المجلة الإلكترونية الشاملة متعددة التخصصات
العدد الثاني والثلاثون شهر (١) ٢٠٢١

Sustainability of Reinforced Concrete Buildings: A Review Study

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Abstract

Sustainability issues are now taking most of the researchers attention in the different fields where the construction filed is not an exception. Due to the popularity of the reinforced concrete structures, discussing the main sustainability strategies in them is becoming an urgent call. In this study, the main studies reviewed the sustainability strategies mainly Basalt Fiber (BF), double façade skin (DFS) and some efficient structural systems to optimize CO2 emission.

Keywords; RC, BF, DFS, CO2 emission, sustainability .

ملخص البحث

تستحوذ قضايا الاستدامة الآن على اهتمام معظم الباحثين في المجالات المختلفة حيث لا يمثل مجال البناء استثناءً. نظرًا لشعبية الهياكل الخرسانية المسلحة ، أصبحت مناقشة استراتيجيات الاستدامة الرئيسية فيها دعوة عاجلة. في هذه الدراسة ، استعرضت الدراسات الرئيسية استراتيجيات الاستدامة بشكل رئيسي الألياف البازلتية (BF) وجلد الواجهة المزدوجة (DFS) وبعض الأنظمة الهيكلية الفعالة لتحسين انبعاثات ثاني أكسيد الكربون.

الكلمات المفتاحية: RC ، BF، DFS، انبعاثات ثاني أكسيد الكربون ، الاستدامة

Introduction

After water, concrete is the most common product used worldwide and a significant building material (Hájek, Fiala, & Kynčlová, 2011; Vieira, Calmon, Zulcão, & Coelho, 2018). Therefore, it is essential for sustainable development to consider the associated environmental impacts of reinforced concrete structures. The Global emissions of CO_2 from cement production, fossil fuel besides other industries compose 70% of the greenhouse emissions globally with 35.8 GtCO2 in 2016 (Olhoff & Christensen, 2018).

This kind of emissions could be significantly minimized by optimizing emissions in the design stage for every structural material (K. S. Moon, 2008; Park et al., 2013; Yeo & Gabbai, 2011; Yeo & Potra, 2015). Actually, reducing the requirements of the material is one the measures that could reduce environmental effects effectively in the construction industry (Miller & Doh, 2015). Usually, reinforced concrete structures are constructed to meet criteria including durability, serviceability, and safety (Vitek, 2013), whereas measures to minimize energy consumption were not incorporated properly (Miller & Doh, 2015).

The most obvious examples of strategies to ensure the sustainability of reinforced concrete buildings is by applying advanced materials, appropriate technology and efficient structural systems (Vitek, 2013). In this study, the main studies that discussed the sustainability of reinforced concrete buildings will be reviewed and the gap in the related literature will be identified.

Followed methods to evaluate sustainability

The task of quantifying the environmental effects for a building requires an evaluation consisting of the building life cycle. This evaluation can be accomplished by the Life Cycle Assessment (LCA) (Carre & Crossin, 2015; Fraile-Garcia, Ferreiro-Cabello, Martinez-Camara, & Jimenez-Macias, 2016; Guardigli, Monari, & Bragadin, 2011; Hájek et al., 2011; Puskás & Moga, 2016; Xing, Xu, & Jun, 2008; Yeo & Potra, 2015). Nonetheless, conducting the LCA evaluation is not an easy task as it require time and experts in the field to continuously enhancing the approach to handle the issues associated with transparency, inconsistency, availability and quality of the data and comparability (Schlanbusch et al., 2016). According to the related literature, LCA has been used widely within the building and construction industry (Carre & Crossin, 2015; Fraile-Garcia et al., 2016; Guardigli et al., 2011; Hájek et al., 2011; Lˇpez-Mesa, Tomßs, & Gallego, 2009; Müller, Haist, & Vogel, 2014; Purnell, 2012; Silva, de Brito, & Gaspar, 2016; Xing et al., 2008). This assessment tool can be used on the different types of buildings and structures (Schlanbusch et al., 2016).

Furthermore, LCA has been applied to the entire building analysis including various structural systems (Cole, 1998; Jonsson, Bjorklund, & Tillman, 1998) in addition to the entire life-cycle operations. Cole and Kernan (1996) assessed both initial and recurring embodied energy that are linked with repair and maintenance for an office building consists of concrete, steel and wood structural systems (Cole & Kernan, 1996). Suzuki and Oka (1998) have used the economic (input/output) approach to estimate CO2 emission and energy successfully in an office building (Suzuki & Oka, 1998). Related methods with the simulation tools for energy and without them were used to examine the environmental performance for the buildings life cycle of different types (Asif, Muneer, & Kelley, 2007; Cabeza, Rincón, Vilariño, Pérez, & Castell, 2014; Chua & Chou, 2010; Hu, Shiue, Chuang, & Xu, 2013; Scheuer, Keoleian, & Reppe, 2003). Other used the same method for different climates and geographical locations (Dong & Ng, 2015; Junnila, Horvath, & Guggemos, 2006) while other used them for different innovative sustainability schemes (De Gracia et al., 2010; Pargana, Pinheiro, Silvestre, & de Brito, 2014).

