A Review on Carbon Emissions of Ultra-High-Performance Fiber Reinforced Concrete as a Building Construction Material

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ABSTRACT

Cement, as the most important component used in concrete, contributes 5-8% of global CO_2 emissions due to its highly energy intensive manufacturing process. Traditional reinforced concrete (RC), which is commonly used building material contains approximately 15% of the cement. But due to increasing demand and bulk design volume, RC requires high quantity of cement. In 2021, the global cement production was 4.4 billion metric tons. Ultra-High-Performance Fiber Reinforced Concrete (UHPFRC) is an emerging high-tech building material with an increased strength and durability compared to conventional concrete. This is achieved by low water-to-binder ratio (w/b<0.25), steel fibers and a very dense particle packing using finer sand and silica fume. UHPFRC requires significantly less material and less maintenance for similar mechanical performance and provides higher lifespan. But it also consists higher cement content contributing to high carbon footprint. The mechanical properties of UHPFRC are being widely researched and improved but the environmental impacts are rarely considered. So, there is a need to review and compare the long-term environmental impacts of UHPFRC and conventional RC. In this study, a review of the life cycle environmental impact analysis is presented which compares the Global Warming Potential (GWP) of conventional concrete to UHPFRC over a construction phase and cradle-to-grave phase. It is observed that the GWP of UHPFRC is at least 60% greater than conventional concrete but when the cradle-to-grave phase is considered, the GWP of UHPFRC outperforms the conventional concrete.

1. INTRODUCTION

Buildings and construction sector account for 40% of global energy consumption and concrete has largely been used as a building material. The most significant environmental impact of concrete is cement, which reportedly contributed 36% to the carbon dioxide emissions of 7.7 gigatons (Bajželj et al., 2013). Hence, building construction materials present a huge potential for decarbonization. Considering that new concrete constructions account for 8% of global greenhouse gas emissions (Favier et al., 2019), it is imperative to reduce their global warming potential. Many researchers have demonstrated that the type of cement used and concrete design mix are major factors influencing the environmental impacts (Bertola et al., 2021).The use of alternative binders to replace cement such as silica fume, fly ash, and slag, have been developed as solutions for reducing concrete's environmental impact.

Ultra-High-Performance Concrete (UHPFRC) has garnered increased interest in the past three decades for building applications because of its excellent durability (Alkaysi et al., 2016; Graybeal & Tanesi, 2008; Magureanu et al., 2012) and high compressive strength compared to conventional concrete (ACI 239R, 2018; de Larrard & Sedran, 1994). The specialized concrete intended for high performance like ultra-high-performance concrete (UHPFRC) often includes steel fibers as a part of the concrete granular structure to improve the mechanical performance of concrete. The optimization of specialized concrete for both environmental performances along with the mechanical performance is crucial to maintain the benefits of these novel construction practices.

Ultra-high-performance concrete (UHPFRC) can be defined as fiber-reinforced cement-based composite material with characteristic strain hardening properties, compared with conventional concrete where once concrete cracks, it loses its tensile capacity very sharply. Finely graded, homogeneous matrix and high fiber content allow UHPFRC to achieve very high mechanical properties (e.g., flexural strength higher than 2,000 psi comparing with about 500 psi for conventional concrete). Figure 1 provides a comparison of the mechanical properties of conventional concrete and UHPFRC.

Table 1: Mechanical properties of UHPFRC and conventional concrete (ACI 239R, 2018)

Material characteristics	**Conventional Concrete**	**Ultra-High-Performance Concrete**
Compressive strength	3000 to 6000 psi (20 to 40 MPa)	22,000 to 36,000 psi (150 to 250 MPa)
Direct tensile strength	150 to 440 psi (1 to 3 MPa)	900 to 1700 psi (6 to 12 MPa)
Elastic modulus (ASTM C469/C469M)	3,600,000 to 4,400,000 psi (25 to 30 GPa)	6,000,000 to 7,200,000 psi (40 to 50 GPa)

