ENVIRONMENTAL BENEFIT OF TWO-LAYER STEEL FIBERED HIGH-PERFORMANCE CONCRETE BEAMS

Svetlana Pushkar[1]* and Yuri Ribakov[2]

ABSTRACT

This study evaluated Life-Cycle Assessment (LCA) of two different designs of high-performance concrete beam: (1) a single-layer beam (SLB) that consisted of steel fibered high-strength concrete in both the compression and tensile zones and (2) a two-layer beam (TLB) that consisted of steel fibered high-strength concrete and normal-strength concrete in the compression and tensile zones, respectively. The SLB and steel fibered high-strength concrete layer of the TLB were of the same concrete class C70/85. LCAs of the SLB and TLB were conducted using the ReCiPe2016 midpoint and endpoint-single-score methods. The difference between the two endpoint-single-score results was evaluated using a two-stage nested analysis of variance. The ReCiPe2016 midpoint results showed that replacing the SLB with the TLB reduces the environmental impact of global warming potential, terrestrial ecotoxicity, water consumption, and scarcity of fossil resources by 15%, 17%, 11%, and 17%, respectively. The ReCiPe2016 endpoint-single-score results showed that the environmental damage from the TLB compared to the SLB was statistically reduced ($p = 0.0256$). Therefore, considering two different designs of steel fibered high-strength concrete beams, the TLB design was found environmentally preferable to SLB design on both, midpoint and endpoint-single-score evaluations.

KEYWORDS

Steel fibered high-strength concrete, two-layer beam design method, life-cycle assessment (LCA), two-stage nested ANOVA

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1. INTRODUCTION

High- and ultra-high-strength concretes have a wide application in the construction industry due to their improved mechanical properties and higher durability compared to normal-strength concrete. The only drawback of these concretes is their low tensile strength and weak deformation capability, which can lead to brittle failure under the ultimate load (Lu and Hsu, 2006). Thus, the ductility of high- and ultra-high-strength concretes can be improved by addition of steel fibers, resulting in steel fibered high- and ultra-high-strength concretes (Stengel and Schiessl, 2014).

1.Department of Civil Engineering, Ariel University, Israel;
*corresponding author: svetlanap@ariel.ac.il
2.Department of Civil Engineering, Ariel University, Israel; ribakov@ariel.ac.il

However, steel fibered high- and ultra-high-strength concretes require more cement content than normal-strength concrete, about 450–752 kg/m^3 (Bilim et al., 2009; Stengel and Schiessl, 2014) versus 360 kg/m^3 for normal-strength concrete (Al-Mashhadani et al., 2018). Moreover, steel fibered high- and ultra-high-strength concretes require around 40 kg/m^3 (Iskhakov et al., 2014) and 242 kg/m^3 (Stengel and Schiessl, 2014) of steel fibers, respectively. Thus, the additional quantities of cement and steel fibers could lead to additional environmental impacts.

Life-Cycle Assessment (LCA) of Portland cement and steel fibers on material levels was conducted by Stengel and Schiessl (2014). The authors reported that the production of 1 kg Portland cement led to 0.833 kg CO_2 -eq (global warming potential), 2.241×10^{-8} kg CFC_{11}-eq (ozone depletion potential), 4.211×10^{-5} kg C_2H_4 -eq (photo chemical ozone creation), 1.138×10^{-3} kg SO_2 -eq (acidification potential), and 1.702×10^{-4} kg PO_4^{3-} -eq (eutrophication potential), and the production of 1 kg of steel fibers led to 3.44 kg CO_2-eq (global warming potential), 1.85×10^{-7} kg CFC_{11} -eq (ozone depletion potential), 8.15×10^{-4} kg C_2H^2 -eq (photo chemical ozone creation), 1.84×10^{-2} kg SO_2 -eq (acidification potential), and 1.35×10^{-3} kg PO_4^{3-} -eq (eutrophication potential). The cement production releases this large amount of CO_2 emission due to high energy consumption and calcination of limestone during clinker production (Van den Heede and De Belie, 2012), while the steel fibers production is also a high energy consuming process (Stengel and Schiessl, 2014). Thus, if the construction industry produced less Portland cement and fewer steel fibers, the environmental impacts related to these building materials would be decreased. In this respect, much research has been focused on revealing the possibility to decrease these two environmentally harmful materials in the concrete industry.

Ultra-high-strength concrete is usually used for rehabilitation of existing concrete structures such as bridges (Brühwiler and Denarié, 2013). Habert et al. (2013) conducted LCAs of an existing bridge. The ultra-high-strength performance concrete and traditional rehabilitation systems with 25 mm of steel fibered ultra-high-strength concrete and with 80 mm of normal-strength concrete and waterproofing membrane, respectively, over the top surface of the existing bridge were analyzed. The authors reported that despite high cement content and steel fibers, which were used in the steel fibered ultra-high-strength performance concrete, this solution involved only 0.1–0.3 times more CO_2 than the traditional solution. This is because a much lower volume of steel fibered ultra-high-strength performance concrete was needed compared to the volume of normal-strength concrete (Habert et al., 2013).

