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Evaluating the Sustainability of Ultra-high-performance Concrete Mixes: A Multi-criteria Life Cycle Assessment Incorporating Embodied Carbon and Energy

Hussain Abdulatif Karam, Ashraf A. Bahraq*, Mohammed A. Al-Osta, and Shamsad Ahmad

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ABSTRACT

Ultra-high-performance concrete (UHPC) represents a modern class of cementitious materials characterized by superior strength and durability. However, the high embodied carbon and energy of UHPC relative to those of normal concrete (NC) pose major sustainability challenges. This study presents a comprehensive evaluation of 40 UHPC mixes through an integrated life cycle assessment that incorporated embodied carbon, embodied energy, and compressive strength. The assessment focused on the raw material product, transportation, and maintenance stages and examined both local and global material-sourcing scenarios. The findings showed that UHPC produced locally in Saudi Arabia exhibited 3.28% to 8.21% higher embodied carbon and 1.33% to 4.34% higher embodied energy than its global equivalents, highlighting the need to optimize regional production practices. To evaluate sustainability from a performance-based perspective, an eco-strength index (ESI) was employed to capture the tradeoff between embodied carbon and compressive strength. The ESI values ranged from 7.3 to 14.9 kg·CO_2/MPa. A case study involving a single-girder bridge constructed with both UHPC and NC revealed that although UHPC exhibited a higher impact per cubic meter, its superior mechanical performance enabled material reduction, thereby lowering the total emissions per meter of bridge length. These results emphasize that when structural efficiency is considered, UHPC represents a sustainable solution for high-performance infrastructure applications.

Keywords: ultra-high-performance concrete, life-cycle impact assessment, embodied carbon, embodied energy, sustainable performance index, sustainability goals

1. INTRODUCTION

Construction industry growth in recent years has greatly increased the need for concrete with superior performance for various construction projects. Ultra-high-performance concrete (UHPC) is a novel class of concrete that exhibits high mechanical strength and durability and thus represents a promising option to meet this need[1]. UHPC is characterized by compressive and tensile strengths exceeding 120 MPa and 6.9 MPa, respectively, along with resistance to chloride attack and freeze–thaw cycles, compared to conventional concrete[2–4]. These superior properties are achieved via high amounts of binders and fine aggregates that increase the packing density, a low water-to-binder ratio, and the inclusion of specialized chemical admixtures and steel fibers[5].

Despite its superior mechanical properties, concerns regarding the environmental impact of UHPC have increased because of its high cement content compared with that of normal concrete (NC). Cement accounts for approximately 8% of all greenhouse gas emissions worldwide because of the exorbitant energy required to heat the raw materials used to produce cement[6]. Therefore, numerous researchers have investigated various mix designs to reduce the embodied carbon of UHPC. These designs include substituting cement with other binders such as fly ash, silica fume, and ground-granulated blast furnace slag to reduce the carbon footprint without compromising the mechanical properties[7].

The existing literature has primarily focused on optimizing the strength and enhancing the durability of UHPC blends, with few studies having investigated comprehensive sustainability assessment frameworks that account for environmental burdens alongside mechanical performance. Moreover, most life cycle assessment (LCA) studies on UHPC are confined to cradle-to-gate analyses and often overlook critical phases, such as transportation, maintenance, and structural efficiency. In addition, the influence of regional variability in material sourcing, particularly the environmental implications of locally manufactured materials, has rarely been addressed.

Therefore, in this study, we performed a multicriteria sustainability evaluation of 40 UHPC mixes that integrates embodied carbon, embodied energy, and compressive strength into a unified framework. The environmental sustainability of the UHPC formulations was evaluated by analyzing their embodied carbon and energy using the LCA method. A selection of UHPC mix designs from the existing literature was used to estimate their environmental footprints relative to that of NC to identify more sustainable alternatives. In addition, an eco-strength index (ESI) of the UHPC and NC mixes was used to assess both the environmental and mechanical performance, thus providing a balanced sustainability perspective that integrates structural efficiency and carbon footprint. To further capture the combined effects of environmental impact and structural efficiency, we propose a sustainable performance index. This index enables a more holistic comparison of UHPC mixes and supports the classification of their sustainability profiles based on performance trade-offs.

The remainder of this paper is structured as follows. Section 2 presents the research methodology adopted in this study; describes the UHPC criteria, life cycle inventory (LCI) analysis development and assumptions, life cycle impact assessment (LCIA) categories and methods, and ESI calculations; and presents a case study comparing UHPC and NC bridges. Section 3 presents a comparative analysis of the UHPC mixes that showcase the trends and influence of the raw materials, a comparison of the mixes with NC, a detailed analysis of the key contributors to environmental impact, a comparison of the eco-strength evaluation of UHPC and its tradeoffs, and a comparison of the environmental impact and long-term sustainability of both UHPC and NC bridges as part of the case study. Finally, Section 4 concludes the paper by summarizing the key findings, showcasing the implications and recommendations, and establishing a path for future research.

2. RESEARCH METHODOLOGY

2.1. Ultra-High-Performance Concrete Mixes. Criteria for source selection were used to ensure a fair and consistent comparison of the UHPC mixes. First, there were no restrictions on the year of publication. Although some sources were older, they contain mixed designs comparable to those in more recent literature. Second, only mixes composed of the following materials were used: Ordinary Portland Cement (OPC) as the primary cementitious material and silica fume (SF), natural pozzolan (NP), fly ash (FA), and ground granulated blast-furnace slag (GGBFS) as secondary cementitious materials. Quartz powder (QP) and fine aggregates were considered as filler materials, and superplasticizer (SP), steel fibers, and water were also included. These criteria ensured a fair and consistent application of environmental impact comparisons using the available EPDs. Finally, all selected UHPC mixes were required to have a minimum 28-day compressive strength of 120 MPa, as specified by ASTM C1856[8], which is commonly used to define UHPC[2–4].

Based on the above conditions, 40 UHPC and 3 NC mix designs were collected from the literature, as presented in Table 1 and Table 2. The selected mixes were established in various geographic regions, including North America, Europe, and Asia, and captured a broad spectrum of UHPC compositions. Each mix included detailed information on the raw material proportions facilitate consistent analysis of the environmental effects based on the raw material quantities. All mixes incorporated one or more supplementary cementitious materials (SCMs) and varying steel fiber and SP contents. The compressive strengths at 28 days ranged from 120 MPa to over 160 MPa, supporting broad high-stress structural applications. This dataset forms the basis for the LCA and ESI comparisons in the subsequent sections.

To evaluate the impact of material sourcing, this study distinguished between locally produced materials within the Kingdom of Saudi Arabia and imported materials that were sourced internationally. Internationally sourced materials generally exhibit lower environmental impacts at the raw material product stage (A1–A3) due to more efficient manufacturing practices (Figure 1). However, these benefits are partially offset by the additional environmental burden associated with long-distance transportation (A4). In contrast, local materials offer advantages in terms of logistics, availability, and supply chain resilience, particularly in responding to site-level demands or shortages. Of all the raw materials, only two had local EPDs: OPC and NP. Although some materials may have local manufacturing facilities, such as fine aggregate, local materials were considered the average of global materials and assigned zero transportation emissions. Therefore, in the comparisons of local and global UHPC mixes, the only factors that impacted the outcome of the LCA were OPC, NP, and transportation.

2.2. Life Cycle Assessment Framework. To evaluate the environmental performance of the proposed materials and mix designs, a structured LCA approach was developed. The following framework outlines the overall structure and boundaries adopted in this study's LCA, describing the stages, inclusions, and exclusions considered throughout the analysis. The LCA primarily followed a cradle-to-gate system boundary (raw material product stage, A1–A3), although downstream modules were also included, namely, the transportation of raw materials (A4) and maintenance-related activities (B2–B5) during the service life of the structure. Other life cycle phases, such as construction and installation (A5), use-phase operations (B1, B6, and B7), and end-of-life stages (C1–C4), were explicitly excluded from the analysis because their contributions were considered irrelevant or negligible.

2.3. Life Cycle Inventory Analysis. LCA measures environmental impact via a standardized framework through various steps of an item's life cycle, starting with the extraction of raw materials and ending with the demolition of structures. The LCA process includes several key phases according to ISO 14040[32]: defining the assessment's goals and scope, conducting a comprehensive LCI to gather data on resource use and emissions, performing an LCIA to evaluate the environmental consequences of these activities, and interpreting the results to reach meaningful conclusions[7]. Applying these standardized methods will help to estimate the emissions associated with UHPCs, thereby enabling the discovery of more viable options for enhancing sustainability.