UHPFRC is being widely researched but not yet fully commercialized due to its high commercial cost (Administration, 2013; Kay Wille & Boisvert-Cotulio, 2015). A major portion of the material cost of UHPFRC can be attributed to the two constituents of the mix design: cementitious materials and steel fibers. Cementitious materials used in UHPFRC usually consist of cement and silica fume and they can contribute as much as 20% and steel fibers can contribute as much as 40% of the overall cost of UHPFRC (Administration, 2013; Kay Wille & Boisvert-Cotulio, 2015). Figure 2 provides the constituents of a typical UHPFRC mixture design and their contribution to the overall cost.

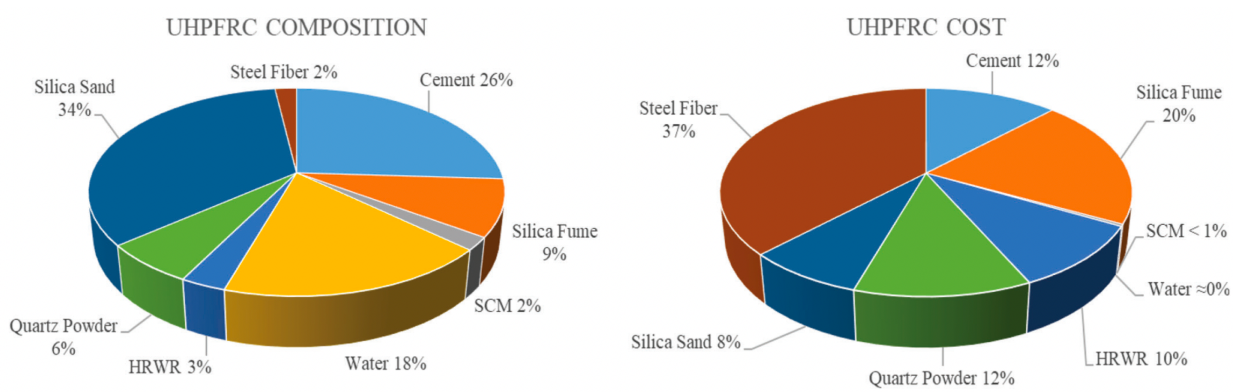

Figure 1: UHPFRC components and their contribution toward UHPFRC cost (Abellán-García et al., 2021)

UHPFRC exhibits a brittle failure mode and fibers are added to provide enhanced ductility (ACI 239R, 2018; Larsen & Thorstensen, 2020). Steel fibers are the most commonly used fibers in UHPFRC and their performance is very well documented (Christ et al., 2019; Larsen & Thorstensen, 2020; Shehab El-Din et al., 2016; K. Wille et al., 2014). Steel fibers make it possible for UHPFRC to exhibit superior flexural properties and strain-hardening behavior after the UHPFRC matrix cracks initially to exhibit superior ductility (K. Wille et al., 2014). The most common obstacle of using UHPFRC has been the steel fiber cost.

Fibers other than steel (glass and PVA fibers) can be used in UHPFRC (Kay Wille & Boisvert-Cotulio, 2015). Pourjahanshahi et. al used a combination of steel fibers with barchip, kortta, glass, carbon, and polypropylene fibers to investigate a UHPFRC mix design with hybrid fibers (Pourjahanshahi & Madani, 2021a). Among non-metallic fibers, glass fibers have become a popular alternative to steel fibers especially where steel corrosion is a concern. Glass fibers have relatively low cost than steel fibers (Ghosh et al., 2021; Kay Wille & Boisvert-Cotulio, 2015) and good durability properties (Gooranorimi & Nanni, 2017; He et al., 2021; Rigaud et al., 2012).

Non-proprietary cost-effective UHPFRC materials can be developed for building construction. The mixture designs can be optimized in their efficiency considering workability, mechanical performance, and cost-effectiveness, which will significantly impact the current construction practices.

