Construction and Building Materials 175 (2018) 152–160

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

Life cycle cost analysis of structural concrete using seawater, recycled concrete aggregate, and GFRP reinforcement

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HIGHLIGHTS

- A LCCA was performed for structural concrete using seawater and recycled aggregates.
- Glass fiber reinforced polymer displaced black steel as the reinforcement material.
- The proposed combination achieved a 50% cost saving over a 100-year life cycle.
- GFRP was more cost effective as reinforcement than black steel and stainless steel.
- Results are most sensitive to the selected discount rate and construction costs.

ARTICLE INFO

Article history:
Received 30 June 2017
Received in revised form 27 November 2017
Accepted 23 April 2018

Keywords:
Sustainability
Cost performance
Life cycle costing
Stainless steel
GFRP-reinforced concrete
Recycled concrete aggregate
Seawater

ABSTRACT

Using seawater and recycled concrete aggregate (RCA) in a concrete mix is potentially advantageous from a sustainability perspective. However, the high chloride levels expected in such a case demands the use of non-corrosive reinforcement in lieu of normal black steel to avoid corrosion problems. Glass fiber reinforced polymer (GFRP) is considered promising as an alternative reinforcement owing to its corrosion resistance and acceptable mechanical properties that minimize maintenance and repairs and extend service life. However, the relatively high initial cost of GFRP bars may mitigate its potential use. To account for these factors, a life cycle cost analysis (LCCA) has been conducted to establish the relative cost savings of structural concrete combining seawater, RCA, and GFRP reinforcement in high-rise buildings compared with a traditional concrete mix and other reinforcement materials, such as black steel and stainless steel.

The proposed combination of seawater, RCA, and GFRP in structural concrete was found to achieve cost savings over a 20-year period following initial construction. The life cycle cost (LCC) obtained for the proposed combination was approximately 50% less than that of the conventional counterpart (i.e. concrete with freshwater, natural aggregates, and black steel) based on a 100-year study period. The use of stainless-steel reinforcement to enhance durability was also found to be potentially advantageous but less cost-effective than using GFRP. The LCC of stainless-steel reinforced concrete was estimated to be 15% lower than that of the traditional steel-reinforced counterpart, with a payback period of 50 years.

Results were found to be highly sensitive to the assumed discount rate and construction costs. The proposed combination achieved cost savings only with a real discount rate (r) of 5.9% or higher. Likewise, using stainless-steel reinforcement was found cost-effective at $r \leqslant 1.35\%$ and nominal construction costs exceeding 85% of the material cost. The differences in concrete mixture cost, however, appeared to have insignificant influence on the ultimate LCCA results compared to those obtained from altering the reinforcement material.

1. Introduction

It has been estimated that around two-thirds of the global population live under conditions of severe water scarcity for at least one month every year [1], leading to the increased use of desalination to provide potable water. The global capacity of

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https://doi.org/10.1016/j.conbuildmat.2018.04.183
0950-0618/

desalination plants has increased from 5 million m^3/day in 1980 to 80.9 million m^3/day in 2013 [2]. However, desalination is energy intensive, making the desalted water relatively expensive, and generates a brine waste stream which negatively impacts on the environment [3]. The average cost of reverse osmosis (RO), the most commonly-used desalination technique worldwide [2], ranges between 0.50 and 1.20 $/$m^3$ [4] and is associated with an energy consumption of 3–4 kWh/m^3 as well as emitted CO_2 levels of 1.4–1.8 kg/m^3 product water [3]. The volume of brine generated is estimated to reach 156 km^3 by 2050 [2].

One important step towards overcoming the challenge of freshwater scarcity and the corresponding increasingly high demand for desalination is reducing the unnecessary use of freshwater for construction purposes. Concrete is the most commonly-used construction material worldwide, and is typically produced by mixing cement, freshwater, aggregates, and admixtures [5]. The construction industry uses over a billion tons of potable water every year to produce concrete [6], with the use of reinforced concrete increasing globally each year. Seawater can represent a valid alternative to freshwater in concrete production but, despite it being more a sustainable water source, the use of seawater in concrete is currently prohibited because its high salinity (3.5% on average [7]) promotes corrosion of steel reinforcement [8].

Construction and demolition wastes make up about 30% of the total waste worldwide [9]. In the US alone, the annual construction and demolition waste has been estimated at ~480 million tons, of which more than 50% is primarily concrete [10]. Without recycling, the yearly accumulation of these wastes is likely to lead to significant economic and environmental problems [11]. Using recycled concrete aggregate (RCA) can largely reduce the negative effects of the demolition waste and control the harvesting of natural aggregates (NA) while providing acceptable properties of the resulting concrete [12,13]. However, one of the main concerns in using RCA is the likelihood of saline contamination, given the high diversity in RCA sources, promoting corrosion of the steel reinforcement [14].

