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COMPARISON OF ENERGY CONSUMPTION, CO_2 EMISSIONS BETWEEN NORMAL CONCRETE AND UHPC IN RURAL BRIDGE APPLICATION

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Abstract

Due to its outstanding mechanical properties and durability, Ultra High-Performance Concrete (UHPC) has been gradually used for different types of structures in recent years. However, the analysis of environmental impacts and the assessment of the overall sustainability performance of UHPC applications is quite limited. This study presents the results of determining the total energy embodied and CO_2 emissions causing the greenhouse effect of a rural bridge using UHPC compare to the normal concrete (NC) one by the life-cycle analysis (LCA) method. Environmental impacts are comprehensively considered at all stages from material production; materials and structures transportation; in-situ construction and installation; maintenance and repair during the service life; and finally demolished at the end of the project's life. The analysis shows that the UHPC application in rural bridge construction can reduce the total volume of materials used by 40-58%, lower 65% total energy consumption and eliminate up to 76% CO_2 emissions compared with a conventional concrete bridge. The results also confirm that using UHPC is a viable technical and eco-friendly option for rural bridge construction in Vietnam.

Keywords: ultra high-performance concrete UHPC; environmental impact; life- cycle analysis- LCA; CO_2 emission; energy consumption; rural bridge.

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1. Introduction

The construction industry is one of the largest energy-consuming industries in the world and is primarily responsible for greenhouse gas emissions. With the very high growth rates of the construction industry, especially in developing countries, the level of energy used in the construction sector is also increasing sharply. In Europe, about 40% of total energy is consumed by residential areas and office buildings [1]. The extraction and production of materials, construction and demolition of buildings not only consume large amounts of energy but also generate a huge quantity of CO_2 emissions. According to Joseph and Tretsiakova-McNally, constructions consume about 25% of the annual global timber production; 40% of natural stone, sand and gravel; and 16% of water and also produce 50% of global greenhouse gases [2]. Therefore, to develop a green construction industry with minimum CO_2 emissions and low energy consumption, we must choose environmentally friendly materials, and at the same time, we must optimize environmental performance throughout the project's life cycle.

To assess the life cycle of a building, it can be divided into four different stages such as production, construction, use and disposal at the end of life [3]. BIS [4] found that CO_2 emissions when using materials are the largest, accounting for 82.2% in civil buildings; while total energy consumption is the largest, accounting for 38.1% in the producing materials for bridge works, then 30.3% in the

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using materials [5]. However, the level of CO_2 emissions and energy consumption depend on the type of load-bearing structure of the building [6]. Green building materials use little or no resources and have low environmental impact, which do not cause harm to human health during use and handling [7]. Selecting the right materials with high sustainability and minimal environmental impact can save up to 30% CO_2 emissions [8]. Therefore, the application of sustainable and long-life construction materials, which is required the lowest repair and maintenance costs is increasingly interesting.

Concrete is the most popularly material in the construction of bridges and roads; buildings and other infrastructure. On average, about 3 tons of concrete are produced per year per person in the world [9]. Concrete consists of three main components: aggregates; binder and water. Aggregates in concrete make up 75% of the total volume of concrete and are mainly extracted from natural resources. Cement is the component that emits the highest CO_2 emissions. In particular, the cement industry is estimated to be responsible for 8–10% of all human- driven CO_2 emissions in the global [10, 11]. Therefore, minimising the environmental impact of concrete structures without affecting their quality is one of the main concerns for the sustainable concrete industry in the future. Sustainability in concrete production can be achieved by improving concrete mix composition design methods [2] and enhancing the quality, and longevity of concrete products. Improving the mechanical properties and durability of concrete can also indirectly reduce CO_2 emissions by increasing its service life and reducing the need for repairs over time. Habert and Roussel [12] estimate that reducing the volume of concrete by improving its mechanical strength can reduce CO_2 emissions by about 30%. The use of concretes such as high-strength concrete, Ultra High-Performance concrete (UHPC), and self-compacting concrete can also increase sustainability in concrete production, offers flexibility in product design and improve structural quality [2].