However, when LCAs of the existing normal-strength concrete and steel fibered ultra-high-strength concrete bridges with the same deck slab thickness (175 mm) were analyzed by Stengel and Schiessl (2014), an opposite conclusion was drawn. The authors reported that despite only half of the steel fibered ultra-high-strength performance concrete being used in the girders of this bridge compared to the normal-strength concrete bridge, this solution involved 1.5–2.4 times more global warming potential, ozone depletion potential, photo chemical ozone creation, acidification potential, and eutrophication potential impacts than the normal-strength concrete bridge.

Hajiesmaeili et al. (2019) evaluated LCAs of three different interventions on an existing bridge: (1) complete demolition and new reconstruction, (2) strengthening ultra-high-strength performance concrete with steel fiber, and (3) strengthening ultra-high-strength concrete with polyethylene fiber. The strengthening in interventions (2) and (3) was performed with a 40 mm-thick layer of reinforced ultra-high-strength concrete, which was cast over the top surface of the existing bridge. The authors reported that the use of ultra-high-strength concrete with polyethylene fiber compared to complete demolition and new construction and ultra-high-strength

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concrete with steel fiber led to a reduction in global warming potential by 55% and 29%, respectively.

High- and ultra-high-strength concretes are also used in the beam industry. Stengel and Schiessl (2014) studied LCAs of a prestressed ultra-high-strength concrete girder and a hot rolled I-beam with similar height. The authors reported 5% and 39% decreases in the global warming potential and acidification potential, respectively, of the ultra-high-strength concrete beam compared with the hot rolled I-beam. Further, Zingg et al. (2016) evaluated LCAs of replacing a high-strength concrete beam prestressed with steel with a high-strength concrete beam prestressed with carbon fiber reinforced polymer and reported a 50% decrease in the global warming potential of the high-strength concrete beam prestressed with carbon fiber reinforced polymer compared with the high-strength concrete beam prestressed with steel. In these beam-related LCAs, all the volumes of the beams were reinforced with steel fibers. However, the quantity of steel fibers can be decreased with consideration of the two-layer beam (TLB) concept (Iskhakov et al., 2007).

This TLB concept was first introduced by Iskhakov and Ribakov (2007), who proposed using steel fibered high-strength concretes in the compression zone and normal-strength concrete in the tensile zone and presented theoretical grounding of an original TLB idea. In 2012, Holschemacher et al. (2012) performed a laboratory study of high-strength cylindrical specimens and a small scale TLB (150 × 150 × 700 mm) studying optimal steel fiber content, which can yield the highest Poisson coefficient and consequently, higher ductility of the beams. In 2014, Iskhakov et al. (2014), based on the results of theoretical (Iskhakov and Ribakov, 2007) and experimental (Holschemacher et al., 2012) studies, performed experimental investigation of the full scale simple supported TLBs (with a beam span of 3 m). The mechanical behavior of the TLBs from the beginning of loading and up to collapse was analyzed (Iskhakov et al., 2014). The authors reported that the TLBs had a bearing capacity that is comparable with high-strength concrete and improved ductility. Moreover, it was concluded that TLBs have relatively low cost. This is because of the decreased amount of cement and steel fibers, which only need to be applied in the concrete compressed zone of TLBs (Iskhakov et al., 2014).

This study continues to investigate the TLB design, exploring its environmental aspect. The question guiding this study is the following: How intently and realistically does the TBL design handle environmental improvements of the high-strength concrete beam? Therefore, the aim of this study was to conduct LCAs of the high-strength concrete beams using two design methods: (1) a beam that consisted of steel fibered high-strength concrete in both the compression and tensile zones, a single-layer beam (SLB) and (2) a beam that consisted of steel fibered high-strength concrete in the compression zone and normal-strength concrete in the tensile zone, a TLB. For both design methods, the LCA was conducted based on the concrete mixtures described by Iskhakov et al. (2014).

2. RESEARCH METHODOLOGY

2.1 Beam designs and concrete mixtures

The LCAs of two steel fibered high-strength concrete designs were analyzed: (1) a beam that consisted of steel fibered high-strength concrete in both compression and tensile zones, a SLB and (2) a beam that consisted of steel fibered high-strength performance concrete in the compression zone and normal-strength concrete in the tensile zone, a TLB. The constructive scheme of the analyzed SLB is presented in Figure 1.