A comprehensive literature review is conducted to analyze various mixture designs of UHPFRC with different fibers. It is noticeable that most work on UHPFRC focuses on investigating the mechanical performance. Very few researchers have analyzed the cost and emissions. A handful of articles have conducted a life cycle analysis and reported global warming potential of concrete and UHPFRC, both during construction process and maintenance. Furthermore, all those papers are based on the bridge construction as a case study. We couldn't find any work that investigates cost-saving and decarbonization potential of UHPFRC for buildings' construction.

This paper provides a review on UHPFRC to establish that it can be a promising building construction material to decarbonize concrete construction industry. The literature review in section 2 summarizes the advancements in incorporating alternate fibers. Section 3 and 4 provide an analysis on the cost and carbon emissions of conventional concrete versus UHPFRC.

2. LITERATURE REVIEW ON UHPFRC

As mentioned above, the high cost of UHPFRC compared to conventional concrete is a hurdle in the widespread adoption of UHPFRC and hence, the development of cost-effective UHPFRC has been a major research focus. It has been shown that this can be achieved to variable extents in different ways such as by using locally available materials, substituting Portland cement by cheaper and sustainable binder alternatives, and replacing steel fibers by cost effective glass, carbon, and synthetic fibers.

Numerous research studies have investigated these cost-cutting measures (Abellán-García et al., 2021; Christ et al., 2019; Gesoglu et al., 2016; He et al., 2021; Holubová et al., 2017; Liu et al., 2019; Madhkhan & Saeidian, 2021; Mohammed et al., 2021; Pourjahanshahi & Madani, 2021b; Kay Wille & Boisvert-Cotulio, 2015; Yan et al., 2021) but the primary focus has been the mechanical properties and the impact on environment and cost is seldom reported. Because of that, it is difficult to comprehend what environmental and cost benefits these studies bring.

Gooranirimi et. al investigated the performance of glass fiber reinforced polymer (GFRP) bars that were exposed to concrete alkalinity conditions after 15 years of service and did not find any deterioration in the microstructures and change in chemical composition (Gooranorimi & Nanni, 2017). He et.al used glass fiber (GF) and high-performance polypropylene (HPP) fiber in UHPFRC and claimed that glass fibers outperformed the high-performance polypropylene fibers in compressive, tensile and bending properties (He et al., 2021). Riguad et. al developed a self-placing, ductile, ultra-high performance concrete containing glass fibers for thin structural elements. This UHPFRC maintained ductility even after accelerated aging tests (Rigaud et al., 2012).

Ghosh et. al used glass bars in High-Early-Strength concrete and achieved a compressive strength of 22.1 MPa at 6 hours (Ghosh et al., 2021). UHPFRC is characterized by a minimum compressive strength of 150 MPa at 28 days as defined in ACI 239R-18. According to the cost estimation by Ghosh et. al, these fibers are 33% cheaper compared to steel fibers and therefore, they have the potential to reduce the cost of UHPFRC.

Table 1 below summarizes a comprehensive literature review where attempts are made to find suitable alternatives to steel fibers that exhibit similar mechanical properties. Different types of fibers include glass, polypropylene, carbon, basalt, and PVA fibers. These fibers are used as either partial or complete replacements of steel fibers and their mechanical properties (compressive strength, tensile strength, ductility etc), fracture properties, and durability are evaluated.

Table 2: UHPFRC research with various fibers

Author	Fiber	Cost reported	Emissions reported	Key Findings
Madhkhan et.al 2021	Glass fibers	No	No	Brittle after accelerated aging
He et. al 2021	Glass and High-performance Polypropylene fibers	No	No	2% fiber provides better performance. GF is better for compressive and tensile strength. HPP is better for toughness
Liu et. al 2019	GF,	No	No	Hybrid fibers have best