Over the past three decades, concrete technology has made incredible advances. One of the breakthroughs of the 1990s was the development of UHPC. With many outstanding features such as good fluidity, high uniform structure, and compressive and flexural strength can reach over 150 MPa and 40 MPa, respectively [13], so UHPC has been widely applied in both buildings and bridge construction [13, 14]. Many studies have confirmed that UHPC usage is an effective solution for sustainable construction [15–18]. Yen Lei Voo et al. [15] stated that building structures from UHPC are often sustainable and environmental friendly in terms of reduced energy consumption, minimising CO_2 emissions and global warming potential. The high durability of UHPC also results in significant improvements in building life. The reduction in consumption of non-renewable raw materials, the use of by-product materials (Silicafume, GGBS, FA) in manufacturing and the ability to recycle UHPC by the end of its life have also contributed to the increase in efficiency and sustainability of this concrete. Using UHPC for bridge piers in highways can save up to 75% of the material compared to using ordinary concrete. This results in faster construction and a smaller pier area, allowing for better traffic flow. Furthermore, the use of a UHPC with a compressive strength of about 172 MPa can result in a reduction of up to 35% in carbon emissions and can go down by four to five times reduction in pier inspection and maintenance costs due to the durability and long life of the UHPC [16]. However, the consideration and assessment of the environmental performance of the entire life cycle from production to construction, use and demolition at the end of the life of construction when applying UHPC has not had many analytical studies [19]. This study focuses on analyzing and determining the amount of CO_2 generated and the total energy consumed by UHPC in rural bridge construction at all stages in Vietnam.

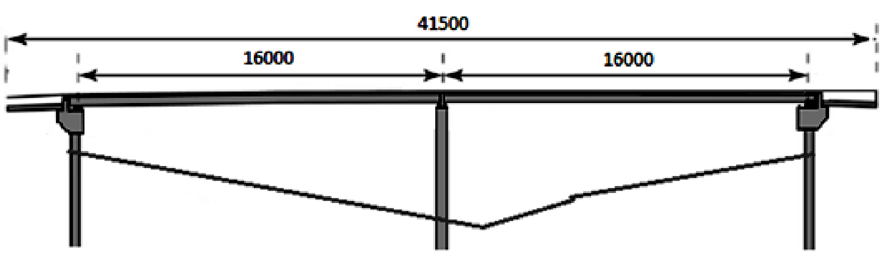
2. Case studies and methods

2.1. Case studies

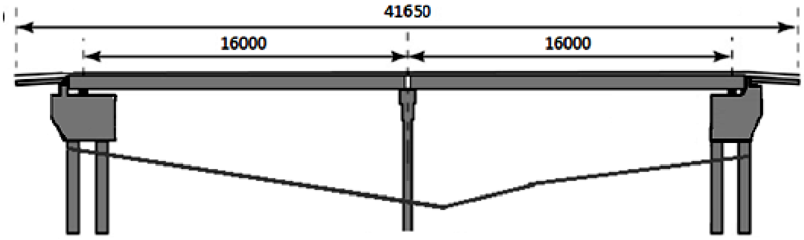
The Lang Co bridge is located at Lam Vy commune- Dinh Hoa district- Thai Nguyen province, in the northern mountain region of Vietnam. The bridge has only one lane for the daily traffic link between the two sides of a river. It is 3.5 m wide, 41.5 m long, over two spans [20]. The two bridge alternatives were the UHPC bridge (Alt 1) and the NC bridge (Alt 2). The design comparison is presented in Table 1. The span elevation and crosssection for both options are shown in Figs. 1 and 2.

Table 1. Comparison of structure Alternatives

Characteristics	Alt 1- UHPC bridge	Alt 2- NC bridge
The bridge Length, m	41.5	41.65
Superstructure: Height, m Girders/thickness, cm	 0.5 2/5	 1.06 4/20
Substructure: Abutment height, m Bored pile foundation D×L, m	 34.28 1.0×11	 60.66 1.2×11
Price (VNĐ)	1.919.658.000	1.992.900.000
Advantages/ Disadvantages	New reinforcement concrete girder type (UHPC) Light, slender span structures, and low architectural height lead to the short embankment length. Reduced the self-weight of abutments, reducing the number of piles. Strict quality control by factory materials; ensure the high architecture requirement.	Popular reinforcement concrete T girder type (NC) Simple plan, easy to manufacture and construction The height of the bridge is more than Alt1. Cast in place, the structure maybe does not meet the architectural requirement
Estimated construction time, months	2.0	3.5

