Life Cycle Assessment of Concrete Masonry Units with Waste Paper Fibres

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Abstract Renewable or recycled materials have been widely used in the construction industry to achieve a sustainable target. As a kind of short cellulose fibre, a massive amount of waste paper fibre was generated annually from the industrial and construction sectors. However, the research on the use of waste paper fibres in construction/building materials is limited. The feasibility and sustainability of papercrete used as a building material were investigated based on a Life Cycle Assessment (LCA) method by analysing its characteristics compared to four production scenarios. LCA results demonstrate waste paper fibres used as the cement substitute in concrete benefit to reduce the environmental impact compared to traditional disposal.

Keywords Concrete masonry unit · Life cycle assessment (LCA) · Waste paper fibres · Waste disposal management

Abbreviations

ALOP	Agricultural Land Occupation
CMU	Concrete Masonry Unit
FDP	Fossil Depletion Potential
FEP	Freshwater Eutrophication Potential
FETP	Freshwater Ecotoxicity Potential
GWP	Global Warming Potential
HTP	Human Toxicity Potential
IRP_HE	Ionising Radiation Potential
LCA	Life Cycle Assessment

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MDP	Metal Depletion Potential
MEP	Marine Eutrophication Potential
METP	Marine Ecotoxicity Potential
NHL	Natural Hydraulic Lime
NLTP	Natural Land Transformation Potential
ODP	Ozone Depletion Potential Potential
OPC	Ordinary Portland Cement
PB	Papercrete Block
PMFP	Particulate Matter Formation Potential
POFP	Photochemical Oxidant Formation Potential
TAP	Terrestrial Acidification Potential
TETP	Terrestrial Ecotoxicity Potential
ULOP	Urban Land Occupation Potential
WDP	Water Depletion Potential
WPF	Waste Paper Fibre

1 Background

Construction industry and activities related to construction involve natural resources utilisation and high energy consumption activities, which make significant contributions to global carbon emissions. The natural resources and emissions during the production and operation processes of construction sectors are closely related to environment benefit and human health (Sustainability; Fucic 2012).

Concrete as an essential constructional material is widely used globally due to low cost, appropriate mechanical properties and favourable durability. Consumption of 25 gigatonnes per year was reported, with high natural resource consumption and environmental burden (Petek Gursel et al. 2014). Predominantly, the most contribution issues from cement production in the concrete production sector, contributing to around 5% of CO_2 emissions caused by human activities (Worrell et al. 2001).

To reduce the anthropogenic burden on the environment, several substitutes of raw materials were investigated and gradually applied in civil engineering sectors, where industrial by-product or recycled materials were the most common, such as recycled aggregates, GGBS, fly ash, scrap tyres, etc. (Van Den Heede and De Belie 2012; Gartner and Hirao 2015; Chen et al. 2010). Cellulose fibres derived from renewable vegetable materials are considered a sustainable material for replacing the artificial fibres (Ardanuy et al. 2015). Meanwhile, cellulose fibre used as raw materials (cement or aggregate) were investigated to fabricate "green concrete" called papercrete. The concept of papercrete known as an environmental-friendly material due to the utilisation of recycled components is composed of recycled and re-pulped waste paper (Fuller et al. 2006; Manuel 2002).

Some literature studies the properties and utilisation of waste paper in cement or concrete (Booya et al. 2019; Khandelwal et al. 2015). The use of waste paper is supposed to be an environmentally friendly treatment due to the recovery of resources (Ardanuy et al. 2015; Bentchikou et al. 2012; Aigbomian and Fan 2013). On the one hand, the waste paper used as the substitute for cement or aggregates reduces the depletion of natural resources. Furthermore, the use of waste paper in the construction industry provides a promising recycling approach to replace waste paper's current disposal. Typically, waste paper's favourable disposal hierarchy is regeneration as a raw material of recycled paper, incineration, and landfill, respectively (Hanan et al. 2013; Schmidt et al. 2007). Nevertheless, the clarification of environmental benefit by using waste paper is undefined. There is no quantification investigation on the potential environmental benefits for utilising waste paper in civil engineering materials.

To assess the feasibility of waste paper utilisation in terms of environmental impact, this section establishes a comprehensive production system to analyse the overall environmental impact of papercrete block (PB) production and waste paper treatment using the Life Cycle Assessment (LCA) method. Four scenarios of concrete block production systems combining with varying waste paper treatments (incineration, landfill and recycling) were investigated to determine whether the use of waste paper in concrete can obtain higher environmental credits than the traditional processes. Sensitivity analysis was conducted on the influence of partial input flow. The mixing ratio change on the environmental impact was investigated by comparing three mixed proportion schemes and considering the transportation distance.