Moreover, the reinforced concrete structure environmental evaluation necessitates the environmental effect assessment throughout materials production, maintenance, construction, operation/use, and the end of the building life. With the massive amount of used materials in the construction projects in the world, the associated emissions with materials are important for the emissions throughout the entire lifetime of the building (Purnell, 2012). However, the operation stage is the responsible for most of the emissions of reinforced concrete buildings (Heeren et al., 2015; Park et al., 2013; Purnell, 2012). On the other hand, the use stage represents just a modest amount of emissions in the building lifecycle (Yeo & Gabbai, 2011).

Previous literature has reported that as there is an obvious renewable sources presence in the energy matrix, the structural system will be a contributor in the reinforced concrete building environmental loads (Haapio & Viitaniemi, 2008; K. Moon, 2009; Oliveira, 2013; Andy van den Dobbelsteen, Arets, & Nunes, 2007; AAJF Van Den Dobbelsteen, Arets, & Van Der Linden, 2005). Therefore, the significance of CO2 emissions and energy consumption caused by phases other than the building use is increasing and the prediction methodologies accuracy are improving, leading to further energy efficient designs for building (Oka & Sawachi, 2013). Current methodologies concerning RC buildings sustainability assume that the environmental impacts degree must be integrated with design approaches such as environmental performance in addition to well recognized durability, safety and serviceability performances (Kawai, 2011).

Methodology

This is review study aiming to summarize the sustainability technologies in the reinforced concrete structures. An extensive search on the literature for relevant peer-reviewed reports and scientific articles was conducted; this review was performed using Internet searches. Keywords search was conducted by the terms ‘RC’ or ‘sustainable RC’. The strength and relevance of every article were dealt with.

Enhancing the sustainability of reinforced concrete

Applying advanced materials (Basalt Fiber (BF))

Basalt fiber (BF) is a commonly used material because of its exceptional functionality and cost-effectiveness (Fiore, Scalici, Di Bella, & Valenza, 2015; Ramakrishnan & Panchalan, 2005). Lately, it has been focused on since adding BF to the concrete (basalt fiber-reinforced concrete, BFRC) was approved to enhance the mechanical properties of the reinforced concrete structure. Elshafie and Whittleston (2015) discussed the BF contents and lengths influences on the concrete mechanical strength where they found that BF can enhance the mechanical strength when its length is (12 – 24) mm and its content (0.10% - 0.50%) (Elshafie & Whittleston, 2015).

Katkhuda et al. (2017) argued that the concrete compressive strength could increase minimally while the content of BF increases till it becomes 1%; however, the splitting and flexural concrete tensile strength revealed a significant enhancement (Katkhuda & Shatarat, 2017). Moreover, Zhang et al. (2017) examined the BFRC properties at various fiber contents where they found a significantly enhanced dynamic concrete compressive strength with appropriate content of basalt fiber within various loading rates (H. Zhang, Wang, Xie, & Qi, 2017).

The studies discussing BF environmental effects and application within concrete have gradually arisen lately. Jamshaid et al. (2016) argued that BF material can be considered as sustainable as BF consists of natural materials with no addition of chemicals, pigments, solvents or any other harmful material (Jamshaid & Mishra, 2016). De Fazio (2011) found the required energy for BF production in electric furnaces is 5 kWh/kg (De Fazio, 2011).

It was found that chloride attack is one of the main factors affecting the reinforced concrete structures durability (Mehta, 1991; Suryavanshi, Swamy, & Cardew, 2002).

The related literature showed that BF addition to concrete can benefit in reducing the coefficient of chloride diffusion (Niu, Su, Luo, Huang, & Luo, 2020).

In fact, the majority of concrete structures are subjected to what is called external loads, which is caused by the transportation of chloride within concrete that is influenced by some of the environmental issues (Ghahari, Ramezanianpour, Ramezanianpour, & Esmaeili, 2016) besides the external loads (Al-Kutti, Rahman, Shazali, & Baluch, 2014; Wu, Li, Wang, & Liu, 2016). Therefore, it is essential to perform comprehensive research regarding chloride diffusion in the external loads coupling interaction as well as chloride action.