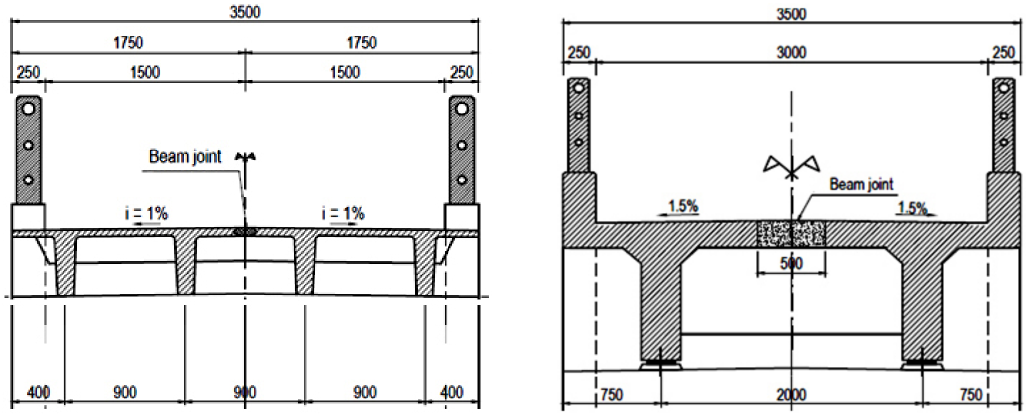


(a) Alt 1- UHPC bridge



(b) Alt 2- Normal Concrete bridge

Figure 1. Elevation of the span for the bridges



(a) UHPC (b) NC

Figure 2. Cross-sections for the superstructure bridge using UHPC and NC

2.2. *Materials and construction method*

This study focused on the comparison of the two types of design such as the UHPC beam and the NC beam so that the difference in the quantity of major materials (concrete, steel, soil) was considered for the construction of the superstructure (span beams) and the lower structure (abutments, piers); Other substrates and structures (foundations and pavements of the approach road) are considered to have the same mass and little effect on the environmental assessment of the two Alternatives. All types of concrete and their uses for both Alts are shown in (Table 2). According to technical- economic report of Lang Co bridge, quantities of main materials for two alt bridges showed in Table 3 [20].

Table 2. Concrete types for structure

Type of concrete	Strength f'_c (MPa)	Structure use
UHPC-C150	150	UHPC girder and deck
NC-C28	28	The reinforced concrete deck was poured in place, reinforced concrete girder and Precast concrete piles, and bored piles;
NC-C25	25	The abutment, pier, and reinforcement concrete transition slab
NC-C20	20	Concrete cement carriageway, range beacon, manhole, . . .
NC-C15	15	Cutoff dike conbcrete, Slope Protection concrete.
NC-C8	8	Flat bottom concrete of foundation, concrete padding of the approach road.

Table 3. Quantity of main materials for UHPC bridge (Alt 1) and NC bridge (Alt 2)

Item		Alt 1			Alt 2		
		Super-structure	Sub-structure	Total	Super-structure	Sub-structure	Total
Concrete, m^3	UHPC-C150	16.1	0.5	16.6	0.0	0.0	0.0
	NC-C28	3.7	9.5	13.1	52.1	17.1	69.2
	NC-C25	6.4	33.4	39.9	19.9	53.1	73.0
Steel, kg	Rebar	2696.8	6556.4	9253.2	14725.2	9295.8	24021.0
	Prestressed cable	1124.4	0	1124.4	483.4	0.0	483.4
	Total	3821.2	6556.4	10377.6	15208.6	9295.8	24504.4
Soil*, m^3		0.0	1103.6	1103.6	354.1	1490.5	1844.6

Note: *The total volume soil of leveling, digging soil grade 3 and embankment K90

From Table 3, it is clear that the number of concrete, steel and soil materials used on the UHPC bridge reduce respectively by 41.1%; 57.7% and 40.2% compared to the total volume and mass of these materials used for the NC bridge, that is because the use of UHPC in the superstructure has reduced the self-load and the size of the substructures of the bridge [15, 16].