2 Raw Materials and Mix Proportion

In this study, raw materials, including Ordinary Portland Cement (OPC), sand, gravel, natural hydraulic lime (NHL) and superplasticiser, are used for concrete masonry unit (CMU). The use of NHL aims to adjust the interface of waste paper in papercrete (Mohr et al. 2007). Table 1 shows the physical properties of aggregates used in the experiment.

Waste paper fibre (WPF) used in this study was commercially available, purchased from a millwork plant of China's mineral products. WPF adopted is made from a mixed source mainly consisting of newspaper, roll paper and book paper. All fibres

Table 1 Physical properties of aggregates adopted

Materials	Properties	Value
Coarse aggregate (crushed gravel)	Specific gravity (OD)	2.68
	Absorption (%)	0.70
	Dry bulk density (kg/m^3)	1512.30
Fine aggregate (river sand)	Specific gravity (OD)	2.64
	Fineness modulus	2.72
	Absorption (%)	0.50

were bleached and cut into a short scale with an average length of 1.34 mm. Figure 1 and Table 2 shows the properties and profile of used WPF.

In this study, papercrete was used to fabricate CMU, which requires the slump of fresh concrete closing to zero. Therefore, the initial concrete mixing scheme was designed based on ACI 211 (American Concrete Institute 2009) as a control group, as shown in Table 3. Additionally, there are two application strategies for WPF, replacing cement (WPF-C) and aggregates (WPF-A) by volume, respectively. Table 4 shows the significant properties of conventional CMU, and PB is at a comparable level.

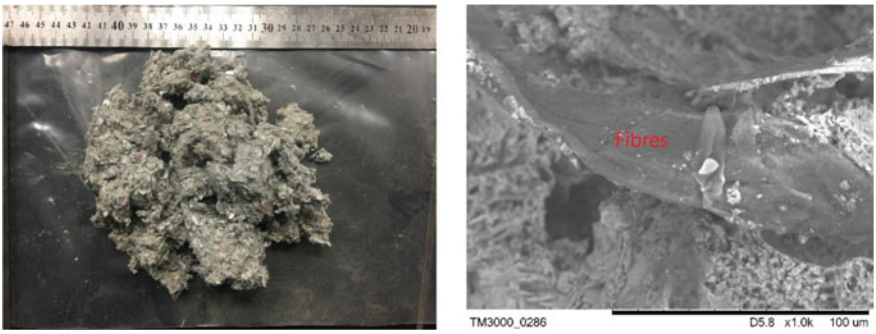


Fig. 1 Image of WPF used in the experiment and Scanning Electron Microscopy of WPF at 1000 magnification

Table 2 Physical properties of WPF

Properties	Values
Average length (μm)	1344.0
Average width (μm)	24.4
Coarseness (mg/m)	0.32
Water retention (g)	1.25
Specific gravity	0.58

Table 3 Materials and mix proportion for 1 m^3 typical concrete and papercrete

CMU	Raw materials (kg/m^3)						
	Cement	NHL	Sand	Gravel	WPF	Tap water	Superplasticizer
Conventional	354.17	/	626.77	1238.57	/	170	17.71
Papercrete	293.96	53.13	614.23	1213.8	15.2	199.37	17.71

Table 4 Major properties of typical concrete block and PB

CMU	Density	Absorption	28-day Compressive Strength	Thermal Conductivity
	kg/m^3	%	MPa	W/m·K
Conventional	2385.21	3.47	8.87	1.82
Papercrete	2103.38	3.97	8.51	1.36

3 The Methodology of LCA

The LCA used in this study is a qualitative and quantitative method to evaluate the potential environmental impact of a process or product within a specific life cycle by calculating inputs and outputs (Jusselme et al. 2018). In general, a complete LCA approach involves a variety of processes in the production system, from the extraction of raw materials to on-site use to final disposal or recycling (LCA definition systems can be summarised as "cradle to grave", "cradle to use" or "cradle to cradle"). All environmental impacts are related to the flow of matter, energy and pollutants into the air and water. LCA method can be used to compare different production plans effectively. Finkbeiner et al. (2006), ISO 14044 (2006) and ILCD handbook guidelines (European Commission 2010) describes and establish a systematic approach for LCA flowchart as shown in Fig. 2, the procedures of LCA are summarised to be