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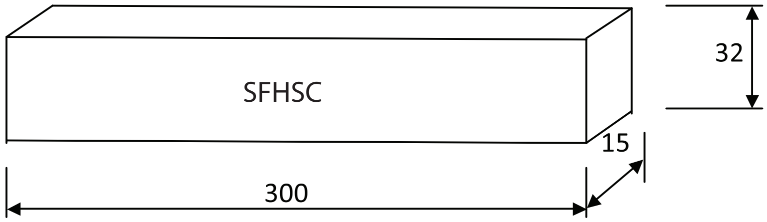
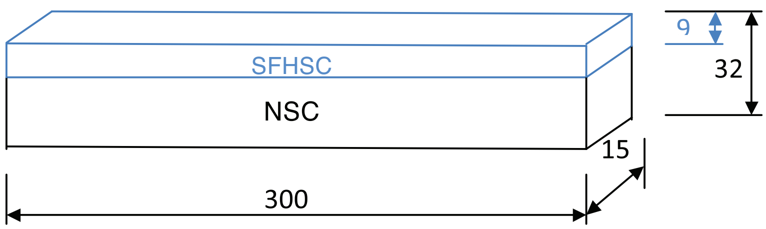
FIGURE 1. Constructive scheme of the analyzed single-layer beam (SLB) (300 × 15 × 32 cm).



All dimensions are in cm

FIGURE 2. Constructive scheme of the analyzed two-layer beam (TLB) (300 × 15 × 32 cm).



All dimensions are in cm

The constructive scheme of the analyzed TLB is presented in Figure 2. The constructive schemes and concrete mixtures are based on Iskhakov et al. (2014), who designed and casted three full scale TLBs and studied their serviceability limit state and ultimate limit state according to crack formation, deflections, and deformations up to the ultimate load capacity of 104.17 kN.

Reinforcement steel for both SLB and TLB

Longitudinal at the bottom of the cross section: 2 Ø 20 mm, l = 296 cm.

Longitudinal at the upper of the cross section: 4 Ø 10 mm, l = 101 cm.

Links (in the left and right parts of the beam span): 14 Ø 8 mm, l = 80 cm.

The concrete mixtures of the analyzed SLB and TLB are presented in Table 1. These mixtures were prepared using the following materials: Portland cement CEM II/A-M (3.05 kg/dm^3), fly ash (2.3 kg/dm^3), natural sand (a fraction size of 0 to 2 mm), two types of gravel (fraction sizes of 2 to 8 mm and 8 to 16 mm), poly-carboxylic ether-based super-plasticizer (1.07 kg/dm^3), and long-term retarder (1.17 kg/dm^3) (Iskhakov et al., 2014).

2.2 Life-cycle assessment

To conduct LCAs of the SLB and TLB, first the functional unit (FU) and the system boundaries were defined. Then, the life-cycle inventory (LCI) and the life-cycle impact assessment (LCIA) of the defined FU within the defined system boundaries were evaluated (ISO 14040, 2006).

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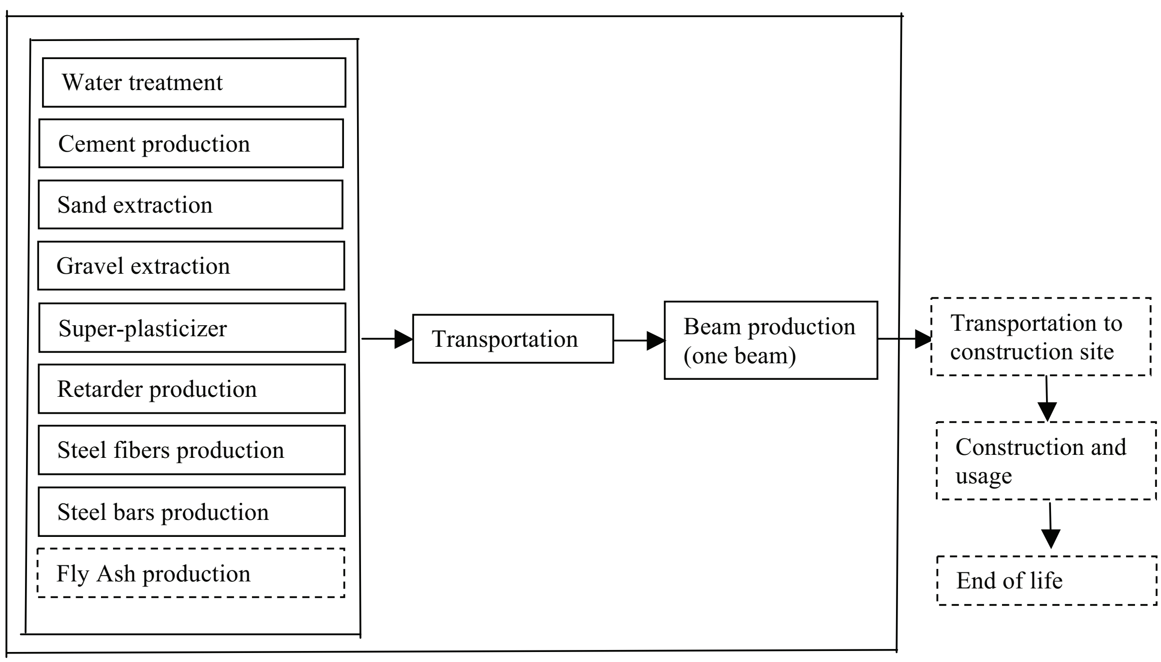
TABLE 1. Concrete mixture (kg) of the analyzed SLB and TLB.