LCI involves collecting data on all material inputs, specifically the associated carbon emissions and energy use of these inputs, and the outputs for the defined product system. This study's LCI focused exclusively on the constituent materials of the UHPC mixtures. The scope included raw material extraction and manufacturing as well as transportation to Dammam Port, Saudi Arabia for imported materials. Downstream processes such as mixing, placement, and end-of-life treatment were excluded. EPDs were used to obtain standardized, third-party verified environmental

Table 1. *UHPC mix designs, including their various proportions, 28-day compressive strength, and flow*

Ref.	Mix No.	Quantity (kg/m^3) OPC	SF	NP	FA	GGBFS	Fine Agg.	QP	SP	Water	Steel fiber	Compressive strength (MPa)	Flow (mm)
Li et al.[1]	1	856.5	214.1	-	-	-	1177.5	-	19.7	184	120	157.0	n/a
Ha et al.[9]	2	625	250	-	-	375	1100	-	70	170	156	151.3	n/a
	3	1000	250	-	-	-	1100	-	70	170	-	159.3	n/a
Regalla and Kumar[10]	4	712	231	-	-	-	1020	211	24.92	178	-	144.0	240
Huang et al.[11]	5	488.8	135.2	-		416	1114	-	26	187.2	-	125.0	225
Du et al.[12]	6	470.7	-	-	108.3	433.3	990	-	4.2	232.4	156	120.0	n/a
Abdolpour et al.[13]	7	697	190	-	150	-	1068	-	25	182	79	153.6	220
	8	820	190	-	150	-	1068	-	25	182		168.7	290
Nassar et al.[14]	9	780	95	-	-	35	1185	-	18.2	195	22.75	143.2	219
Shafieifar et al.[15]	10	712	231	-	-	-	1020	211	30.7	109	156	138.0	n/a
Alsalman et al.[16]	11	1044	261	-	-	-	1212	-	113.7	261	-	158.0	200
Dingqiang et al.[17]	12	900	125	-	-	-	1060	-	36	180	-	130.0	212
Hasnat and Ghafoori[18]	13	991	70	-	-	-	1174	-	13.6	216	156	143.0	244
	14	881	31	-	122	-	1174	-	18.3	205	234	136.0	248
	15	660	47	-	81	120	1174	-	13.7	184	156	131.0	245
Shi et al.[19]	16	744	159	-	159		1169	-	19.1	181	120	124.0	240
	17	641	160	-	-	267	1175	-	14.3	182	120	138.0	240
Li et al.[20]	18	872	261	-	-	131	1046	-	51	240	156	158.6	n/a
Ahmad et al.[21]	19	900	165	55	-	-	1021	-	40	163	157	154.8	198
	20	810	220	90	-	-	1002	-	40	163	157	157.2	201
Al-Osta et al.[22]	21	900	220	-	-	-	1005	-	40	163	157	149.5	200
Ahmad et al.[23]	22	1000	250	-	-	-	818	-	44	188	157	137.0	200
	23	1000	250	-	-	-	784	-	25	219	157	135.0	200
Ahmad et al.[24]	24	900	220	-	-	-	1005	-	40	162	157	161.0	230
	25	900	88	132	-	-	1042	-	40	162	157	150.0	195
	26	900	88	-	132	-	1005	-	40	162	157	158.0	210
Wu et al.[25]	27	792	264	-	-	-	1056	-	21.1	173	156	158.8	n/a
Mousavinezhad et al.[2]	28	839	104	-	83	21	920	-	62.3	147	119	134.5	370
	29	839	104	-	62	42	921	-	65.3	147	119	132.5	370
Randl et al.[26]	30	401	124	-	-	328	833	211	30	170	155	139.4	285
	31	401	124	-	328	-	833	397	30	170	155	124.7	290
Wu et al.[27]	32	729	124	-	-	-	833	397	30	170	155	166.1	280
	33	863	216	-	-	-	923	-	92.79	194	156	153.6	240-250
Wu et al.[28]	34	472	262	-	-	315	1049	-	21	178	157	125.8	227
	35	792	264	-	-	-	1056	-	21.1	173	156	149.8	n/a
	36	475	264	-	-	317	1056	-	21.1	173	156	144	n/a
	37	317	264	-	475	-	1056	-	21.1	173	156	142.5	n/a

(Continued)

Table 1. *Continued*

Ref.	Mix No.	Quantity (kg/m^3)										Compressive strength (MPa)	Flow (mm)
		OPC	SF	NP	FA	GGBFS	Fine Agg.	QP	SP	Water	Steel fiber		
Feng et al.[29]	38	833.3	208.3	-	-	-	1041.6	-	31.3	193.7	152.9	127.61	200
Tafraoui et al.[30]	39	691	172	-	-	-	759	276	22	187.3	138	155	n/a
Guo et al.[30]	40	565.1		-	-	780.4	780.4	-	40.5	225.1	117	134.2	280

Table 2. *NC mix designs*

Ref.	Class	Quantity (kg/m^3)					
		OPC	SF	Fine aggregates	Gravel	SP	Water
Han et al.[31]	C40	400	0	700	1125	0.116	152
	C60	400	0	700	1125	0.166	120
	C80	600	67	550	800	0.266	173.42

data for each material. These documents were sourced from recognized platforms, including the International EPD System, EPD Hub, and manufacturer websites depending on the material type and regional availability[33]. Transport distances were treated as a key assumption in this analysis. For locally sourced materials, transport distances were assumed to be negligible. For globally sourced materials, only port-to-port maritime shipping was considered. Saudi Arabia was selected as the case study location because of its prominent position in the Middle East and ambitious Vision 2030 development agenda. The Kingdom is undertaking numerous giga-projects that demand high-performance concrete solutions, including UHPC, making it a strategically relevant context for environmental assessment.

The analysis included both local and global sources to represent real-world sourcing scenarios. Internationally sourced materials frequently offer greater consistency and purity, whereas locally sourced materials support regional supply chains and exhibit lower transportation-related emissions. Evaluating both options allows for a more thorough understanding of the environmental tradeoffs in the UHPC formulations. Table 3 lists the average embodied carbon and energy of the materials collected from the respective EPDs (A1–A3 scope). Figure 1 presents a comparative analysis of the average environmental impacts of OPC production from local and global sources. The results indicate that local OPC production in Saudi Arabia exhibits a higher global warming potential (GWP) (approximately 900 kg·CO_2/t) and total energy use (1600 MJ/t) than its global counterparts, which include factories from the USA, UK, and Europe. Although global factories also have considerable environmental loads, their mean GWP and energy use are lower, suggesting more efficient production technologies or cleaner energy inputs. This highlights the need for targeted improvements in regional cement manufacturing to align with the global sustainability benchmarks. Furthermore, this disparity in the impact of OPC production plays a critical role in the LCA of UHPC mixes, as OPC is a primary contributor to the overall embodied carbon and energy. This influence is discussed further in the subsequent sections of this study.

Table 3. *Average embodied carbon and energy of the materials collected from respective EPDs (A1–A3 scope)*

Material	GWP (Kg·CO_2/kg)	Total energy* (MJ/kg)
OPC	0.8983	5.272
SF	0.3435	5.773
NP	0.205	3.097
FA	0.0348	0.415
GGBFS	0.2045	2.549
Fine aggregate	0.00201	0.043
QP	0.0232	0.817
SP	0.8045	17.773
Steel fibers	2.275	27.308

*Total energy is the sum of renewable primary, renewable secondary, non-renewable primary, and non-renewable secondary.

2.4. Life Cycle Impact Assessment.

A typical LCIA includes a range of environmental indicators such as GWP, energy use, ozone depletion potential, acidification potential, and water deprivation potential. In this study, GWP and energy use were selected as the primary LCIA indicators and determined across the entire life cycle of the UHPC mixes, thereby