According to the construction design dossier [20]: in alt 1, the UHPC beam was pre-casted at Song Da Viet Duc concrete factory in Ha Nam province, then transported by tractor to the site, using a crane truck ≥25T to install the modules to the abutments and pier position. After alignment will use concrete joints along the bridge, pouring concrete connecting beams with abutments and piers, and then casting concrete pavement block in place before finishing the deck. For the alt 2, T beams are cast at the yards near the bridge construction site after the concrete has reached the strength, T beams will be installed by a crane bridge. After properly aligning to the abutments and pier, the formwork and reinforcement steel will prepare and pour the joints concrete of the beams, construct horizontal beams, the concrete casting the barrier and the installation of railing handrail before finishing.

Based on the survey of raw materials resources, the transport distance of each material for the two options is shown in Tables 4 and 5. Transportation of cement, fly ash, silica fume, plasticizer admixture, steel fibre and reinforcing steel is carried out by trucks. Silica sand and Silica powder should use the combined transport method due to long-distance transportation, from Cam Ranh to Nha Trang for about 55 km by truck, from Nha Trang to Phu Ly by rail for about 1230 km and from Phu Ly station to factory continue to transport by truck about 7 km.

Table 4. Typical composition and Transportation distance materials for UHPC

Materials, kg/m^3	Composition	Distance, km	Transport location from
Portland cement	1025	7	But Son - Ha Nam
Fly ash	175	100	Pha Lai - Hai Duong
Silica fume	330	60	Ha Noi Centre
Plasticizer	30.75	60	Ha Noi Centre
Silica Powder	300	1270	Cam Ranh - Nha Trang
Silica Sand	650	1270	Cam Ranh - Nha Trang
Tap water	246.3	0	Phu Ly - Ha Nam
Micro Steel fibre	235	60	Ha Noi Centre

Table 5. Concrete composition and transportation distance materials for NC

Materials, kg/m^3	NC Composition		Distance, km	Transport location to the Construction site - Lang Co
	C28	C25		
Portland cement	392	343	65	Thai Nguyen city
Plasticizer	4.7	4.1	143	Thai Nguyen city
Gravel or crush stone	1138	1146	72	Dong Hy - Thai Nguyen
Crushed Sand	674	707	72	Dong Hy - Thai Nguyen
Tap water	195	195	0	Dinh Hoa - Thai Nguyen

Note: Typical NC composition according to QĐ1329/BXD [21] The typical use of materials in the construction works.

2.3. Research Methods

To perform the environmental evaluation, the Life Cycle Assessment (LCA) method was used. It is a methodology for evaluating an environmental load of processes and products during their life cycle, from cradle to grave [22]. In this study, the functional unit is the new construction of the specific bridge used the beam and deck structure with NC and/ or UHPC, thus comparing the environmental effect of the entire bridge structure. The combined environmental effects include (1) the Materials production process (including concrete, steel production and soil exploitation); (2) the structural transportation from the manufacturer to the construction site and installing at the site; (3) Maintenance during the service life; (4) Demolition at the end of project life service. The two key criteria for environmental used performance are the total amount of CO_2 emissions and the total energy used are specifically calculated for the two first processes. Since no actual bridges have used UHPC to the end of their life, the following two processes are analyzed and evaluated according to current regulations for NC bridges and assumptions about the UHPC bridge life according to the results of UHPC durability studies in the laboratory.

a. Calculation method for the CO_2 emission and energy consumption during materials production

The production process includes the production of concretes (C28, C25, UHPC), and the production of steel and cables. The production process takes into account the process of exploiting and transporting the raw materials, the process of mixing and manufacturing, etc. Through the collection of data from a variety of relevant environmental reports [23–25], CO_2 emission factors and energy consumption figures generated by the exploiting/ manufacturing and transportation process used in the calculation are summarized in Table 6.

The total amount of CO_2 emitted by each material is calculated by the following formula (1):

$$CO_{2total} = \sum m_i \left(d_i e_i + p_i\right) \tag{1}$$

which m_i is mass of the material composition i; d_i is transportation distance for material i; e_i is CO_2 emission factor (depending on the mode of transport); p_i is CO_2 emissions per unit mass of the material composition i.