	Polypropylene, and Hybrid			performance. Polypropylene has better performance than GF
Chanvillard et. al 2012	GF	No	No	Durability and ductility maintained after aging tests
Christ et. al 2019	Hybrid steel and polypropylene fibers (50-100% steel, 0-50% PP)	No	No	80% steel and 20% PP gave the best performance in lowering cement content while maintaining compressive strength, and toughness
Pourjahanshahi et. al 2021	Steel, glass, carbon, and hybrid	No	No	Some fibers and combinations performed better in various scenarios of strength and durability
Yan et. al 2021	Basalt fiber, glass fiber, and polypropylene fibers	No	No	Enhanced compressive, flexural, modulus of rupture, toughness index with the addition of fibers compared to no fibers
Wille et. al 2015	Steel, glass, and PVA	Yes	No	Proposed cost-effective mix designs in different regions of US
Mohammed et. al 2021	Micro Glass fibers	No	No	Performance and ductility increased with addition of fibers
Gesoglu et. al 2016	Micro steel, and glass fibers	No	No	Properties enhanced with increase in fiber percentage
Holubova 2017	Alkali-resistant glass fibers	No	No	Durability was not affected, and fibers did not deteriorate even after 1 year
Pernicova 2015	Glass fibers	No	No	Type of glass fibers did not impact the compressive, flexural, and modulus of elasticity
Abellán-García 2021	Steel fibers	Reviewed	No	1% fiber was enough to achieve strain hardening. 2% of deformed fiber produced more strain-hardening

It is evident from these studies that a lot of emphasis is placed on the mechanical properties and durability but the attempt to quantify and compare the cost and environmental impact against conventional concrete is lacking. Mechanical strength and durability are very important for a construction material, and while numerous studies have investigated the performance and reported promising results, it is important to study the environmental impacts. Upcoming sections attempt to provide an overview of the life cycle analysis of UHPFRC to determine its global warming potential in comparison to conventional concrete.

3. EMISSIONS ASSOCIATED WITH CONVENTIONAL REINFORCED CONCRETE

The construction of new buildings is a significant source of greenhouse emissions. The emissions are produced at various stages when building materials are processed, manufactured, and transported for construction. Concrete is a widely used building construction material and while some residential buildings are made of sustainable materials like wood and glass, concrete structures still dominate the commercial and industrial sectors. Particularly, concrete and steel production contribute significantly to global greenhouse gas emissions (Amiri et al., 2020; Davis et al., 2018).

Concrete structures are not only resilient and durable but are easy to build and relatively cheaper than other building materials. That's why reinforced concrete is commonly used for buildings ("Concrete Needs to Lose Its Colossal Carbon Footprint," 2021). About 70% of the global population lives in reinforced concrete buildings. Each year, 30 billion tonnes of concrete are used around the world (Monteiro et al., 2017). In the United States, more than 50% of low-rise buildings are constructed from concrete (*Buildings & Structures*, 2016).

A typical concrete is composed of hydraulic cement, water, fine and coarse aggregates, and chemical admixtures in a properly proportioned mixture. Concrete is categorized based on compressive strength and normal or conventional concrete has a compressive strength ranging from 20 to 40 MPa.

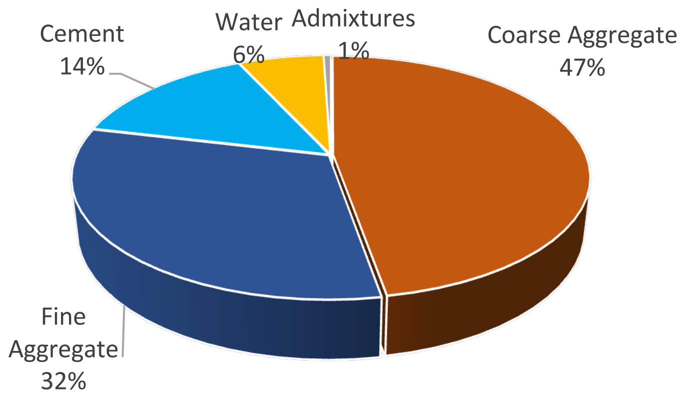

Figure 2: Composition of conventional reinforced concrete (RC) (Behravan et al., 2022)

Concrete is a composite material composed of 60-75% aggregates, 5-10% water and 10-15% cement. An important part of the cement making process entails heating the limestone to temperatures of 1500 °C, for a long period of time, producing high amount of carbon emissions (U.S. Geological Survey, 2020). 80% of the CO_2 generated during the concrete production, comes from this process. 822 kg of CO_2 is added to the environment for 1 ton of cement produced (Andrew, 2022).

