/(ASCE)MT.1943-5533.0001237.
[19] W.-C. Choi, H.-D. Yun, Long-term deflection and flexural behavior of reinforced concrete beams with recycled aggregate, Mater. Des. 51 (2013) 742–750, https://doi.org/10.1016/j.matdes.2013.04.044.
[20] F. Al Mahmoud, R. Boissiere, C. Mercier, A. Khelil, Shear behavior of reinforced concrete beams made from recycled coarse and fine aggregates, Structures 25 (2020) 660–669, https://doi.org/10.1016/j.istruc.2020.03.015.
[21] W. Xing, V.W. Tam, K.N. Le, J.L. Hao, J. Wang, Life cycle assessment of sustainable concrete with recycled aggregate and supplementary cementitious materials, Resour. Conserv. Recycl. 193 (2023), 106947, https://doi.org/10.1016/j.resconrec.2023.106947.
[22] S.A. Khan, M. Jassim, H. Ilcan, O. Sahin, İ.R. Bayer, M. Sahmaran, M. Koc, 3D printing of circular materials: comparative environmental analysis of materials and construction techniques, Case Stud. Constr. Mater. 18 (2023), e02059, https://doi.org/10.1016/j.cscm.2023.e02059.
[23] O. Mahmoodi, H. Siad, M. Lachemi, M. Şahmaran, Comparative life cycle assessment analysis of mono, binary and ternary construction and demolition wastes-based geopolymer binders, Mater. Today Proc. (2023), https://doi.org/10.1016/j.matpr.2023.05.658.
[24] R. Kurda, J. de Brito, J.D. Silvestre, Influence of recycled aggregates and high contents of fly ash on concrete fresh properties, Cem. Concr. Compos. 84 (2017) 198–213, https://doi.org/10.1016/j.cemconcomp.2017.09.009.
[25] C. Lima, A. Caggiano, C. Faella, E. Martinelli, M. Pepe, R. Realfonzo, Physical properties and mechanical behaviour of concrete made with recycled aggregates and fly ash, Construct. Build. Mater. 47 (2013) 547–559, https://doi.org/10.1016/j.conbuildmat.2013.04.051.
[26] H. Ilcan, O. Sahin, Z. Unsal, E. Ozcelikci, A. Kul, N. Cağatay Demiral, M. Ozkan Ekinci, M. Sahmaran, Effect of industrial waste-based precursors on the fresh, hardened and environmental performance of construction and demolition wastes-based geopolymers, Construct. Build. Mater. 394 (2023), 132265, https://doi.org/10.1016/j.conbuildmat.2023.132265.
[27] N. Mir, S.A. Khan, A. Kul, O. Sahin, E. Ozcelikci, M. Sahmaran, M. Koc, Construction and demolition waste-based self-healing geopolymer composites for the built environment: an environmental profile assessment and optimization, Construct. Build. Mater. 369 (2023), 130520, https://doi.org/10.1016/j.conbuildmat.2023.130520.
[28] A. Abushanab, W. Alnahhal, Bond strength of corroded reinforced recycled aggregate concrete with treated wastewater and fly ash, J. Build. Eng. 79 (2023), 107778, https://doi.org/10.1016/j.jobe.2023.107778.
[29] A. Abushanab, W. Alnahhal, Flexural capacity of sustainable RC beams manufactured with treated wastewater, RCA, and Fly Ash (2023) 1226–1232, https://doi.org/10.1007/978-3-031-32519-9_124.
[30] ISO 15686-5: 2017, ISO 15686-5: 2017:, Buildings and Constructed Assets–Service-Life Planning–Part 5: Life-Cycle Costing, International Organization for Standardization, 2017.
[31] N. Makul, Cost-benefit analysis of the production of ready-mixed high-performance concrete made with recycled concrete aggregate: a case study in Thailand, Heliyon 6 (2020), e04135, https://doi.org/10.1016/j.heliyon.2020.e04135.
[32] R. Kurda, J. de Brito, J.D. Silvestre, CONCRETop method: optimization of concrete with various incorporation ratios of fly ash and recycled aggregates in terms of quality performance and life-cycle cost and environmental impacts, J. Clean. Prod. 226 (2019) 642–657, https://doi.org/10.1016/j.jclepro.2019.04.070.
[33] M. Reiner, K. Rens, High-volume fly ash concrete: analysis and application, Pract. Period. Struct. Des. Construct. 11 (2006) 58–64, 10.1061/ASCE)1084-0680(2006)11:1(58.
[34] E.A. Ohemeng, S.O. Ekolu, Comparative analysis on costs and benefits of producing natural and recycled concrete aggregates: a South African case study, Case Stud. Constr. Mater. 13 (2020), e00450, https://doi.org/10.1016/j.cscm.2020.e00450.
[35] ASTM 1602/C1602M − 18, Standard Specification for Mixing Water, Used in the Production of Hydraulic Cement Concrete, 2018, https://doi.org/10.1520/C1602_C1602M-18.
[36] ASTM C192/C192M − 19, Standard Practice for, Making and Curing Concrete Test Specimens in the Laboratory, 2019, https://doi.org/10.1520/C0192_C0192M-19.
[37] G. Bekdaş, S.M. Nigdeli, X.-S. Yang, in: X.-S. Yang, G. Bekdaş, S.M. Nigdeli (Eds.), Optimum Reinforced Concrete Design by Harmony Search Algorithm, Springer International Publishing, Cham, 2016, pp. 165–180, https://doi.org/10.1007/978-3-319-26245-1_8.