The total energy consumed for the production and transport of each material is also calculated according to the formula (2):

$$Q_{total} = \sum m_i \left(d_i q_{ei} + q_i\right) \tag{2}$$

which q_{ei} is energy consumption in transit (depending on the type of transportation method and fuel consumption); q_i is the energy consumption per unit mass of the i material production.

Table 6. CO_2 emissions and Energy consumption units of materials

Materials	CO_2 emissions due to		Energy consumption due to	
	Production (p_i), kg/t	Transportation (e_i), kg/t.km	Production (q_i), GJ/t	Transportation (q_{ei}), GJ/t.km
Portland cement	865.000	0.09675	4.920	0.00131
Fly ash	196.500	0.09675	2.410	0.00131
Silicafume	7.000	0.09675	0.040	0.00131
Plasticizer	92.000	0.09675	0.447	0.00131
Gravel or crush stone	0.892	0.09675	0.025	0.00131
Sand	0.892	0.09675	0.025	0.00131
Silica sand	0.892	0.0774	0.025	0.00105
Silica powder	1.784	0.0774	0.050	0.00105
Micro Steel fibres	929.9	0.09675	13.121	0.00131
Restressed steel	929.9	0.09675	13.121	0.00131
Steel rebars	929.9	0.09675	13.121	0.00131

Assumptions with Portland cement, Fly ash, Silica fume, Plasticizer, Coarse Aggregate, Sand, Micro Steel fibres, Restressed steel, and Steel rebars are transported by truck 27 tons, each 100 km needs 86 litres [26], corresponding to the transport of 24 tons material. CO_2 emissions for 1 litre of standard fuel are equal to 2.7 kg; The unit energy emission factor of diesel oil is 42 GJ/t and the density of diesel oil is 0.87 kg/l. Then the coefficients and are calculated as q_{ei} = 0.00131 GJ/t.km and e_i = 0.09675 kg CO_2/t.km.

For the transport of silica sand and silica powder use both by rail and truck, so the CO_2 emission factor and the energy consumption factor should be temporarily reduced by 20%.

b. Calculation method for the CO_2 emission and energy consumption during construction

The construction process consists of the following steps: transporting the precast structures from the factory to the site, building and installing the structures, and materials at the site. For the transportation and installation of bridge beams the two options are as follows:

UHPC beam is transported about 250 km from the concrete factory to the site by truck 27 tons. For the installation of a 19.71T UHPC beam, we need to use two crawler cranes with a 40T lifting capacity to ensure a range of 18m to 20 tons, the fuel gauge of the crawler crane with a lift capacity of 40T is 51 litres of diesel [26]. Due to the crane having only 2 beams, we can calculate the working time of the crane as only 4h (a haft shift). The total fuel used to complete the UHPC beam is 51 litres of diesel oil.

For NC weights 29.19 T we need to use two crawler cranes with a lift capacity of 63T to ensure a range of 18 m to 30 tons, the fuel gauge of the crawler crane with the lift capacity is 56 litres of diesel [26]. Due to the need to crane 4 beams so we can calculate the working time of the crane as 8h (a full shift). The total fuel required to complete the UHPC girder is 112 litres of diesel oil.

This assessment does not take into account the environmental effects brought by some comparisons between the two options: (1) 7-15% labour costs fall due to the prefabricated UHPC at the factory compared to the casting at the construction site; (2) the investment cycle- return is shorter by 1.5 months of construction progress (2 months for UHPC bridge and 3.5 months for NC bridge, Table 1); (3) Reduced costs due to the construction method of UHPC bridge do not need a large area for castings and setting up a concrete mixing plant, materials store in castings, ...; (4) reducing the height of the UHPC bridge can be up to 2.5-4 m compared to the NC bridge, thereby reducing the slope of the approach road, flow and communication height, as well as saving materials for the approach path. The calculation of total CO_2 emission and energy consumption in the construction process is mainly for the superstructure and substructure of the two bridges, the structure of the approach road to the two bridges in this project is considered the same. In these superstructures and substructure, the calculation only for the mainly used materials include: UHPC-C150, NC consists of two grades C28 and C25; reinforced steel consists of rebars and prestressed cable; total volume soil of levelling construction, grade 3 digging and embankment/ backfilling K90 of foundation. Other materials are considered unchanged between the two alternatives or have a low mass and little effect on the total amount of CO_2 emissions and total energy consumed in the production and use process.