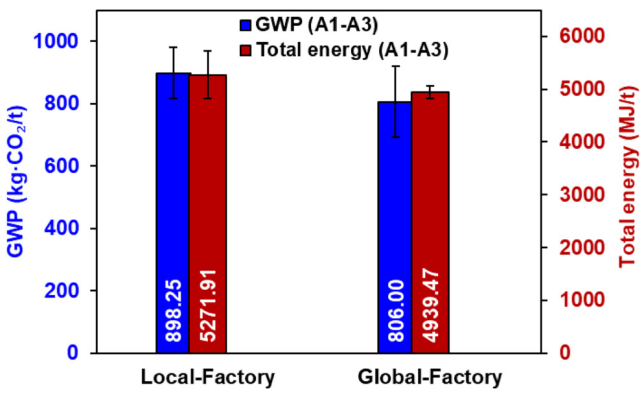
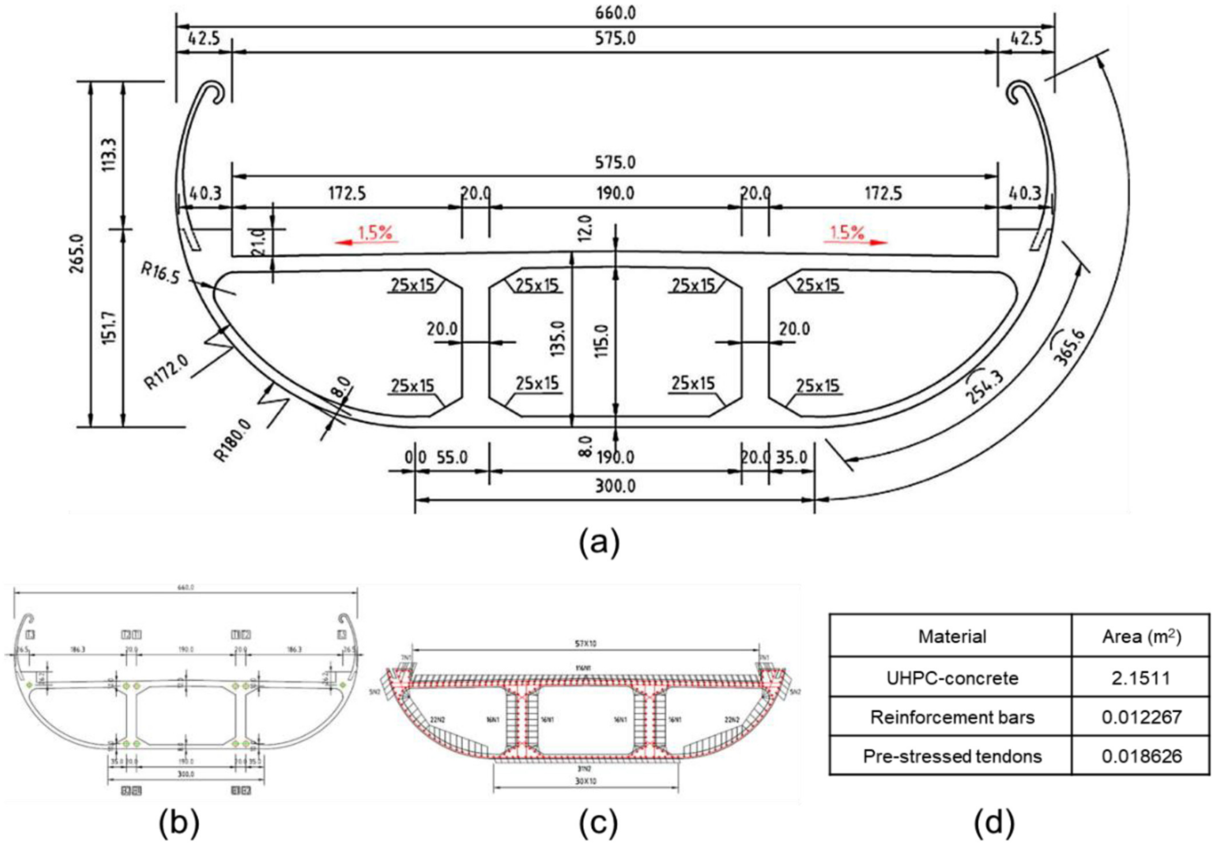


Figure 1. Comparison of average GWP and total energy consumption (A1–A3 scope) for OPC produced by local and global factories



Material	Area (m^2)
UHPC-concrete	2.1511
Reinforcement bars	0.012267
Pre-stressed tendons	0.018626

Figure 2. UHPC bridge: (a) Cross-section; (b) Configuration of pre-stressed tendons; (c) Details on the reinforcement bars; and (c) Cross-sectional areas of materials used in the bridge design (Adopted from Dong[34] with modification)

encompassing the manufacturing, transportation, and maintenance phases. A functional unit of 1 m^3 of concrete was adopted for all LCIA calculations. The results were subsequently compared to identify the concrete mix with the lowest environmental footprint based on the ESI.

The GWP and embodied energy of the manufacturing phase were determined by calculating the infrastructure's cumulative CO_2 emissions and energy use for each mix. The embodied carbon (kg·CO_2/m^3) and embodied energy (MJ/m^3) associated with concrete (EC_{manu} and EE_{manu}, respectively) were calculated as follows[34]:

$$EC_{manu} = \sum_{i=1}^{n} m_i \cdot cf_i \tag{1}$$

$$EE_{manu} = \sum_{i=1}^{n} m_i \cdot ef_i \tag{2}$$

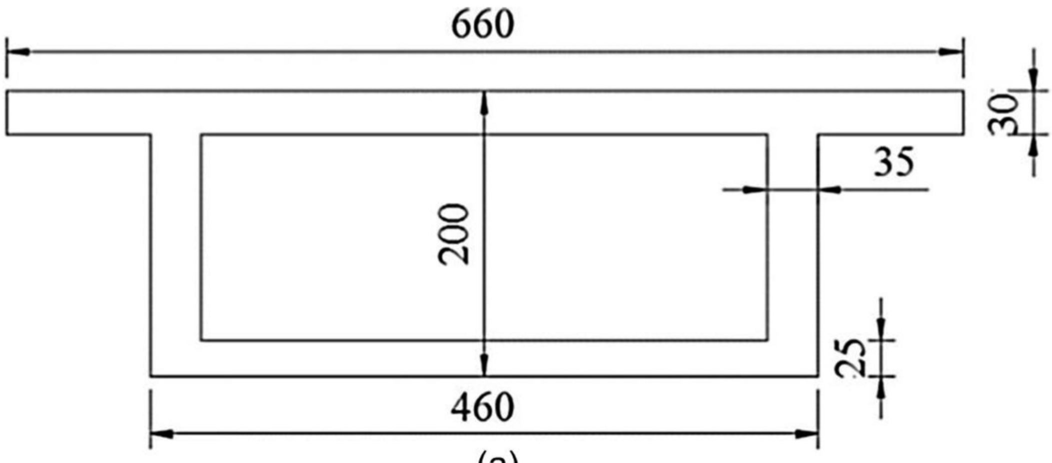
where m_i is the amount of constituent materials in the concrete mix (kg/m^3); cf_i and ef_i are the CO_2 emissions and energy use factors associated with the manufacturing of constituent material *I*, respectively (Table 3); and *n* is the number of constituent materials within the concrete. For a typical UHPC mix, the total CO_2 emissions and energy expenditure associated with the production phase of the concrete can be calculated as long as the CO_2 emissions and energy expenditure factors are known.

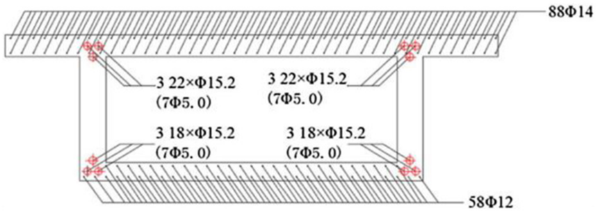
The CO_2 emissions of the transportation phase were determined based on the assumptions that all global materials are shipped by large container vessels from nearby ports and emissions within a country are negligible. The CO_2 emissions associated with transportation were calculated using the following formula:

$$EC_{trans} = \sum_{i=1}^{n} m_i \cdot d_i \cdot T \tag{3}$$

where m_i is the amount of constituent materials in the concrete mix (kg/m^3); d_i is the average distance from ports close to multiple manufacturing facilities for material *i* (km) to Dammam Port in Saudi Arabia; and *T* is the CO_2 emissions factor associated with very large container vessels, which is equivalent to 0.003 kg·CO_2/ton·km[35].

Over time, all buildings deteriorate and corrode and thus require maintenance to prevent their structural performance from deteriorating. This type of maintenance can be minor or major. Minor maintenance can halt or slow down a structure's degeneration, whereas major maintenance is performed when the structure's corrosion reaches a certain threshold at which performance is compromised and requires immediate attention[36]. For example, if a bridge's corrosion reaches the point at which the structural performance is affected, then essential maintenance is applied to reverse this process. The embodied carbon linked to





Material	Area (m²)
NC-concrete	4.145
Reinforcement bars	0.020106
Pre-stressed tendons	0.033360

(b)

Figure 3. NC bridge: (a) Cross-section; (b) Details of pre-stressed tendons and reinforcement bars; and (c) Cross-sectional areas of materials used in bridge design (Adopted from Dong [34] with modification)

maintenance was expressed using the following formula [34]:

$$EC_{main} = \sum_{i=1}^{n} EC_{ini} \cdot r_{m,i} \tag{4}$$

$$EE_{main} = \sum_{i=1}^{n} EE_{ini} \cdot r_{m,i} \tag{5}$$

where EC_{ini} is the initial embodied carbon associated with manufacturing and transport and $r_{m,i}$ is the ratio between the embodied carbon of maintenance action i and the embodied carbon of EC_{ini}. In this study, the maintenance period was 80 years, which is considered the average life expectancy of an NC bridge [37]. The maintenance interval was set at 20 years for UHPC bridges and 10 years for NC bridges, based on previous studies [34]. The maintenance ratio $r_{m,i}$, is defined as 0.1 for minor maintenance and 0.5 for major maintenance activities [34]. Given the superior durability and longer service life of UHPC, these structures were assumed to require only minor maintenance throughout the analysis period. In contrast, NC bridges are expected to undergo major maintenance every fourth cycle [34,38], thus reflecting their higher vulnerability to deterioration over time.