Water	Cement	0/2 Sand	2/8 Gravel	8/16 Gravel	Fly ash	Super-plasticizer	Retarder	Steel fiber	Steel bars
The analyzed SLB									
19.01	57.60	100.45	63.90	92.02	14.40	1.38	0.29	5.76	21.33
The analyzed TLB									
20.86	49.73	103.82	65.59	93.71	8.78	1.12	0.23	1.26	21.33

Functional Unit (FU) and system boundaries

FU is a unit to which all the inputs and outputs should be connected (ISO 14040, 2006). In this study the FU was one beam (300 × 15 × 32 cm). A "cradle-to-grave" LCA of concrete elements should be composed of (i) the design stage, (ii) the production/execution stage, (iii) the usage stage, and (iv) the end-of-life stage (ISO 13315-1, 2012). However, it was supposed that the SLB and TLB had a similar usage stage because they both belonged to the same concrete class C70/85 with design load of 72.48 kN and ultimate load capacity of 104.17 kN (Iskhakov et al., 2014). The end-of-life stage is highly dependent on the different demolition/disposal practices, and therefore, it is highly uncertain (Napolano et al., 2015). Therefore, this study was a "cradle-to-gate LCA," in which only the design stage and the production/execution stage were considered. As a result, Figure 3 shows the system boundaries applied to the SLB and TLB.

FIGURE 3. Life-cycle assessment (LCA) system boundary illustrating production of the SLB and TLB (plain line—included processes; dashed line—nonincluded processes).



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Life-cycle inventory (LCI) and life-cycle impact assessment (LCIA). To model the LCIs of the production of the SLB and TLB components such as water, cement, sand, gravel, super-plasticizer, retarder, steel fibers, and steel bars, the Ecoinvent v3.2 database was used (Table 2). To model the transportation of the beams' components, the local distances from producer/supplier to the SLB and TLB casting place (the laboratory in Leipzig University of Applied Sciences, Leipzig, Germany) were used (Table 3). These data from the Ecoinvent v3.2 database (Table 2) were used due to the absence of local German data. However, such an analysis of secondary data was appropriate considering the aim of this study, i.e., to compare different beam designs (SLB and TLB for the same concrete class C70/85).

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TABLE 2. References from the EcoInvent v3.2 database (SimaPro, Version 9.0.0.35) for modeling the Life-cycle inventory (LCI) of the SLB and TLB.

Material	Reference
Water treatment	Tap water, at user/CH U
Cement, CEM II/A-M with 6%–20% granulated slag and limestone	Portland slag sand cement, at plant CH/U
0/2 sand, natural sand with a fraction size of 0 to 2 mm	Sand, at mine CH/U
2/8 gravel, gravel with a fraction size of 2 to 8 mm	Gravel, crushed, at mine CH/U
8/16 gravel, gravel with a fraction size of 8 to 16 mm	Gravel, crushed, at mine CH/U
Super-plasticizer	Polycarboxylates, 40% active substance
Retarder	Borax, anhydrous, powder
Steel fibers, straight fibers with end hooks, with a length of 50 mm and a diameter of 1 mm	Steel wire rod/EU
Steel bars, normal ductile steel bars	Steel rebar/EU
Transportation	Lorry transport, Euro 0, 1, 2, 3, 4 mix, 22 t total weight,17.3 t

TABLE 3. Transportation distances from producer/supplier to the beams casting place.

Material	Producer/supplier location	Distance (km)
Cement	Karsdorf	75
0/2 sand	Sand quarry	45
2/8 gravel and 8/16 gravel	Brand-Erbisdorf	122
Super-plasticizer and retarder	BASF at Staßfurt	98
Steel fibers and steel bars	Neidenstein	472
Fly ash	Langgons	351

According to the Ecoinvent v3.2 database, the water production included infrastructure and energy use for water treatment and transportation to the end user. The cement production included the manufacturing processes, mixing, grinding, internal transport, and infrastructure. The sand and gravel production included the digging process, internal transport, and infrastructure. The steel bars and fibers production included coal, iron, and ore extraction and processing of scrap, coke making, sinter, blast furnace, basic oxygen furnace, electric arc furnace, and rolling mill. The lorry was fueled by diesel. The lorry data set included the whole fuel supply chain from exploration and extraction of crude oil to preparation to transportation to consumer. Thus, the production of the beams and the component's transportation to the casting site resulted in the LCI that is presented in Table 4.