3. Results and discussion

3.1. The materials production

Total CO_2 emissions and Energy consumption of the main types of concrete production process are shown in Fig. 3.

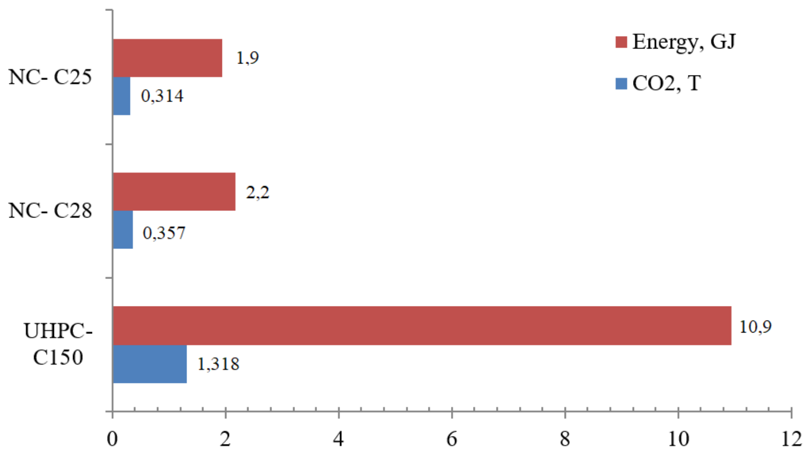
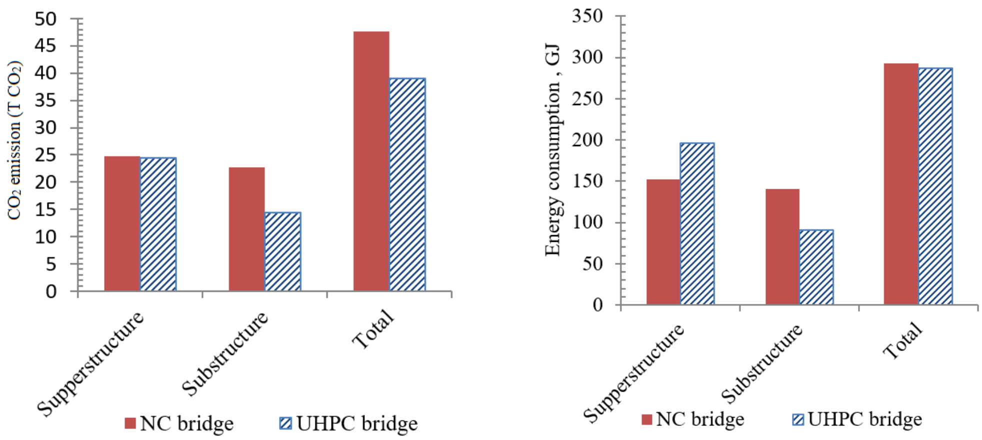


Figure 3. Comparison of CO_2 emissions and Energy consumption per 1m^3 for concrete production

From Fig. 3, it is found that for each 1 m^3 of concrete production, the CO_2 emissions and energy consumption of the UHPC are much higher than that of conventional concrete (C28 and C25). Specifically: CO_2 emission from UHPC production is up to 3.7 times higher than that of C28 and 4.2 times than that of C25. Total energy consumption for 1 m^3 of UHPC production is 5.0 times higher than that of C28 concrete and 5.7 times that of C25 concrete. This result is consistent with Voo's studies [15]. This is mainly due to the large amount of cement used in the UHPC mix (2.6÷3.0 times higher than the cement in the C28 and C25 concrete mix, Table 4 and Table 5).

For the construction process of soil work including levelling, digging, embankment and K90 compaction, the CO_2 emission factor and energy consumption factor are mainly from the normalized fuel combustion for the working machines. These values are calculated as 0.027 kg CO_2/m^3 and 0.0024 GJ/m^3, respectively.