Wang et al. (2011) conducted a study on the concrete chloride diffusivity within compressive and tensile zones. They found that the concentration of chloride enlarged with the flexural stress within the concrete tensile zone, in spite of stress level, reduced at first with the compressive stress and enlarged till the stress reaches 55% of the compressive strength within the concrete compressive zone (H. Wang, Lu, Jin, & Bai, 2011). In order to examine the chloride diffusivity characteristics within various concrete sections depths, Wang et al. (2014) suggested a model that was built through founding the association between the coefficients of chloride diffusion and the levels of flexural load (Y. Wang, Lin, & Cui, 2014).

On the other hand, concrete structures chloride diffusivity with BF in the external loads chloride action coupling and interaction was not documented appropriately. For that reason, Zhang et al. (2020) found that the RC beam with BF average coefficient of chloride diffusion is larger compared with regular RC beam regardless of the level of applied load. Furthermore, the LCA results were significantly different with the functional preset units. They found that adding BF with RC is an appropriate solution for improving the RC beams sustainability while taking into consideration the cracking capacity (Y. Zhang, Mao, Wang, Gao, & Zhang, 2020).

Table 1: Summary of studies discussed the sustainability effects of applying advanced materials (Basalt Fiber (BF))

Study	Sustainability aspect
Elshafie and Whittleston (2015)	Enhance the mechanical strength
Katkhuda et al. (2017)	Increase the concrete compressive strength
Zhang et al. (2017)	Enhanced dynamic concrete compressive strength
Niu et al. (2020) Zhang et al. (2020)	Reducing the coefficient of chloride diffusion
Jamshaid et al. (2016)	BF consists of natural materials with no addition of chemicals, pigments, solvents or any other harmful material
De Fazio (2011)	Does not require a lot of energy to be produced

Appropriate technology (Double façade skin (DFS))

Many studies have discussed the ways to resolve the challenges of operational energy where there is a need for additional efforts to reduce the energy demand (Pomponi, Piroozfar, Southall, Ashton, & Farr, 2016). The results showed that one of most efficient approaches is reducing cooling and heating loads in the interiors of the building by enhancing the building envelopes' thermal resistance (Agency, 2013; McGregor, Roberts, & Cousins, 2013). Particularly, double skin façade (DSF) consisting of an external glass layer, a cavity and a normal façade (Barbosa & Ip, 2014) is a technology with promising abilities because of its ability to minimize cooling and heating operation energy besides other related advantages including daylight, ventilation, sound insulation and glare control (Ghaffarianhoseini et al., 2016).

Pomponi et al. (2016) discussed the exceptional performance of the DFS system compared with the conventional façade in view of the Global Warming Indicator (Pomponi, Piroozfar, & Farr, 2016). de Gracia et al. (2014) investigated the different DSF system innovative features where they found that it could decrease the total environmental effect of the building by 7.7% more than the conventional system (de Gracia, Navarro, Castell, Boer, & Cabeza, 2014).

Pomponi and D'Amico (2017) investigated DSF system innovation with timber framing and the results showed that it performed better than aluminum or steel framing, which is an indication for its potential employment as low-carbon restorations (Pomponi & D'Amico, 2017). Dependably, in arid and warm climates, DSF with shading or glazing devices showed a potential for energy savings during the use phase (Baldinelli, 2009; Chan, Chow, Fong, & Lin, 2009; Hamza, 2008; Mulyadi, 2012). The majority of the related studies investigating the sustainability potential of DSF system pointed to its related superior environmental impacts in spite of its high cost as a main disadvantage (Barbosa & Ip, 2014; Ghaffarianhoseini et al., 2016; Pomponi, Piroozfar, Southall, et al., 2016).

Through the preview of the related studies, it was noticed that glass has been always a vital part in the system where limited studies investigated its suitability in the reinforced concrete buildings. Using concrete in the envelope of the building could enhance its R-value or thermal resistance through increasing the thickness of the envelope. On the other hand, DSF could increase the thermal mass or the capacity of heat absorption for the envelope, which may affect the building implication cooling on nighttime. The concrete elements within the DSF system can be combined with air due to its characteristic low thermal conductivity.

Kurt (2011) found that an air gap insulation can resolve many issues related to the material thickness, heating cost and insulation cost (Kurt, 2011). Furthermore, Fallahi et al. (2010) found that incorporating concrete thermal mass within a DSF mechanically-ventilated glass reduced cooling energy nearly 21-16% during summer (Fallahi, Haghighat, & Elsadi, 2010).

Hay and Ostertag (2018) proposed an innovative DSF system that can be achieved with a novel concrete composite known as HP-G-HyFRC "High Performance Green Hybrid Fiber-Reinforced Concrete". The results revealed that DSF system presented a higher ductility and structural capacity more than the SW counterpart did. Moreover, DSF could possibly decrease the annual CO2eq emission and operational energy by 9.2%, regardless of the higher materials cost and embodied energy (Hay & Ostertag, 2018).