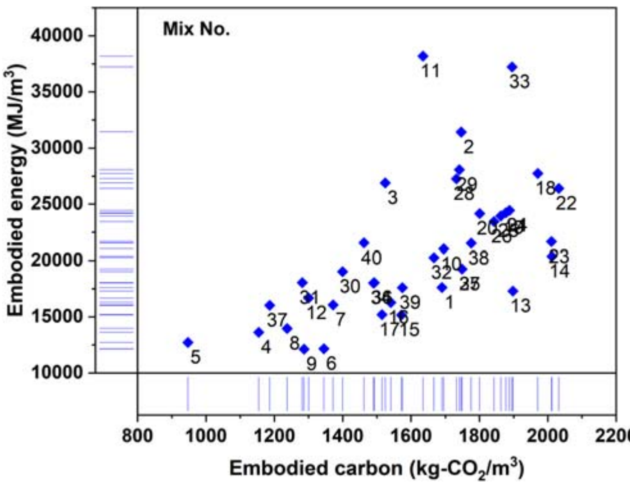


Figure 4. LCA plot of UHPC mixes (each point is labeled by the mix number)

2.5. Eco-Strength Index Calculation.

Another metric used in this study to compare the UHPC mixes was the ESI, which measures the total embodied carbon over the strength in MPa at 28 days. The ESI is calculated as follows [39]:

$$ESI = \frac{EC}{f_c'} \tag{6}$$

where EC is the total embodied carbon over the concrete's lifecycle and f_c' is the 28-day compressive strength of the concrete, expressed in MPa. This index offers a combined perspective on environmental and mechanical performance. A higher ESI indicates that a mix emits a larger amount of CO_2 per unit strength, suggesting lower environmental efficiency. Conversely, a lower ESI reflects a more sustainable mix that achieves higher strength with a smaller carbon footprint. When comparing concrete mixes, a lower ESI is preferred because it signifies the potential to construct high-strength environmentally efficient structures with reduced carbon emissions. In addition to the ESI, this study analyzed the relative contributions of embodied carbon, embodied

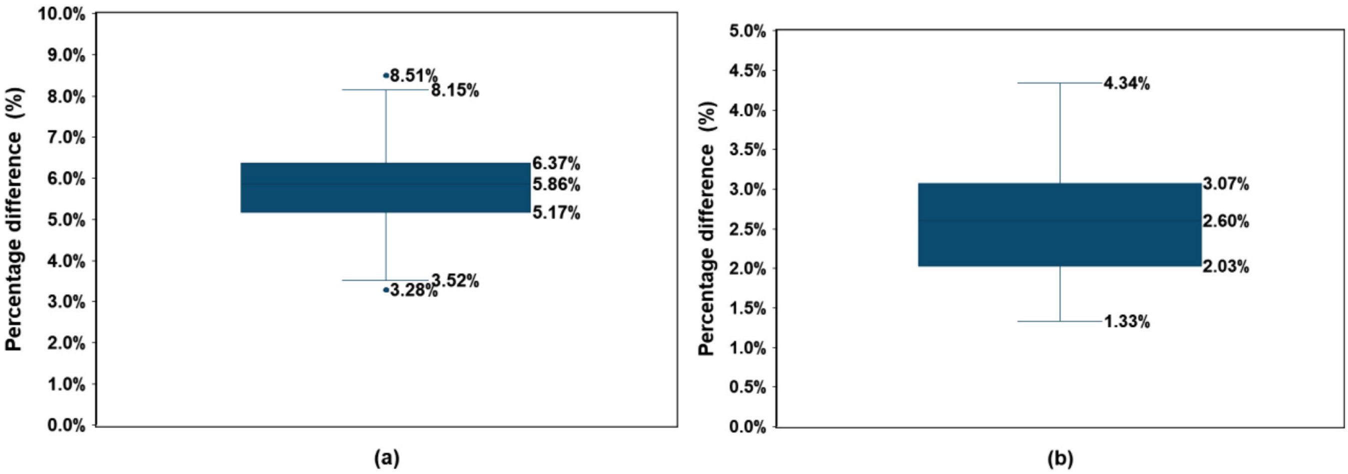


Figure 5. Percentage difference in the sustainability performance of UHPC mixes using locally sourced materials compared to global sources: (a) Embodied carbon and (b) Embodied energy

energy, and compressive strength to provide a comprehensive perspective on the sustainability of UHPC mixes.

2.6. Case Study: Ultra-High-Performance Concrete vs. Conventional Bridge. The case study examined the UHPC and NC bridges reported by Dong[34]. The previously described LCA techniques were applied to both bridges to evaluate and compare their environmental performance. The UHPC bridge was designed as a single-girder structure with a cross-sectional width of 6.6 m (Fig. 2), and its prestressed tendons and reinforcement layout are detailed in Fig. 2(b–c). In contrast, the NC bridge features a different cross-sectional geometry and reinforcement configuration (Fig. 3). Owing to the lower mechanical performance of NC compared to UHPC, the NC bridge required a larger cross-sectional area to carry equivalent loads.

Using the previously defined equations, the embodied carbon and energy of both the UHPC and NC bridges can be calculated. The cross-sectional areas of the materials, including concrete, prestressed tendons, and reinforcement, in each bridge are shown in Fig. 2(d) and 3(b). These areas were multiplied by the corresponding unit LCA values for UHPC and NC to compute the total environmental impact per unit length of the bridge. This method enables a direct comparison of the two materials and facilitates the assessment of the environmental performance across any bridge length.

3. RESULTS AND DISCUSSION

3.1. Comparative Analysis of the Ultra-High-Performance Concrete Mixes. The indices presented in Section 2 were calculated, and the results were analyzed to identify key trends. Figure 4 shows the outcomes of the embodied carbon and energy of all 40 UHPC mixes considered in this study. The marginal distributions along the axes represent the density of the mixes in terms of their respective embodied environmental burdens. A notable observation was the variation in

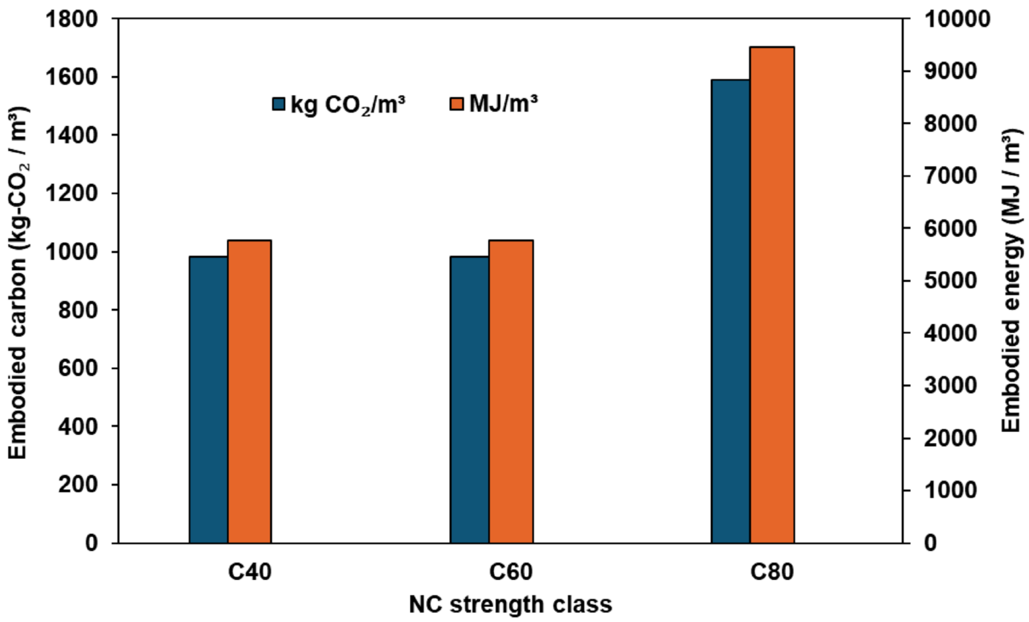


Figure 6. Total embodied carbon and energy for NC mixes at different strength classes