From 1928 to 2018, cement production has generated an estimated 38 billion tonnes of total global greenhouse emissions. Of that amount, 71% was generated after 1990. In 2019 alone, 4.1 billion tonnes of cement was produced globally (Kuijpers, 2020). As of today, cement production generates the largest emissions of CO2 in the industrial sector, accounting for 8% of global CO2 emissions (2.8 Gtons/yr), and 2-3% of energy usage for fuel combustion (Ellis et al., 2020).

It's not surprising that concrete is increasingly being used for climate-resilient construction, as it is durable and long-lasting, but it comes at an environmental cost of a colossal carbon footprint. Cement production is projected to increase annually by 50% by 2050. The anticipated increase in greenhouse gas emissions and energy demand over the next 33 years would be additional 85–105 Gt of CO2 and energy demand of 420–505 TJ (equivalent to the combined global emissions from 2009 and 2010, and the world's primary energy supply in 2005) (Miller et al., 2016; Monteiro et al., 2017).

The sustainability standards and regulations are usually based on buildings' energy consumption and performance, causing the construction and maintenance pollution go undetected. More than half of a building's lifetime carbon emissions come from the embodied carbon, i.e., the CO_2 emitted during building construction. The embodied carbon is almost never taken into the account and needs to be addressed by shifting towards alternate building materials and UHPC.

4. REVIEW ON LIFE CYCLE ENVIRONMENTAL IMPACT ANALYSIS

Previous research work on UHPC focuses mostly on the mix design and mechanical properties. Very few works have been done to evaluate the environmental impact of conventional concrete and UHPFRC. As explained in the previous section, enormous amount of carbon emissions is generated during the concrete mixing, and cement production. The final built structure requires maintenance during all its lifetime. The emissions analysis of the maintenance is completely different and has been considered by some researchers while determining the global warming potential of conventional concrete and UHPC.

A life-cycle assessment (LCA) is an evaluation of the potential environmental impacts of a system during their entire life cycle. This helps understand how a process impacts the environment and is very beneficial for researchers, policy makers, and end users (Dong, 2018). In this paper, the life cycle of concrete is defined in two phases: construction and maintenance. The construction phase includes the production of individual components of concrete such as production of cement, aggregates, and chemical admixtures. After the production, the individual components are transported to the concrete mixing plant where they are mixed to produce concrete and this concrete is transported to the construction site where it is placed and cured. The curing duration of concrete is typically 28 days. The maintenance phase comprises of routinely monitoring the surface conditions, cracks, deformations, and signs of degradation of the concrete structure. If needed, repairs are performed to maintain the serviceability or if that is not possible, the structure is demolished, and the waste is recycled (Sameer et al., 2019).

In this section, a review is presented on the Life-cycle assessment of conventional concrete and UHPFRC. There can be several parameters to determine the environmental impacts of any materials such as global warming potential (GWP), acidification potential, eutrophication potential, and ozone depletion among others (Dong, 2018; Sameer et al., 2019). Since GWP is the most reported parameter, it is quantitively compared for conventional concrete and UHPFRC.

4.1 Global Warming Potential (GWP)

The global warming potential is chosen as the environmental indicator herein. The cumulative environmental impact in terms of CO_2 emissions of the infrastructure over its service life is expressed as global warming potential. It is measured in $kgCO_{2\,eq}$ which is the equivalent weight of CO_2 produced.