In this study, to convert the LCI into the LCIA, the ReCiPe2016 method was used. This method allows the use of individualist (I), egalitarian (E), and hierarchist (H) perspectives with regard to environmental problems, which were adopted from cultural theory (Thompson et al. 1990). Individualist perspective evaluates all of the short-term damaging effects. Egalitarian perspective takes into account all of the possible long-term damaging effects. Hierarchist perspective considers the balance between the short- and long-term damaging effects (Huijbregts et al., 2017).

ReCiPe2016 allows the evaluation of these perspectives with both a midpoint and an endpoint-single-score method. The midpoint method evaluates 22 environmental impacts including global warming potential, terrestrial ecotoxicity, fossil resource scarcity, water consumption, and others. The endpoint-single-score method converts these environmental impacts into three environmental forms of damage: damage to human health, ecosystem quality, and resources. By applying average and particular weighting sets to these forms of damage, they can be converted to a single score evaluation. The average weighting set consists of the individualist/average (I/A), hierarchist/average (H/A), and egalitarian/average (E/A) methodological options,

TABLE 4. Life-cycle inventory for the evaluation of the SLB and TLB (EcoInvent v3.2 database, SimaPro, Version 9.0.0.35).

Production process	GWP (kg CO_2)	TE (kg 1,4-DCB)	FRS (kg oil eq)	WC (m^3)
Water treatment (1 kg)	0.000171	0.000409	—	0.00448
Cement production (1 kg)	0.192	0.251	—	0.565
Sand extraction (1 kg)	0.00242	0.0067	—	0.026
Gravel extraction (1 kg)	0.00445	0.0167	—	0.081
Super-plasticizer (1 kg)	1.03	5.53	0.476	0.02
Retarder (1 kg)	1.62	2.06	0.484	0.00634
Steel fibers production (1 kg)	2.32	0.677	0.527	0.0705
Steel bars production (1 kg)	2.31	0.381	0.471	0.00246
Transportation (1 tkm)	0.0663	0.00589	0.0201	0.00000529

Note: kg 1,4-DCB—1,4-dichloro-benzine equivalent.

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and the particular weighting set consists of the individualist/individualist (I/I), hierarchist/hierarchist (H/H), and egalitarian/egalitarian (E/E) methodological options.

The midpoint and endpoint-single-score methods have different advantages and disadvantages. The midpoint method application results in less uncertainty in environmental evaluations. However, the interpretation of 22 environmental impacts is difficult. The endpoint method results in high uncertainty in environmental evaluations. However, the interpretation of three environmental damage types presented as a single score result is less difficult (Huijbregts et al., 2017).

Therefore, to convert LCIs of the SLB and TLB into LCIA results, both midpoint and endpoint-single-score methods were used. Applying the midpoint H method, the four most significant environmental impacts (global warming potential, terrestrial ecotoxicity, fossil resource scarcity, and water consumption) of the beams were analyzed (Pushkar, 2019a). The single-score method contains the six methodological options I/A, H/A, E/A, I/I, H/H, and E/E.

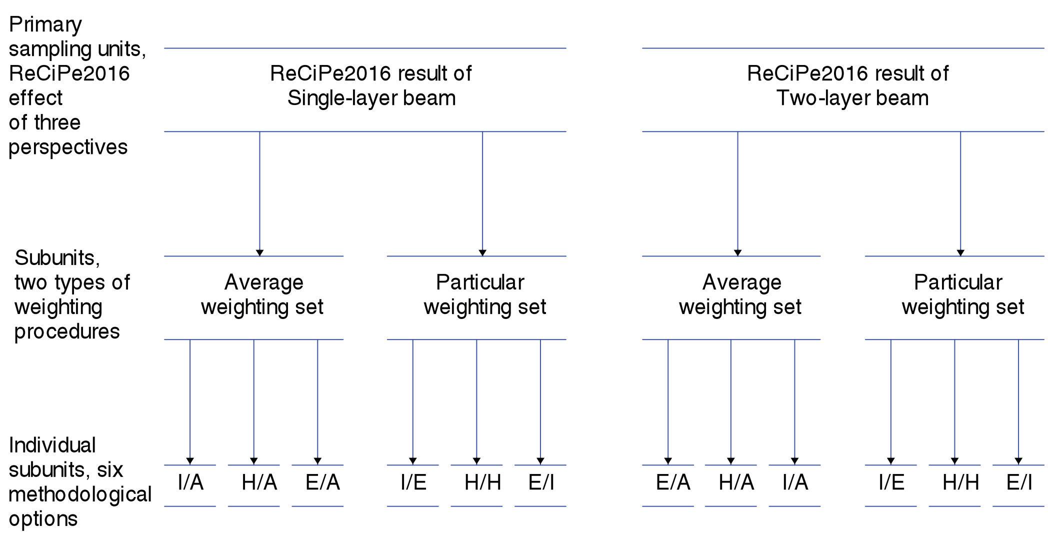
2.3 Design structure

The ReCiPe2016 single-score results (i.e., the I/A, H/A, E/A, I/I, H/H, and E/E methodological options) have the two-stage nested (hierarchical) design structure. Therefore, to conduct a suitable statistical analysis, a two-stage nested mixed analysis of variance (ANOVA) model should be used.