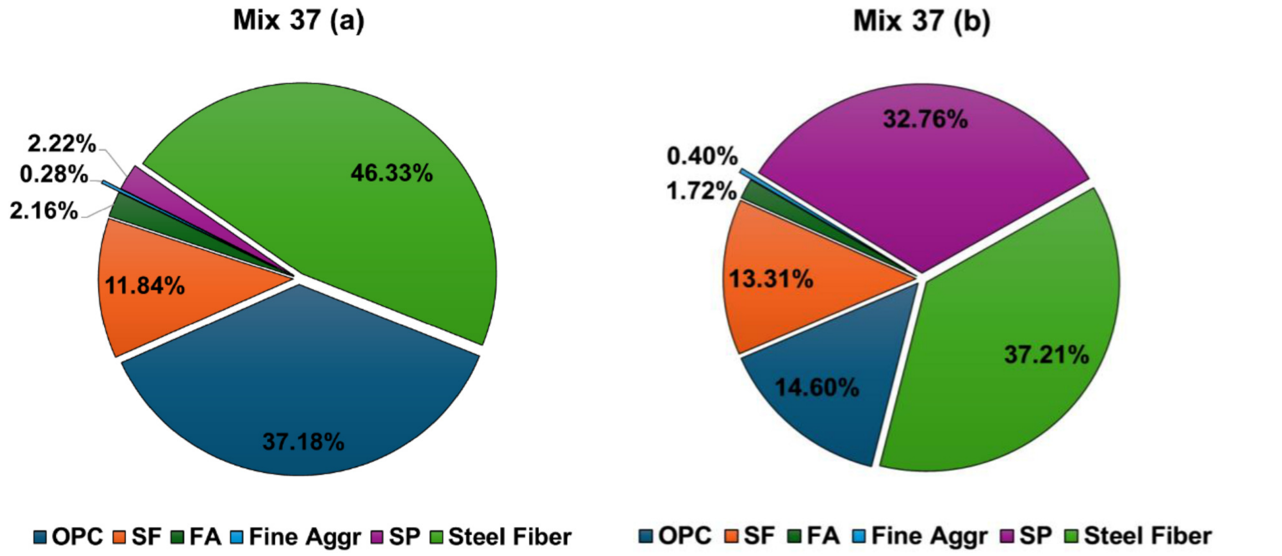


Figure 7. Proportional contribution of each material to the environmental impact of UHPC Mix-37: (a) Embodied carbon and (b) Embodied energy

embodied carbon among the UHPC mix designs, which ranged from 947.5 to 2032.2 kg CO2/m^3. Moreover, the embodied energy values ranged from 12,120.5 to 38,185.9 MJ/m^3. Mixes 4, 5, and 37 exhibited the lowest embodied carbon values, whereas Mixes 14, 22, and 23 exhibited the highest. Mixes 5, 6, and 9 (located in the lower-left quadrant) presented the lowest embodied energy values, whereas Mixes 2, 11, and 33 (located in the upper-right quadrant) presented the highest values.

The LCA conducted on the UHPC mixes revealed that OPC and steel fibers had the highest impact on embodied carbon. Mixes that contained high amounts of OPC and steel fibers exhibited the highest carbon emissions. Meanwhile, mixes produced with a lower OPC content but higher SCM content achieved significant results, even outperforming some mixes with higher embodied carbon.

A comparison of the local and global UHPC mixes showed that only OPC and NP were locally available; therefore, only these materials affected the LCA results. Although local fine aggregate was available, local EPDs were not found; consequently, global EPDs were used to estimate its embodied carbon and energy. Thus, both local and global fine aggregate were comparable. A comparative analysis of the local and global UHPC mixes indicated that local mixes exhibited 3.28–8.51% higher embodied carbon and 1.33–4.34% higher embodied energy throughout the LCA (Fig. 5). These differences in embodied carbon and energy are substantial but may not represent the best option when considering costs or material availability. As such, improving the carbon efficiency of OPC factories within the Kingdom is the best course of action for creating readily available carbon-efficient UHPC mixes.

To identify the most environmentally friendly concrete, the LCAs of both UHPC and NC were compared. The C40 and C60 grades of NC exhibited nearly identical LCA results, with values of approximately 981.0 kg·CO_2/m^3 for embodied carbon

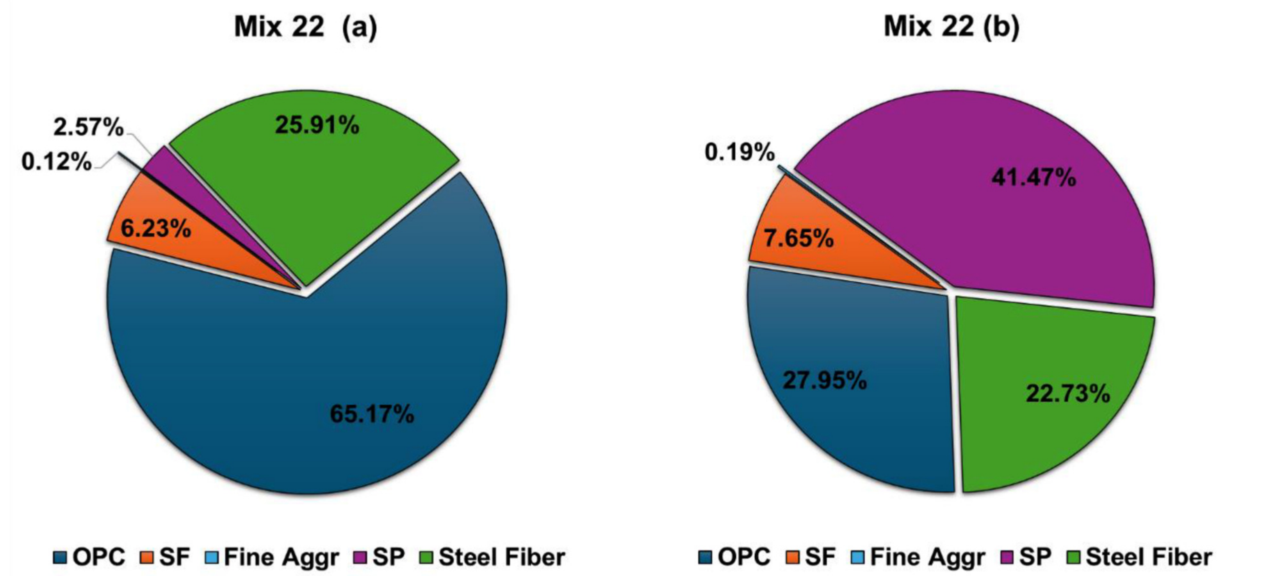


Figure 8. Proportional contribution of each material to the environmental impact of UHPC Mix-22: (a) Embodied carbon and (b) Embodied energy

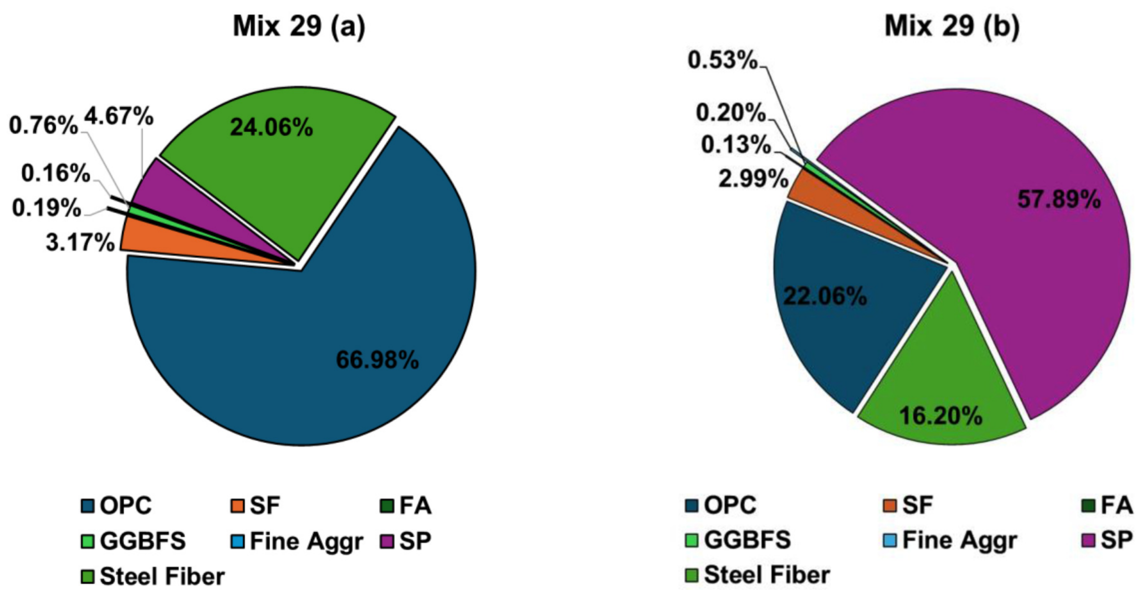


Figure 9. Proportional contribution of each material to the environmental impact of UHPC Mix-22: (a) Embodied carbon and (b) Embodied energy

and 5780 MJ/m^3 for embodied energy (Figure 6). In contrast, the C80 mix showed a significantly higher environmental impact, with 1590.9 kg·CO_2/m^3 and 9452.8 MJ/m^3. In terms of embodied energy, all three NC grades exhibited lower values than the UHPC mixes. In terms of embodied carbon, both C40 and C60 exhibited lower emissions than most of the UHPC mixes, with the exception of Mix 5. The C80 mix fell within the range of UHPC values, outperforming some UHPC mixes while being outperformed by others. Of note, this comparison was based on equal volumes of concrete. However, in practice, a UHPC structure requires less material than an equivalent NC structure owing to its superior strength. Therefore, these results provide only an initial comparison, while the case study offers a more accurate evaluation of the relative environmental efficiencies of UHPC and NC.