It is postulated from the existing literature that the salt, existing either in seawater or in RCA, has no significant negative effects on plain concrete characteristics [14–16]; the negative effect in such a case appears to be limited to the corrosion of steel reinforcement. This can be addressed by using fiber reinforced polymer (FRP) to reinforce concrete structures [17], this material being corrosion-resistant [18,19] and lightweight while still providing sufficient mechanical strength [20]. Despite the higher cost of FRP reinforcement compared to that of black steel, the implementation of economic and environmental studies on FRP-reinforced concrete indicates significant cost savings in the long term [21–23]. Moreover, the technology developed over the last two decades has facilitated the use of FRP to replace steel reinforcement when structure durability is of concern. Several studies have demonstrated the effectiveness of this technology in various applications such as bridge decks [24,25]. Amongst all FRP types applicable to reinforce concrete, glass-FRP (GFRP) is the most common, being less expensive [23] while having acceptable mechanical properties [26,27].

In principle, the sustainability of a product is measured by its associated economic and environmental impacts throughout its life cycle. The life cycle of a product begins with the production of raw material and extends to manufacture, use, transportation, and waste management [28]. Life Cycle Cost Analysis (LCCA) is an established tool for minimizing the cost associated with the generation of a specific product. The LCCA is typically defined in terms of four main cost categories: initial, operational, maintenance, and end-of-life disposal [29]. In effect, the existing literature shows a clear advantage of individually using recycled concrete aggregate [12,30,31] or FRP reinforcement [21,22,32] in structural concrete in terms of cost performance. This paper aims to assess, arguably for the first time, the life-cycle cost implications of combining seawater, RCA, and GFRP reinforcement in the structural concrete for high-rise buildings. The comparative cost of GFRP and stainless-steel reinforcement [33,34] as an alternative to conventional black steel is quantified, along with the sensitivity to key parameters.

2. Materials and methods

2.1. Design alternatives

Three design alternatives for reinforced concrete in high-rise buildings are considered, with reference to the concrete mixture and reinforcement material (Table 1); the rationale for selecting these alternatives is illustrated in Fig. 1. RC1 represents the conventional design – with freshwater, natural aggregates (NA), and black steel reinforcement – as a reference. In RC2, stainless steel is substituted for conventional black steel to counter possible corrosion [33,34]. As opposed to the well-known RC1 and RC2, the proposed design alternative RC3 combines the seawater-based concrete mixture with RCA and GFRP reinforcement.

2.2. Reinforced concrete design

The relative amounts of concrete and reinforcement are critical in achieving a safe and economic concrete structure [35]. For the conventional reinforced concrete (RC1), the structural design data were obtained from Foraboschi et al. [36] in their work concerning the embodied energy of high-rise buildings. These authors performed structural design on several reinforced concrete tall buildings of different height and gross floor area [36]. The compressive strength of concrete was taken as 40 MPa, assumed valid for high-rise reinforced concrete buildings. A uniformly-distributed dead load of 2.5 kN/m^2, in addition to the self-weight, was assumed for loading over the entire floor area to represent internal non-bearing elements. The external facade was reproduced by a uniform dead load of 4 kN/m applied along the perimeter beams. The vertical live load was assumed as 3 kN/m^2, uniformly-distributed over the entire floor area. The wind load was applied as per the Eurocode [37]. Seismic actions were not considered since they are generally deemed to have negligible structural effects on tall buildings compared to those induced by the wind load [38–40]. The structural analyses were performed using the finite element method. The buildings were designed to consistently meet the same safety margins, by imposing the maximum horizontal and vertical displacements for each building to equal 1/400 of the building height and 1/400 of the longest floor span, respectively [36].

The amounts of concrete and reinforcement are summed up for all structural elements (i.e. slabs, beams, columns, etc.) and divided by the gross floor area [36] (Table 2). The reinforced concrete design is thus expressed in terms of the overall concrete volume and reinforcement weight needed per unit floor area. The average concrete volume, reinforcement weight, and reinforcement ratio, ratio (ρ), the latter being the ratio between the volume of reinforcement to the volume of concrete, are taken as 0.32 m^3/m^2, 50.45 kg/m^2, and 2%, respectively for the same unit floor area. These are considered as input quantities for the RC1 and RC2 LCC calculations; stainless steel is presumed to have mechanical and physical properties comparable to that of black steel. The GFRP reinforcement, on the other hand, exhibits a brittle failure at the ultimate stress [20,27] but has a higher tensile strength and lower elastic modulus [26]. Consequently, the balanced reinforcement ratio (ρ_b) of a typical GFRP-reinforced concrete flexural member is approximately one-fifth that of steel-reinforced counterpart [41]. This lower balanced ratio leads to a lower reinforcement volume needed for the structural design of GFRP-reinforced concrete. However, to ensure meeting the minimum reinforcement requirements as per ACI 440.1 [41] the reinforcement ratio of GFRP-reinforced concrete (i.e. RC3) is assumed to be the same as that of steel-reinforced counterpart ($\rho = 2\%$). This assumption yields an over-reinforced section (i.e. $\rho > \rho_b$), recommended due to the corresponding less severe failure mode [41]. The relatively low density of GFRP (1/4–1/5 that of steel [41]), provides a notably lower reinforcement weight per unit area for RC3 compared with the steel-reinforced counterparts.

Table 1
Design alternatives considered in this study.

Design Alternative	Mixing water	Aggregates used	Reinforcement material
RC1	Freshwater	Natural aggregate	Black steel
RC2	Freshwater	Natural aggregate	Stainless steel
RC3	Seawater	Recycled concrete aggregate	GFRP