This two-stage nested ANOVA model has the following statistical terminology: sampling frame, primary sampling unit, subunits, and individual subunits. The sampling frame is a collection of all elements (primary sampling units) that are accessible for sampling in the population of interest. A primary sampling unit contains two or more subunits. A subunit contains two or more individual subunits. Measurements were collected from the individual subunits (Picquelle and Mier, 2011).

Figure 4 shows two primary sampling units: the ReCiPe2016 single-score results of SLB and TLB. The primary sampling unit included two subunits, namely, the particular and average

FIGURE 4. Design structure of the two-stage nested hierarchical analysis of variance (ANOVA) that was used for the endpoint method of the environmental evaluation of the SLB and TLB.



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weighting sets, and each subunit included three individual subunits, giving a total of six methodological options. Measurements were collected from the individual subunits. Recently, Pushkar (2019) used this design structure and this statistical model to evaluate environmental performance of bottom ash instead of sand in concretes.

2.4 Statistical analysis

First, the ReCiPe2016 single-score results were multiplied by 10^3 and were log10-transformed. The difference between the two ReCiPe2016 results were then analyzed using a two-stage nested mixed ANOVA (Picquelle and Mier, 2011). According to the recommendation by Hurlbert and Lombardi (2009), the hybrid of the Paleo–Fisherian and Neyman–Pearsonian paradigms (i.e., null hypothesis significance tests (NHST)) were replaced by neo-Fisherian significance assessments. The neo-Fisherian paradigm (1) does not fix α, (2) does not describe p-values as "significant" or "nonsignificant," (3) does not accept null hypotheses based on high p-values but only suspends judgment, (4) interprets significance tests according to "three-valued logic," and (5) presents effect size information if necessary. The p-values were evaluated according to the three-valued logic: "seems to be positive," "seems to be negative," and "judgment is suspended" (Hurlbert and Lombardi, 2009). Hurlbert and Lombardi (2009) cited the recommendation of Gotelli and Ellison (2004), noting that "in many cases, it may be more important to report the exact p-value and let the readers decide for themselves how important the results are."

Recently, it was revealed that two-stage nested mixed ANOVA rather than a t-test is recommended as a supplemental method in evaluations of ReCiPe due the hierarchical structure of the methodological options (Verbitsky and Pushkar, 2018). Following Hurlbert and Lombardi (2009), the p-values were evaluated according to three-valued logic: it seems to be positive (i.e., there seems to be an environmental damage difference); it seems to be negative (i.e., there does not seem to be an environmental damage difference); and judgment is suspended, regarding the environmental damage difference.

3. RESULTS AND DISCUSSION

3.1 The ReCiPe2016 midpoint results

Figure 5 shows that the environmental impacts of the TLB were lower than the environmental impacts of the SLB. Compared to the SLB-related impacts, the TLB-related global warming potential, terrestrial ecotoxicity, water consumption, and fossil resource scarcity impacts were decreased by 15%, 17%, 11%, and 17%, respectively. This means that when there was SLB replaced with the TLB, the decreased quantity of cement and steel fibers were the main responsible factors for decreasing global warming potential and terrestrial ecotoxicity, the decreased quantity of cement was the main factor for decreasing water consumption, and the decreased quantity of steel fibers was the main factor for decreasing fossil resource scarcity.

In this study, the applied steel fiber content was 40 kg/m^3 (Iskhakov et al., 2014). The global warming potential of steel fibers was about 12% of the total global warming potential of the SLB (Figure 5). Such a result is comparable with those presented by Abdulkareem et al. (2019), who also used a similar amount of steel fiber (38.64 kg/m^3) for steel fibered high-strength concrete and reported that in this concrete, about 17% of the total global warming potential stemmed from production of steel fiber (Abdulkareem et al., 2019). However, in the present study, the share of global warming potential related to steel fibers was further decreased to 3% by replacing the SLB with the TLB (Figure 5). Steel fibers also influenced the fossil

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resource scarcity because of extraction of iron ore for production of this component (SimaPro, Version 9.0 2019) (Figure 5).