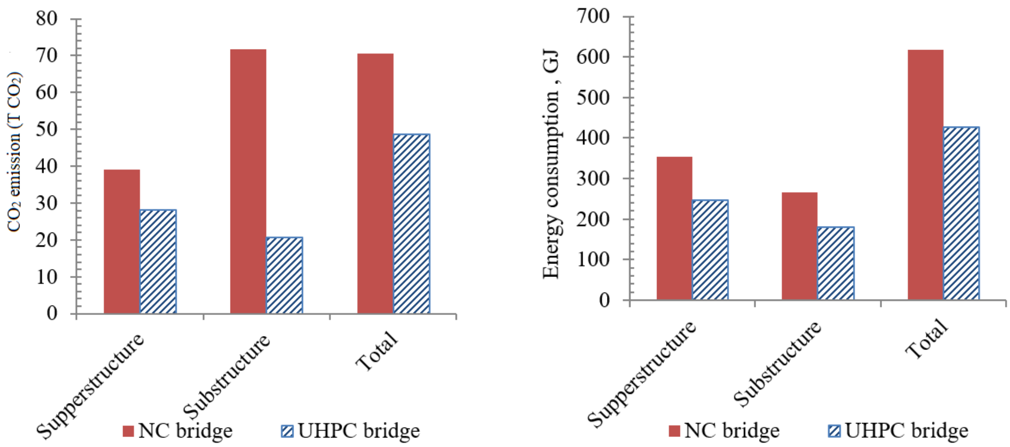
The total CO_2 emissions and Energy consumption of the materials production for each type of structure and the 2 options are shown in Figs. 4 and 5. We could see that CO_2 emissions in concrete production for the superstructure of UHPC and NC bridges are similar. However, for the substructure and total, this value decreased by 36.4% and 18.0%, respectively (Fig. 4(a)). Energy consumption of concrete production for the superstructure of the UHPC bridge is higher by 29.1%. However, this value for the substructure and total still decreased by 35.4% and 1.8% (Fig. 4(b)).



(a) CO_2 emission (b) Energy consumption

Figure 4. O_2 emission and energy consumption of concrete production for UHPC and NC bridge

From Fig. 5, It is clear that the using the UHPC for the bridge, CO_2 emissions and Energy required to produce all the main materials are reduced corresponding to 28.0-71.2% and 30.0-32.6% depending on the type of structures, compared to that of the NC bridge. This result is consistent with the research of Yoshito and Tetsuya [6].



(a) CO_2 emission (b) Energy consumption

Figure 5. CO_2 emission and energy consumption of main materials production for UHPC and NC bridge

3.2. The construction process

The total amount of CO_2 and energy for the transportation and installation of the beams is summarized in Table 7. It can be seen that the amount of CO_2 emission for transport and construction of the UHPC beam is 3.6 times greater than that of the NC bridge. However, the total energy consumed in this process still decreased to over half (up to 54.1%).

Table 7. CO_2 emissions and Energy consumption for the construction process

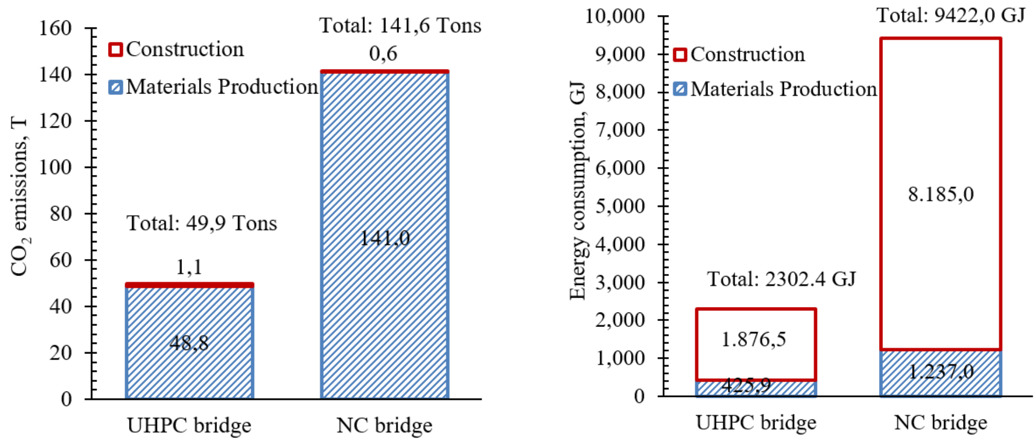
Criteria	UHPC bridge	NC bridge	% Reduction
CO_2 emissions, T	1.091	0.302	−260.8
Energy consumption, GJ	1876.5	4092.5	54.1