3.2. Key Contributors to Environmental Impact.

Identifying the materials that contribute most significantly to the embodied carbon and energy of the UHPC mixtures is critical for improving environmental performance without compromising strength. The targeted reduction of high-impact components and use of alternative materials are essential steps toward achieving more sustainable UHPC mix designs. A major contributor to the material's environmental impact is the production stage within the A1–A3 scope.

Among the UHPC components, OPC exhibited the highest carbon emissions at 0.8983 kg·CO_2/kg. Owing to the large demand for OPC and its substantial carbon footprint, OPC accounts for 5–7% of global CO_2 emissions[40]. The production of OPC is energy-intensive and requires kiln temperatures exceeding 1300 °C, typically achieved by burning fossil fuels[41]. In contrast, SCMs, including SF, NP, FA, and GGBFS, exhibit considerably lower embodied carbon, making them suitable substitutes for OPC. In contrast, filler materials such as fine aggregate and QP have very low emissions and thus do not require substitution. Superplasticizers have relatively high embodied carbon.

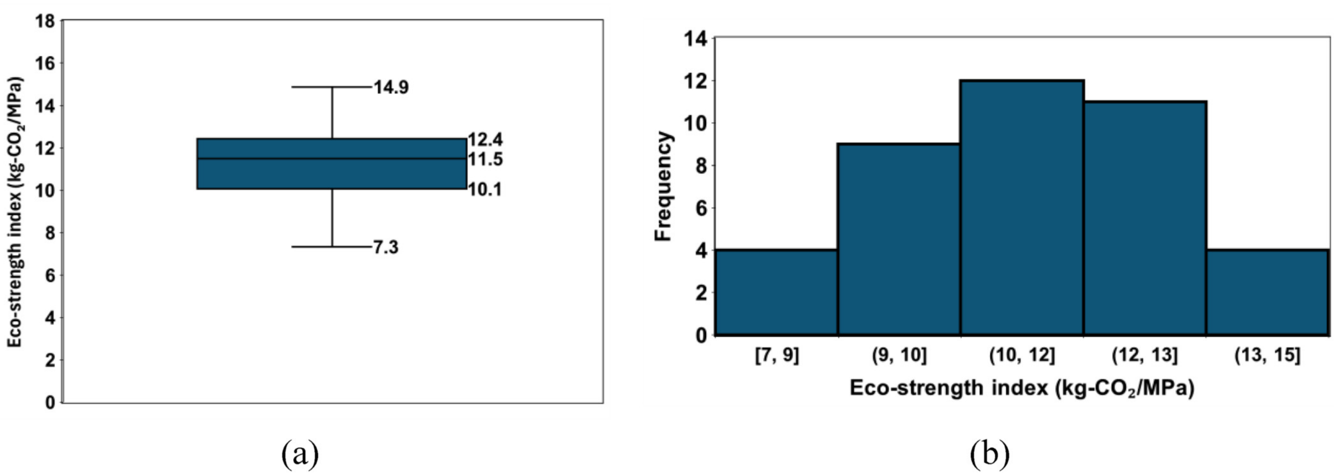


Figure 10. Analysis of the eco-strength index values of the UHPC mixes: (a) Median of the index values and (b) Histogram representing the frequency distribution of the index values

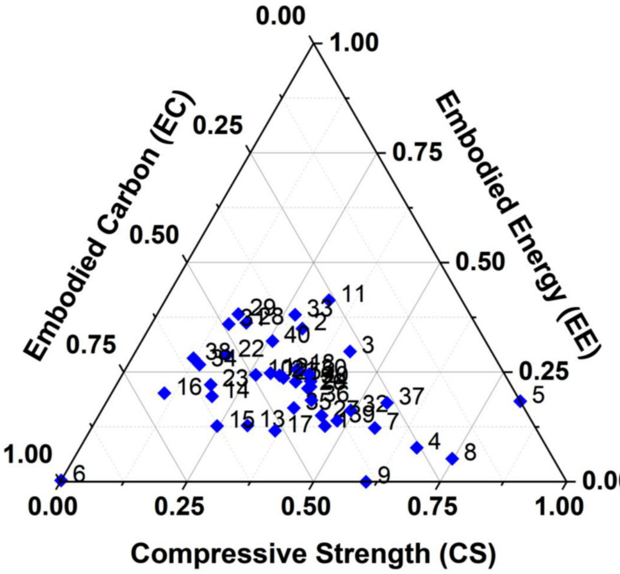


Figure 11. Ternary plot showing the normalized contributions of embodied carbon, embodied energy, and compressive strength for the UHPC mixes

However, given the small dosage required for UHPC and the limited availability of alternatives, the replacement of superplasticizer is not a priority. Steel fibers are the most environmentally intensive components in terms of both embodied carbon and energy because their manufacture requires high thermal energy to form and shape the material, typically through fossil fuel combustion[42].

Based on these data, the most effective strategy for reducing the environmental impact of UHPC is to minimize the use of OPC and steel fibers. This aligns with current UHPC mix design research trends that focus on substituting OPC with low-carbon alternatives. A representative example is Mix 37, which uses 317 kg/m^3 of OPC, 264 kg/m^3 of SF, and 475 kg/m^3 of FA, yielding an OPC-to-SCM ratio of approximately 3:7 (Table 1). Despite its high SCM content, Mix 37 achieved a compressive strength of 142.5 MPa. This mix achieved one of the lowest proportions of CO_2 and energy attributed to OPC among all the collected mixes, making it a strong candidate for eco-efficient design (Figure 7). Although the SCMs investigated in this study are limited, other viable options include limestone powder, rice husk ash, metakaolin, and recycled glass powder[9,30,43–52]. Similarly, steel fibers can be replaced with more sustainable alternatives, such recycled tire-based materials, to further reduce the environmental impact[4,7,53]. With the environmental contributions of the individual materials identified, the next step was to assess which components most strongly influenced the overall footprint of the UHPC mixes. Figure 8 illustrates a high-impact UHPC mix (Mix 22), where OPC contributes the most to embodied carbon, followed by steel fibers. In terms of embodied energy, SP was the leading contributor, followed by OPC and steel fibers. Figure 9 presents a different UHPC mixture for comparison. The figures reveal that OPC and steel fibers are the dominant contributors to embodied carbon while SP, OPC, and steel fibers are the dominant contributors to embodied energy. These insights further support the strategy of material substitution and optimization in UHPC mix design.

3.3. Sustainability Evaluation of the Ultra-High-Performance Concrete Mixes. This section compares the UHPC mixes based on their ESI to understand their overall performance in terms of environmental and engineering aspects. As a lower value indicates better eco-efficiency, the mixes can be ranked based on their ESI to identify the mixes that offer the best balance between strength and environmental impacts. Figure 10 presents an analysis of the calculated ESI values, which range from 7.3 to 14.9 kg·CO_2/MPa, with a median of 11.5 and an interquartile range between 10.1 and 12.4. The histogram shown in Fig. 10(b) further reveals that most mixes fall within the range of 10–13 kg·CO_2/MPa. Only a few mixes exhibited considerably higher or lower index values, which reflected exceptional or poor eco-efficiency. These insights can guide the identification of candidate mixes for optimization or substitution strategies based on their environmental-to-strength performance ratios.

Of the 40 mixes, Mix 8 had the lowest index value of 7.3, making it the most eco-efficient, and it was followed by Mixes 6 (7.6), 4 (8.0) and 37 (8.3). Although these latter mixes were not necessarily the weakest or strongest in performance, they had a low environmental impact relative to their strength. Thus, they can be considered ideal options for sustainable construction, where reducing carbon emissions is a priority. In contrast, several mixes displayed high ESI values, indicating a lower eco-efficiency. For example, Mix 23 and Mix 24 have index values of 14.9 and 14.7, respectively, which are the highest in the dataset. Despite their moderate strengths (135 MPa and 141 MPa), the emissions associated with each strength unit were relatively high. Mixes 13 (13.3) and 28 (12.9) also fell into this category.