[38] P. Foraboschi, M. Mercanzin, D. Trabucco, Sustainable structural design of tall buildings based on embodied energy, Energy Build. 68 (2014) 254–269, https://doi.org/10.1016/j.enbuild.2013.09.003.
[39] EN 1991-1-4, Eurocode 1: Actions on Structures–Part 1-4, General actions — Wind actions, 1991.
[40] S. Marinković, V. Radonjanin, M. Malešev, I. Ignjatović, Comparative environmental assessment of natural and recycled aggregate concrete, Waste Manag. 30 (2010) 2255–2264, https://doi.org/10.1016/j.wasman.2010.04.012.
[41] J. Kneifel, Life-cycle carbon and cost analysis of energy efficiency measures in new commercial buildings, Energy Build. 42 (2010) 333–340, https://doi.org/10.1016/j.enbuild.2009.09.011.
[42] A. Sharma, A. Saxena, M. Sethi, V. Shree, Varun, Life cycle assessment of buildings: a review, Renew. Sustain. Energy Rev. 15 (2011) 871–875, https://doi.org/10.1016/j.rser.2010.09.008.
[43] Inflation Calculator: Current Inflation Rates from 2000 to 2023, Coinnews Media Group LLC, U.S, 2022. https://www.usinflationcalculator.com/inflation/current-inflation-rates/.
[44] R.S. Paranhos, B.G. Cazacliu, C.H. Sampaio, C.O. Petter, R.O. Neto, F. Huchet, A sorting method to value recycled concrete, J. Clean. Prod. 112 (2016) 2249–2258, https://doi.org/10.1016/j.jclepro.2015.10.021.
[45] Rsmeans, Construction and Cost Estimating Data, 2017. https://www.rsmeans.com/.
[46] K. Shwekat, H.-C. Wu, Benefit-cost analysis model of using class F fly ash-based green cement in masonry units, J. Clean. Prod. 198 (2018) 443–451, https://doi.org/10.1016/j.jclepro.2018.06.229.
[47] Sa'd Abdel-Halim Shannak, Could Qatar Use Treated Wastewater to Quench Agriculture's Thirst?, 2022. https://www.qf.org.qa/stories/could-qatar-use-treated-wastewater-to-quench-agricultures-thirst.
[48] Capital Scrap Metal LLC, Price of Scrap Metal, 2022. https://www.priceofscrapmetals.com/.
[49] M. Mistry, C. Koffler, S. Wong, LCA and LCC of the world's longest pier: a case study on nickel-containing stainless steel rebar, Int. J. Life Cycle Assess. 21 (2016) 1637–1644, https://doi.org/10.1007/s11367-016-1080-2.
[50] M. Ehlen, M. Thomas, E. Bentz, Life-365 Service Life Prediction modelTM, 2009, pp. 41–46, version 2.0.
[51] J.G. Cabrera, Deterioration of concrete due to reinforcement steel corrosion, Cem. Concr. Compos. 18 (1996) 47–59, https://doi.org/10.1016/0958-9465(95)00043-7.
[52] C. Broadbent, Steel's recyclability: demonstrating the benefits of recycling steel to achieve a circular economy, Int. J. Life Cycle Assess. 21 (2016) 1658–1665, https://doi.org/10.1007/s11367-016-1081-1.
[53] Office of Management and Budget Circular, A-94 Appendix C: Discount Rates for Cost-Effectiveness, Lease Purchase, and Related Analyses, 2022. https://www.federalregister.gov/documents/2022/05/24/2022-11085/discount-rates-for-cost-effectiveness-analysis-of-federal-programs.
[54] B.H. Goh, Y. Sun, The development of life-cycle costing for buildings, Build. Res. Inf. 44 (2016) 319–333, https://doi.org/10.1080/09613218.2014.993566.
[55] H. Islam, M. Jollands, S. Setunge, Life cycle assessment and life cycle cost implication of residential buildings—a review, Renew. Sustain. Energy Rev. 42 (2015) 129–140, https://doi.org/10.1016/j.rser.2014.10.006.
[56] F.K. Alqahtani, I.S. Abotaleb, M. ElMenshawy, Life cycle cost analysis of lightweight green concrete utilizing recycled plastic aggregates, J. Build. Eng. 40 (2021), 102670, https://doi.org/10.1016/j.jobe.2021.102670.
[57] I. Martínez-Lage, P. Vázquez-Burgo, M. Velay-Lizancos, Sustainability evaluation of concretes with mixed recycled aggregate based on holistic approach: technical, economic and environmental analysis, Waste Manag. 104 (2020) 9–19, https://doi.org/10.1016/j.wasman.2019.12.044.

[58] R.K. Majhi, A.N. Nayak, Production of sustainable concrete utilising high-volume blast furnace slag and recycled aggregate with lime activator, J. Clean. Prod. 255 (2020), 120188, https://doi.org/10.1016/j.jclepro.2020.120188.
[59] J. Wang, Y. Wang, Y. Sun, D.D. Tingley, Y. Zhang, Life cycle sustainability assessment of fly ash concrete structures, Renew. Sustain. Energy Rev. 80 (2017) 1162–1174, https://doi.org/10.1016/j.rser.2017.05.232.
[60] M. Ma, V.W. Tam, K.N. Le, R. Osei-Kyei, Factors affecting the price of recycled concrete: a critical review, J. Build. Eng. 46 (2022), 103743, https://doi.org/10.1016/j.jobe.2021.103743.