3.3. The maintenance, demolition and overall LCA

Under Circular No. 03/TT-BXD [27], the main maintenance for construction works include annual maintenance tasks (regular and periodical inspection of works; annual maintenance plan); periodical and extraordinary repair of works; observation and inspection quality in the service life (if any). In this study, the CO_2 emissions and energy consumption for the annual maintenance and repair works could determine by the percentage (%) of the construction and equipment (including materials, excluding technological equipment). Considering that the UHPC and NC bridge is an urban transport project, river bridges and national highways, the allowance is $t_1 = 0.2\%$ for maintenance and $t_2 = 0.4\%$ for major repairs. For the NC bridge, the life expectancy is 50 years so there are 2 majority repairs. But the UHPC bridge option is calculated to have a life of 100 years and one main repair. So that the total CO_2 emissions and energy consumption for the maintenance of the UHPC bridge have significantly reduced (about 1.8 and 2.6 times respectively) than that of the NC bridge. This is because the improved mechanical properties and durability of UHPC have extended the service life and decreased the cost of structural repairs, resulting in a reduction in CO_2 generation and energy consumption of the bridge structure [15, 18, 19].

CO_2 emissions and energy consumption at the end-of-life phase mainly come from the machinery used during the demolition of the bridges. Additionally, the transportation and treatment of all materials/ demolition waste to the landfill site. The CO_2 emissions and Energy consumption of these processes mainly depend on the total volume and mass of the used materials in the bridges; the distance to transport the materials to the treatment plants and/ or the landfill; the life or number of times of demolition of the structures, and the degree of difficulty in the demolition and handling process of UHPC; the ability to recycle and reuse materials, etc. Because the UHPC structure has just been practical application, it is not possible to fully and accurately assess the factors affecting the total amount of CO_2 generated and energy consumed in the overall project's life. However, if only considering the volume of materials to be demolished and handled, these values of the UHPC bridge may be lower approximately 46.3% than that of the NC bridge.

To forecast CO_2 emissions and energy consumption for overall LCA, we assume that the lifetime of the UHPC bridge is 100 years, which corresponds to two life cycles of the NC bridge. Since CO_2 emissions and energy consumption during the entire life cycle of the building mainly depend on the materials production and construction process, the total CO_2 emissions and Energy consumption of the two bridges are compared in Fig. 6. Fig. 6 shows that the use of UHPC for rural bridge construction reduces about 65% of CO_2 emissions and 76% of Energy consumption. These bring environmental efficiency, ensuring more sustainable development. This is significantly due to the high reduction of main materials production and construction process.



(a) CO_2 emissions (b) Energy consumption

Figure 6. CO_2 emissions and Energy consumption for overall LCA based on the materials production and construction process

4. Conclusions

From the research results, some main conclusions can be drawn as follows:

- The UHPC application in rural Bridge Projects has many advantages in terms of structure and environmental factors, ensuring a more sustainable development than the NC Bridge. Although to produce 1 m^3 of UHPC, CO_2 emission and energy consumption are 3.7 to 4.2 times higher and 5.0 to 5.7 times higher than 1 m^3 of NC.

- With the total volume of used materials saved by 40-58%, the total amount of CO_2 emissions and energy consumption during the construction of the UHPC bridge decreased by 30% and 51% compared to that of the NC bridge. Forecasting these values for the entire life of the UHPC bridge can save up to 65% and 76% only based on the calculations of the material production and construction process.

- In order to fully the environmental assessment, it is necessary to continue to study and calculate in detail the CO_2 emissions and energy consumption in the use, demolition and treatment phases of the UHPC bridge projects. These results also confirm that UHPC is a viable technical and eco-friendly option for rural bridge construction in Vietnam.

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