Table 2: Summary of studies discussed the sustainability effects of applying double façade skin (DFS)

Study	**Sustainability aspect**
Ghaffarianhoseini et al. (2016) Fallahi et al. (2010) Hay and Ostertag (2018)	– Minimize cooling and heating operation energy – Control daylight, ventilation, sound insulation and glare control
de Gracia et al. (2014)	Decrease the total environmental effect of the building
Baldinelli (2009) Chan et al. (2009) Hamza (2008) Mulyadi (2012)	Energy savings during the use phase
Barbosa and Ip (2014) Ghaffarianhoseini et al. (2016) Pomponi et al. (2016)	– Superior environmental impacts – Decrease the annual co2eq emission
Kurt (2011)	– Enhance the building R-value and thermal resistance – Increase the thermal mass or the capacity of heat absorption for the envelope
Hay and Ostertag (2018)	Higher ductility and structural capacity

Efficient structural systems (CO2 Emission Optimization)

The embodied energy CO_2 footprint estimation for the material of buildings is an inaccurate science that needs a "comprehensive" perspective for the whole utilization and manufacturing process like the life cycle assessment (LCA) (Goggins, Keane, & Kelly, 2010). However, CO2 footprint and embodied energy reasonable estimates of popular construction materials was collected (Andrew, 2003; Hammond, Jones, Lowrie, & Tse, 2008; Reddy & Jagadish, 2003). The share of embodied total life-cycle energy was found to be different between countries, with ranging estimates between 5% and 40% (Sartori & Hestnes, 2007). Such percentages will be increased with the decrease of the operating energy amount (Yohanis & Norton, 2002). The embodied energy within RC structures plays a considerable part between 5% and 10% of this share. Regarding used materials within typical mixes of concrete, the values of CO2 footprint and embodied energy per unit volume were relatively low. On the other hand, since concrete is considered as the most commonly used material within the construction industry, their whole values within RC structures were significant. In addition, concrete, unlike steel, is typically not recycled to be reused directly in the majority of structures.

New studies have demonstrated the interest in taking into consideration the environmental factors while discussing RC structures optimization. Paya-Zaforteza et al. (2009) in their study used a based estimated optimization approach on simulated annealing in order to minimize the overall structural cost and the total embodied CO2 emissions within the structure. This study was applied on a six building frames, with one to four bays and with one to eight floors. It was shown that the optimum structure is only marginally (2.8%) from the minimizing emissions standpoint more than the optimum structure intended for minimizing cost (Paya-Zaforteza, Yepes, Hospitaler, & Gonzalez-Vidosa, 2009).

Villalba et al. (2010) studied cantilever earth retaining walls and argued that the optimum structure is marginally cost (1.4%) more than the minimizing cost optimum structure. Remarkably, they found that optimized walls for minimum cost needs nearly 5% more of concrete compared with optimized walls for least embedded CO2 emissions, while the last need nearly 2% steel more than the first (Villalba, Alcalá, Yepes, & González-Vidosa, 2010).

Yeo and Gabbai (2011) examined the consequences, from the cost perspective, of a simple reinforced concrete structural member optimization where embodied energy was reduced. The results showed that the design of structural member optimization for smallest embodied energy leads to decreasing the embodied energy by 10%, causing an increase with 5% in the cost in comparison to a cost-optimized design. The embodied energy reduction depends considerably on the cost ratio value of steel reinforcement with concrete and such ratio should consider the steel and concrete material costs and the construction costs including the concrete placement costs and the reinforcement installation costs. Furthermore, the results showed that the section of minimum-embodied energy has a reduced concrete volume with a higher reinforcement amount than the designed section intended for minimum cost (Yeo & Gabbai, 2011). The previous results were consistent with Villalba et al. (2010) results. In order to ensure the adequately of ductility for the design regardless of the steel amount increase, the restraints in the procedure of optimization include a restraint regarding the reinforcing bars strain.

Yeo and Potra (2015) presented a developed optimization method to help decision makers in balancing economic and sustainability objectives. They used an RC frame under lateral loads and gravity where it was established that the optimized design with CO2 footprint results in a lower CO2 footprint (by 5% to 10%) compared with the optimized design regarding cost. This reduction was smaller in low-rise structures as well as structures with tension-controlled predominantly members. On high-rise structures, this reduction was more significant (Yeo & Potra, 2015).

Conclusion

The production of concrete results in obvious environmental effects. It was proved that BF addition to concrete could enhance the concrete mechanical properties while reducing the coefficient of chloride diffusion. Using concrete in the envelope can enhance its thermal resistance, decrease the operating energy and control daylighting and shading. The embodied energy CO_2 footprint estimation for the material of buildings is an inaccurate science that needs a “comprehensive” perspective for the whole utilization and manufacturing process like the life cycle assessment.

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