Cement was the second influential SLB and TLB component, which decreased both global warming potential and terrestrial ecotoxicity (Figure 5). It should be noted that global warming potential and terrestrial ecotoxicity are among the five main most influenced impacts related to cement production, namely, global warming potential, terrestrial ecotoxicity, photochemical oxidation potential, acidification potential, and eutrophication potential (Chen et al. 2010). Cement production is a highly energy intensive process, and therefore, very high CO_2 emissions are realized when the energy is produced with fossil fuels such as coal, oil, and gas (Van den Heede and De Belie, 2012). The cement calcination process is an additional major source of CO_2 emissions (Van den Heede and De Belie, 2012). Cement production also influenced the water consumption impact due to the water required for processes of mixing and grinding of limestone and aluminosilicate materials such as clay for clinker production.

FIGURE 5. The environmental impacts of the single-layer beam (SLB) and two-layer beam (TLB) evaluated with the ReCiPe2016 midpoint method.

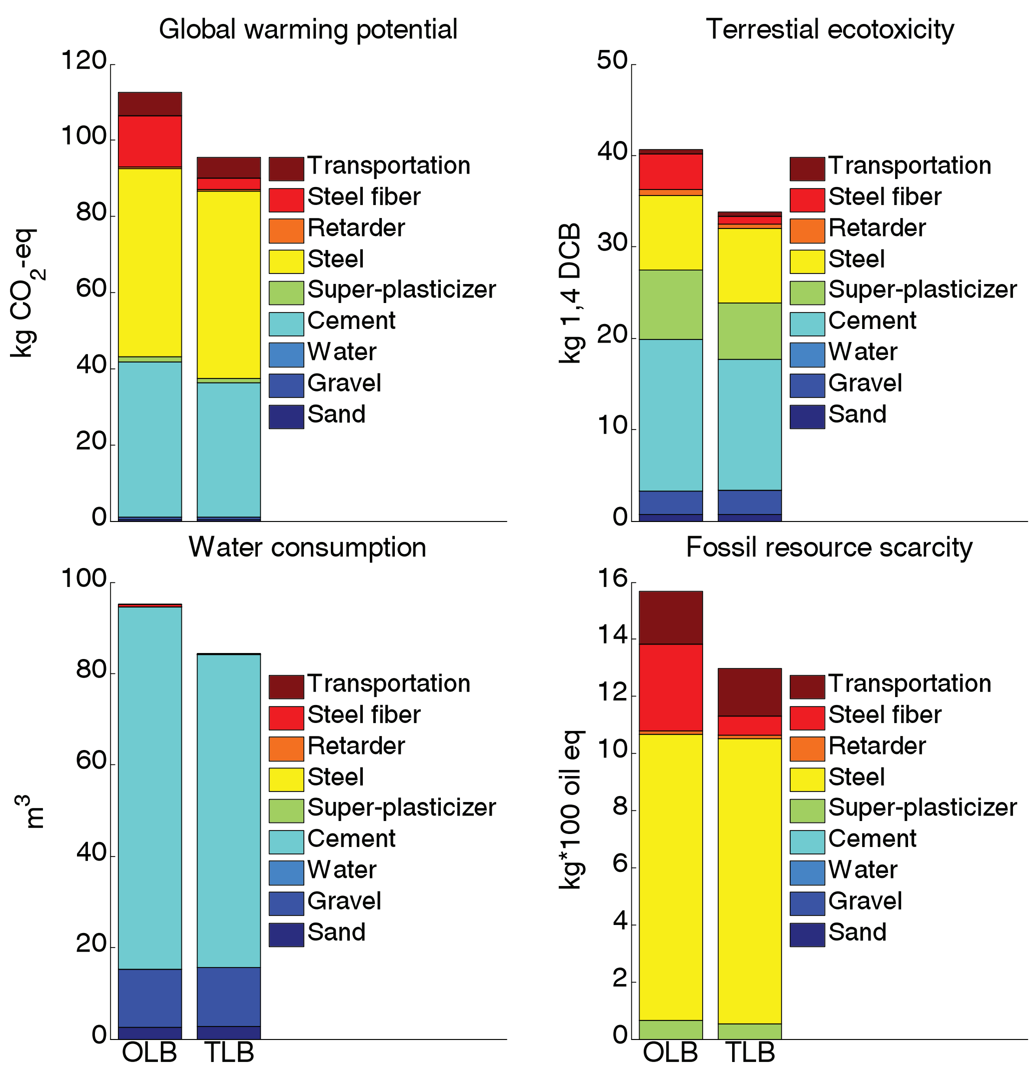

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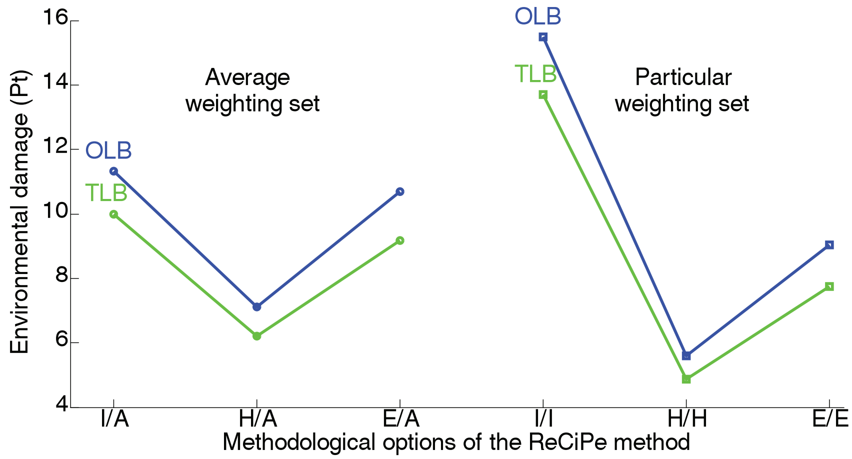
FIGURE 6. The environmental damage of the single-layer beam (SLB) and two-layer beam (TLB) evaluated using the ReCiPe2016 endpoint-single-score method. The difference between the SLB and TLB seems to be positive (p = 0.0256).



3.2 The ReCiPe2016 endpoint-single-score results

Figure 6 shows that the environmental damage decreased when the SLB was replaced with the TBL. This decrease held for all six methodological options. According to the six methodological options evaluated simultaneously, the difference between the SLB and TLB was found to be positive (p = 0.0256). Thus, replacing the SLB with the TLB resulted in a significant decrease of the environmental damage, and this result was found to be independent of applied perspective with regard to different views on the significance of the environmental problem.

The component-related LCIAs of the SLB and TLB were evaluated with the ReCiPe2016 H/A default methodological option (Table 5). Relative to the total environmental damage of the SLB, the cement share was about 63%, reinforcing steel—about 18%, aggregate—about 10%, and admixture—about 1%. Similar results were reported by other researchers; relative to the total environmental impacts/damage of the normal-strength concrete, the shares of cement, aggregate, and admixture were 74%–93%, 0.3%–17%, and 0.7%–1.2%, respectively (O'Brien et al., 2009; Celik et al., 2015; Gursel and Ostertag, 2016) and relative to the total environmental damage of the composite steel column made of high-strength concrete (C100/115), the share of reinforcing steel was 25%–30% (Stengel and Schiessl, 2014).