4.2 Construction Stage

The Global Warming Potential of UHPFRC and conventional concrete is compared quantitatively (Bertola et al., 2021; Dong, 2018; Rangelov et al., 2018; Sameer et al., 2019). It can be observed that in this stage, the GWP of UHPFRC is higher than conventional concrete.

Table 3: GWP comparison of UHPFRC and conventional RC in construction stage

Reference	**Application**	**Global Warming Potential ($kgCO_{2\,eq}$)**		
		Conventional RC	**UHPFRC**	**Percentage difference**
Dong 2018	Bridges	348	877	60%
Bertola et. al 2021	Bridges	7217	10914	66%
Sameer et. al 2019	Bridges	390	1700	77%
Rangelov et. al 2020	Bridges	434	1930	78%

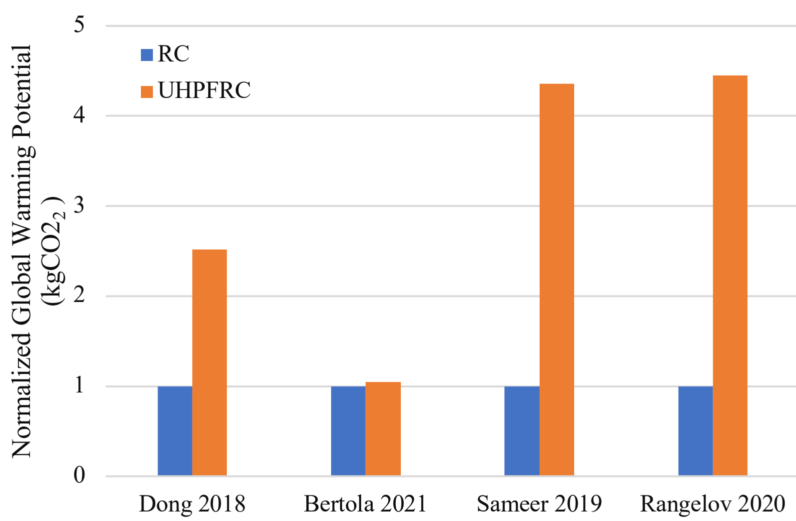

Figure 3: Normalized GWP comparison of UHPFRC and reinforced RC in construction stage

4.3 Cradle-to-Grave

In this stage, the maintenance phase of the life cycle is added which can span decades after construction depending on the specific application. It can be observed that the GWP of UHPFRC is considerably lower than conventional concrete in this phase. In the initial construction phase, the GWP of UHPFRC is higher than conventional concrete. This can be attributed to the increased cement usage in UHPFRC and the presence of steel fibers. As the cement content is much lower in conventional concrete, the GWP is also lower.

But as time goes on, maintenance issues begin to arise. Owing to its superior durability, the maintenance needs of UHPFRC are very low as compared to conventional concrete and hence, the life cycle GWP of UHPFRC is very low as compared to conventional concrete.

Table 4: GWP comparison of UHPFRC and conventional RC in cradle-to-grave stage

Reference	**Application**	**Global Warming Potential (kg$CO_{2\ eq}$)**		
		Conventional RC	**UHPFRC**	**Percentage reduction**
Dong 2018	Bridges	430,370	290,960	32%
Bertola et. al 2021	Bridges	15,878	11,236	29%
Sameer et. al 2019	Bridges	280,000	250,000	11%
Rangelov et. al 2020	Bridges	2,800,000	651,000	77%