Notably, some mixes with high compressive strengths were also relatively eco-efficient, whereas others were not. For example, Mix 3 had one of the highest compressive strengths (159.3 MPa) and a good ESI (9.6), indicating that it delivers substantial performance with reasonable environmental efficiency. In contrast, Mix 2 had a slightly lower strength (151.3 MPa) but a worse ESI (11.5), indicating that it was less efficient in terms of emissions per unit of strength. Meanwhile, Mix 6 and Mix 8 had lower compressive strengths (125.3 MPa and 120.6 MPa, respectively) and the lowest ESI values (7.6 and 7.3, respectively). Therefore, these mixes represent the most sustainable option overall, although they would not necessarily be ideal when strength is also required. These comparisons revealed that the most sustainable UHPC mixtures were not always the strongest. Instead, the best performers achieved a balance, offering reasonable compressive strength while minimizing environmental impact.

To enable a comprehensive assessment of the sustainability performance of UHPC mixes, this study proposes a sustainable performance index (SPI), which serves as a tool to classify and compare different formulations. A ternary plot was produced using the normalized contributions of embodied carbon, embodied energy, and compressive strength for the 40 mixes analyzed (Fig. 11). Each data point in the plot represents a mix, with its position reflecting the relative balance of environmental impact and mechanical performance, which was constrained such that the sum of the three variables equals unity. This visualization enables a simultaneous comparison of trade-offs and supports the classification of mixes into three distinct zones:

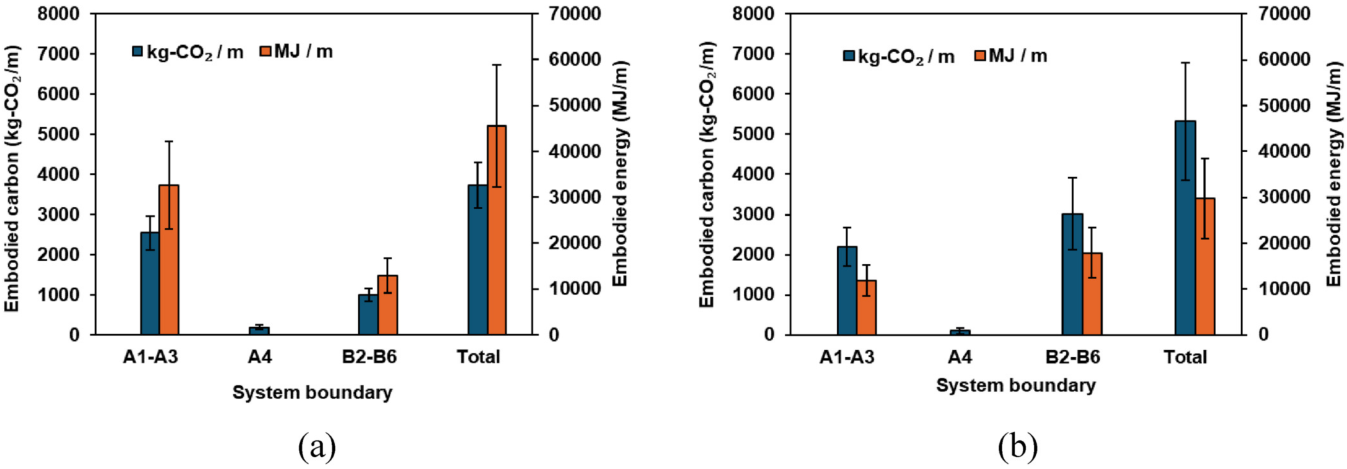


Figure 12. LCA results in terms of embodied carbon and embodied energy across different stages for the two bridge types per meter of span: (a) UHPC and (b) NC

Zone-I: optimized mixes (characterized by high strength and low environmental impact); Zone-II: balanced trade-offs (including mixes with either high strength and high environmental cost or moderate performance across all metrics); and Zone-III: environmentally intensive mixes (marked by low strength and/or high environmental burden).

The distribution of data points shows a concentration of mixes near the center of the ternary diagram, suggesting that many formulations achieved a balance among strength, carbon, and energy metrics. Exceptions were observed in the lower-impact region of the ternary plot, where Mixes 4, 5, and 8 demonstrate moderate to high compressive strength combined with comparatively low embodied carbon and energy. These mixes reflect a favorable trade-off, thus offering environmentally efficient performance without a significant compromise in strength. As such, they align with the criteria for Zone-I, which reflects balanced sustainability, and illustrate how well-optimized UHPC formulations can achieve both reduced environmental impact and adequate structural capacity. In contrast, Mix 6 was situated closer to the embodied carbon vertex, indicating a high carbon footprint relative to its strength. This mix also recorded the lowest compressive strength among all the formulations, which indicates inefficiencies in material utilization and reinforces its classification within Zone-III. Among the most promising formulations was Mix 37, which was located toward the compressive strength-dominant region but also maintained moderate embodied carbon and embodied emission values. Although this mix contained the lowest OPC content (317 kg/m^3), it achieved impressive compressive strength (142.5 MPa). This demonstrates the potential of the optimized binder systems to deliver environmentally efficient and structurally robust UHPC. Accordingly, Mix 37 is representative of the Zone-I category and exemplifies a well-balanced and sustainable concrete mix.

3.4. Case Study Insights: Ultra-High-Performance Concrete vs. Normal Concrete Bridge. The case study compared the environmental impacts of UHPC and NC bridges across different life cycle stages. The UHPC bridge demonstrated an average impact of 2541.5 kg·CO_2/m and 32,615.3 MJ/m for the A1–A3 phase (material production), 186.3 kg·CO_2/m for

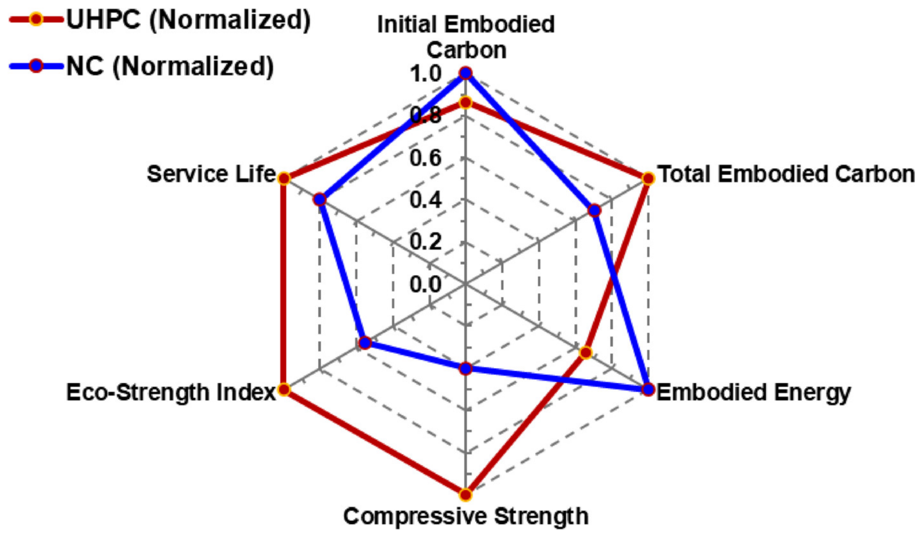


Figure 13. Performance-based comparison of UHPC and NC across six sustainability and structural metrics. Values are normalized relative to the best-performing value in each category

Table 4. *Performance-based indicators for UHPC vs. NC bridges*

Indicator	UHPC bridge	NC bridge	Interpretation
Initial embodied carbon (A1–A3)	High (~2,500 kg·CO_2/m)	Lower (~2,200 kg·CO_2/m)	NC has lower production emissions
Total embodied carbon (A1–B6)	Lower (~3,724 kg·CO_2/m)	Higher (~5,320 kg·CO_2/m)	UHPC is better over full life cycle
Total embodied energy	Higher (~45,500 MJ/m)	Lower (~30000 MJ/m)	UHPC more energy-intensive upfront
Compressive strength	High (120–170 MPa)	Moderate (40–80 MPa)	UHPC structurally superior
Eco-strength index	Low-favorable (11.3 kg·CO_2/MPa)	Moderate (20.3 kg·CO_2/MPa)	UHPC is more carbon-efficient per MPa
Service life	Excellent (100+ years)	Moderate (80 years max)	UHPC expected to last longer

A4 (transportation), and 996.3 kg·CO_2/m and 3,794.7 MJ/m for B2–B6 (use and maintenance) (Fig. 12). This resulted in a total life cycle impact of 3,724.1 kg·CO_2/m and 45,528.1 MJ/m. In contrast, the NC bridge exhibited lower initial values during production, with 2,197.8 kg·CO_2/m and 11,914.1 MJ/m for A1–A3 and 100.6 kg·CO_2/m for A4. However, due to more frequent maintenance requirements, it accumulated 3,021.3 kg·CO_2/m and 17,861.4 MJ/m during B2–B6, leading to a total impact of 5,319.8 kg·CO_2/m and 29,776.1 MJ/m. Although UHPC had a higher environmental impact during the initial stages (A1–A4), it outperformed NC over the entire life cycle, as shown in Fig. 12.