The ReCiPe2016 H/A endpoint-single-score results showed that the replacement of the SLB with the TLB led to decreases in the cement and steel fiber-related damage and to increases in the aggregate-related damage (Table 5). In particular, the share of the cement and steel fiber-related damage decreased from 62.6% to 62.1% and from 5.2% to 1.3%, respectively, while the share of sand and gravel-related damage increased from 1.8% to 2.1% and from 8.4% to 9.9%, respectively.

4. CONCLUSIONS

This study conducted cradle-to-gate LCAs of two different designs of high-strength concrete beams: a SLB that consisted of steel fibered high-strength concrete in the compression and tensile zones, and a TLB that consisted of steel fibered high-strength concrete and normal-strength

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TABLE 5. The environmental damage of the SLB and TLB components with the ReCiPe2016 H/A default methodological option.

SFHSC beam		Water	Cement	Sand	Gravel	Plasticizer	Retarder	Steel fiber	Steel bars	Total
SLB	Pt	0.004	4.46	0.129	0.599	0.077	0.021	0.371	1.26	7.12
	%	0.1	62.6	1.8	8.4	1.1	0.3	5.2	17.7	100
TLB	Pt	0.004	3.85	0.133	0.612	0.063	0.016	0.081	1.26	6.2
	%	0.1	62.1	2.1	9.9	1.0	0.3	1.3	20.3	100

concrete in the compression and tensile zone, respectively. Both the SLB and the compressed steel fibred high strength concrete layer TLB belonged to the same concrete class C70/85. However, the environmental comparison of these two concrete beam designs showed that the TLB was more environmentally preferable than the SLB.

According to the H approach of the ReCiPe2016 midpoint results, the replacement of the SLB with the TLB led to decreases in the environmental impacts of global warming potential, terrestrial ecotoxicity, water consumption, and fossil resource scarcity. The TLB-related environmental impact benefit was possible due to two steel fibered high-strength concrete components: cement and steel fibers. In particular, the decreased quantity of cement led to the decreased global warming potential, terrestrial ecotoxicity, and water consumption and the decreased quantity of steel fibers led to the decreased global warming potential, terrestrial ecotoxicity, and fossil resource scarcity.

Such a preference for the TLB was confirmed by the six methodological options of the ReCiPe2016 endpoint-single-score results. The replacement the SLB with the TLB decreased the cement and steel fiber-related damage and increased the aggregate-related damage, resulting in significant decreasing of the total TLB-related environmental damage. Thus, considering two different designs of HSC beams, the TLB design was found environmentally preferable to the SLB design in both environmental impact and damage levels of evaluations.

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