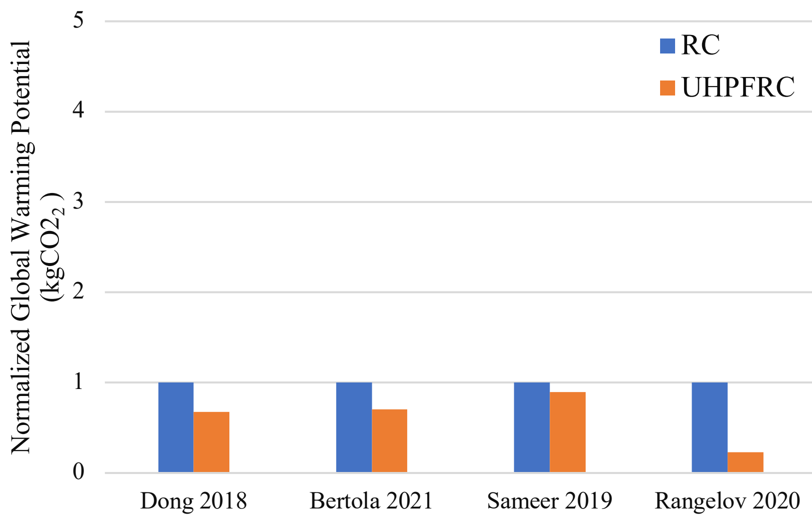

Figure 4: Normalized GWP comparison of UHPFRC and conventional RC in cradle-to-grave stage

Figure 3 gives a comparison of the life cycle GWP between UHPFRC and conventional concrete (Bertola et al., 2021). The GWP of UHPFRC hardly rises even after decades whereas the conventional concrete structure has undergone several maintenance routines in the same time period. This is because the conventional concrete is highly susceptible to damaging durability mechanisms such as alkali-silica reaction, carbonation, chloride penetration, and cracking among others. Because of the tight microstructure and dense particle packing, UHPFRC performs much better in terms of durability.

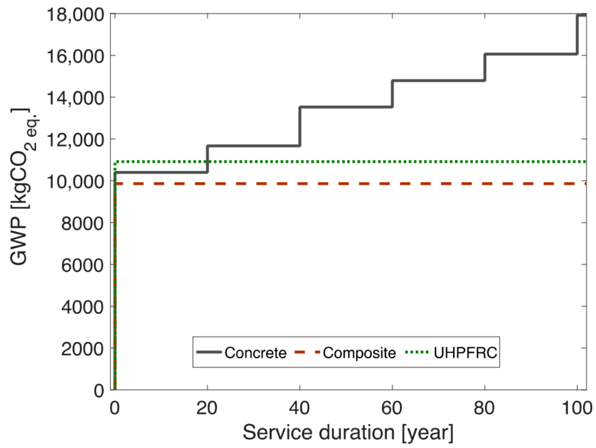

Figure 5: Influence of service duration on the environmental impact (Bertola et al., 2021)

5. CONCLUSIONS

The mechanical properties of UHPFRC are being widely researched with improvements being made in compressive, tensile, and durability properties. However, the environmental impacts are rarely considered. In this study, a review of the life cycle environmental impact analysis is presented which compares the Global Warming Potential (GWP) of conventional concrete to UHPFRC over a construction phase and cradle-to-grave phase. Based on the comparative life-cycle assessment, it can be concluded that although initial GWP of UHPFRC is higher than conventional concrete, UHPFRC requires significantly less maintenance and provides better durability in one lifespan which is from raw material acquisition to demolition. Although the initial GWP of UHPFRC is 60-80% higher than conventional RC, the reduction in GWP over a lifespan in UHPFRC ranges from 11-77% based on application and material design. As the service duration of concrete structure increases, the GWP of conventional concrete exceeds the GWP of composite of UHPFRC of similar capacity. Thus, UHPFRC is estimated to have lower GWP compared to conventional concrete. This comparative analysis is very relevant to current construction industry as a huge portion of USA infrastructure nears the end of its life-expectancy and require more frequent maintenances. Inclusion of UHPFRC in construction projects, despite its initial cost and high GWP, can prove beneficial and economical in the long term.

NOMENCLATURE

UHPFRC	Ultra High-Performance Fiber Reinforced Concrete	
RC	Reinforced Concrete	
GF	Glass Fibers	
GWP	Global Warming Potential	(kg $CO_{2\ eq}$)
PVA	Polyvinyl Alcohol	

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