Based on this analysis, the UHPC bridge is considered more environmentally friendly than its NC counterpart for several key reasons. First, UHPC requires considerably less maintenance over its lifespan, which translates to lower long-term environmental impacts associated with its repair activities. Second, owing to its superior strength, UHPC enables a reduced structural cross-section, which means that less material is needed for the UHPC bridge compared to the NC bridge to achieve an equivalent load-bearing capacity. Third, UHPC generally has a longer service life. Although this LCA assumed an 80-year lifespan, which is aligned with the average for NC bridges, UHPC structures typically exceed this duration. Consequently, NC bridges may require reconstruction or extensive strengthening over extended periods, further increasing their cumulative environmental footprint.

To facilitate a comparative evaluation of UHPC and NC across multiple sustainability and performance metrics, a multicriteria analysis was included in the sustainability assessment. Different aspects were considered, including the initial and total embodied carbon, total embodied energy, compressive strength, ESI, and service life. Table 4 lists the performance-based indicators for the UHPC and NC bridges. Based on this, the relative performance ratio (RPR) method was employed to normalize each metric to a unitless scale based on its best-performing value. The direction of preference was first determined for each metric, namely, whether lower is better (e.g., embodied carbon, embodied energy, and ESI) or higher is better (e.g., compressive strength and service life). For "lower is better" indicators, the RPR was calculated as the ratio of the best (lowest) value to the current value. For "higher is better" indicators, the RPR was calculated as the ratio of the current value to the best (highest) value. An RPR of 1.0 represented the best performance for a given metric, whereas values closer to zero indicated lower relative performance. To ensure a fair comparison, the RPR calculations were based on the average values of each metric for UHPC and NC. For example, the metric for compressive strength was calculated using average values of 150 MPa for UHPC and 60 MPa for NC, as reported in Section 2.1. Thus, the RPR for compressive strength was calculated as follows: $RPR_{NC} = 60/150 = 0.40$ and $RPR_{UHPC} = 150/150 = 1.0$.

Figure 13 illustrates the performance-based comparison of UHPC and NC across six sustainability and structural metrics. The data indicated that NC exhibited superior performance in terms of initial embodied carbon (1.0) and embodied energy (1.0), reflecting its lower material intensity and simpler mix composition. However, its performance declined significantly in terms of structural and service life-related criteria. For instance, its compressive strength (0.4), ESI (0.6), and service life (0.8) indicated substantial trade-offs when strength and longevity are prioritized. In contrast, UHPC performed strongly in all structural and durability metrics, achieving perfect scores (1.0) in compressive strength, ESI, service life, and total embodied carbon. These results highlight the efficiency of UHPC in delivering high mechanical performance with lower long-term environmental burden. While its initial embodied carbon and energy use were relatively higher (normalized scores of 0.9 and 0.7, respectively), they were offset by gains in lifecycle performance.

4. CONCLUSIONS AND RECOMMENDATIONS

This study presents a comprehensive sustainability evaluation of 40 UHPC mixes by integrating embodied carbon, embodied energy, and compressive strength within a multicriteria assessment framework. Based on the analysis and discussion, the key findings, applications, and recommendations are further highlighted.

4.1. Key Findings. By analyzing the UHPC mix designs, a deeper understanding of their environmental and structural performance, such as embodied carbon and energy use, is provided. UHPC mixes generally exhibit higher embodied emissions than NC due to the intensive use of materials such as cement and steel fibers. However, their superior strength enables material efficiency at the structural level, thereby reducing the total life cycle impact.

The ESI (range of 7.3–14.9 kg·CO_2/MPa) effectively captured the balance between carbon emissions and mechanical performance; thus, it represents a practical tool for evaluating the sustainability of UHPC formulations. In addition, the proposed sustainable performance index facilitates classification into optimized, balanced, and environmentally intensive zones by integrating embodied carbon, embodied energy, and compressive strength. Mixes 3, 4, 5, 7, 8, 9, and 37 demonstrated strong sustainability profiles, thus combining high strength with low environmental burdens through the strategic use of low-carbon materials.

A comparative analysis of bridge applications shows that although UHPC had higher initial embodied carbon (2,500 kg·CO_2/m) and energy (45,500 MJ/m) than NC, its total life cycle carbon was lower (3,724 vs. 5,320 kg·CO_2/m) due to its reduced maintenance and longer service life (>100 years vs. 80 years). It also achieved a more favorable ESI (11.3 vs. 20.3 kg·CO_2/MPa), which confirmed its efficiency in delivering structural performance with a reduced carbon footprint.

In conclusion, the optimization of UHPC through mix design and material sourcing produces a highly sustainable material for long-lasting, high-performance infrastructure. Its use is especially justified when durability, strength, and long-term environmental performance are critical, whereas NC may remain suitable for applications with lower structural demands and shorter service lives.

4.2. Implementation and Future Recommendations.

To support the wider adoption of UHPC in sustainable infrastructure, a strategic shift in material design, sourcing, and assessment methodologies is essential. Despite its high initial environmental footprint, UHPC's superior mechanical performance and extended service life position it as a promising material when optimally designed and implemented.

One of the most pressing challenges is the carbon and energy intensity of locally produced OPC, which are higher than those of its international counterparts. This underscores the urgency of regional process improvements, such as cleaner production technologies, clinker substitution, and alternative fuels. These efforts would not only reduce emissions but also create a clearer understanding of how local environmental conditions, production practices, and material compositions influence overall sustainability performance.

To enhance the sustainability profile of UHPC, mix designs should increasingly incorporate low-carbon materials that can effectively lower the embodied carbon and energy without compromising the mechanical strength. Equally important is the need to address the environmental burden of other key components, particularly steel fibers and chemical admixtures. Thus, future research should explore low-carbon alternatives, such as industrial waste/byproducts and recycled steel fibers, to further reduce the environmental intensity of UHPC mixes.

From a performance standpoint, tools such as the ESI and SPI framework proposed in this study offer practical means of evaluating and selecting UHPC mixes that balance structural and environmental priorities. Their adoption, alongside region-specific environmental databases and verified EPDs, will support more localized and informed sustainability assessments, thereby leading to better decision-making in future infrastructure development.

Future research should also incorporate life cycle cost analyses along with environmental assessments to support more robust decision-making. Simultaneously, evaluating the cost and environmental trade-offs will enable the identification of UHPC formulations that not only offer lower emissions but also deliver long-term economic value. This integrated approach can guide both the broader adoption of UHPC and the selection of specific blends with the most favorable life cycle performance, both environmentally and economically.

It is worth mentioning that this study has certain limitations that may influence the interpretation of its LCA results. The system boundary excludes domestic transportation within Saudi Arabia and on-site construction emissions, potentially underestimating the total environmental burden. Additionally, a fixed maintenance schedule and a minimum strength threshold of 120 MPa were used for all UHPC mixes, which may not fully capture real-world variability in durability and performance.

AFFILIATIONS AND AUTHOR DETAILS

Undergraduate Author

Hussain Abdulatif Karam – *Department of Civil & Environmental Engineering, King Fahd University of Petroleum & Minerals, Dhahran 31261, Saudi Arabia;* 0009-0002-8185-4843
Email: s202352030@kfupm.edu.sa

Corresponding Author

Ashraf A. Bahraq – *Research Mentor, Post Doctoral Fellow, IRC for Construction and Building Materials, King Fahd University of Petroleum & Minerals, Dhahran 31261, Saudi Arabia;* 0000-0002-0583-5002
Email: ashraf.bahraq@kfupm.edu.sa

Authors

Mohammed A. Al-Osta – *Professor, Department of Civil & Environmental Engineering and IRC for Construction and Building Materials, King Fahd University of Petroleum & Minerals, Dhahran 31261, Saudi Arabia;* 0000-0002-3678-2695
Email: malosta@kfupm.edu.sa

Shamsad Ahmad – *Professor, Department of Civil & Environmental Engineering and IRC for Construction and Building Materials, King Fahd University of Petroleum & Minerals, Dhahran 31261, Saudi Arabia;* 0000-0001-7939-7319
Email: shamsad@kfupm.edu.sa

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CONFLICTS OF INTEREST AND FINANCIAL DISCLOSURE

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