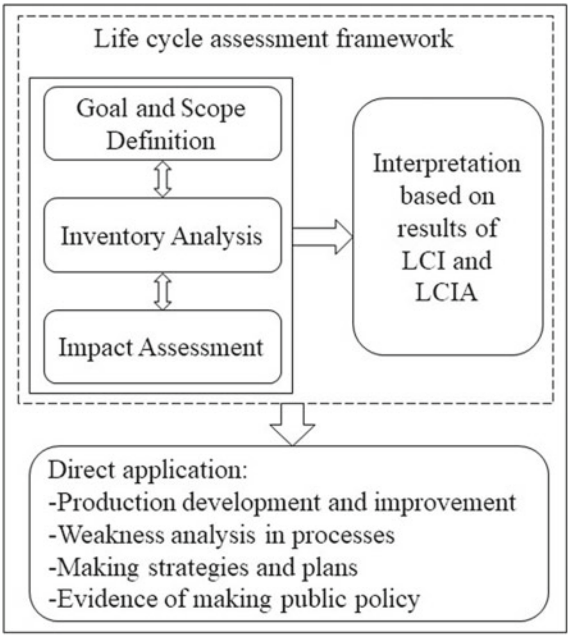


Fig. 2 Flowchart of the LCA method (Finkbeiner et al. 2006)

four stages: (1) definition of the scope and objectives; (2) life cycle inventory (LCI) analysis; (3) life cycle impact assessment (LCIA) and (4) interpretation of results. In this section, the same steps were compiled to expound on the production of a PB.

3.1 Goals and Scope Definition

The primary objectives of LCA study presented herein were to investigate the environmental benefits of lead production over conventional concrete, demonstrate the reasonability of the environmental impact of the use of WPF in concrete, and determine the environmental impact contribution of each step in the production chain. The technical suggestions for improving the environmental protection performance of concrete block production with WPF treatment are put forward. Besides, LCA studies aimed at obtaining clean manufacturing projects are expected to provide information to support developers or decision-makers in making appropriate decisions regarding specific production and waste paper management.

Two main parts of LCA's scope definition should be clarified, the functional unit of production and system boundary. It is crucial to select an appropriate functional unit to assess the production system and compare different production schemes. A volume or weight-based functional unit was adopted in earlier research relating to LCA of construction materials (Ardanuy et al. 2015; Harrison et al. 2010; Hacker et al. 2008). Damineli et al. (2010) pointed out the inaccuracy of volume or weight-based functional unit since in most application cases, the primary function of concrete is physical or mechanical properties. Therefore, considering the functional unit's constant volume or constant weight, a performance-based functional unit is proposed. It is generally accepted that functional performance units considering strength or durability, such as compressive strength, are appropriate and used in many papers (Deschamps et al. 2018; Evangelista et al. 2018; Kleijer et al. 2017; Vieira et al. 2016). In this study, 1 m^3 of a concrete block is adopted to be a functional unit for simplified calculation, which is equivalent to choosing a hollow CMU with the same size as the functional unit (Bakshi 2019), because CMU cells with the same configuration have the same apparent volume. Typically, CUM is used for a non-loadbearing wall or partition wall with a specific volume in practice, additionally owing to the decreased density of PB caused by utilisation of WPF, the volume or the amount of CMU is more appropriate. The prepared hollow CMU with a dimension of 200 $\times$ 200 $\times$ 400 mm, meet the performance requirement of ASTM C140-14 (2018), especially with similar strength. Physical properties were tested according to previous experimental results, and the mix proportion factors of papercrete where w/c, NHL, WPF-C and WPF-A is 0.48, 15%, 2% and 2%, respectively, complied the previous experimental design method to maintain a comparable 28-day compressive strength to the conventional concrete block.

To investigate the reasonability of using WPF as a substitute in concrete by using LCA, the environmental impact caused by CMU production and the potential benefits from avoided WPF disposal should be considered. To produce one functional unit defined previously, the production system started from all raw materials, including upstream production to the finished product transported to the construction site. WPF must be regarded as a raw material in the PB production system, while WPF is discarded and treated in a conventional CMU production system.

Ideally, an integrated life cycle of a product is from the cradle to the grave. However, this research only considers the phases starting from raw materials to the use on-site as above described, the phases of installation, use, maintenance, demolishment and disposal were excluded. Several reasons were considered to limit this system boundary for evaluation: (a) The raw materials production was reported to have a significant environmental impact contribution for building blocks (Galán-Marín et al. 2015). (b) The configuration and properties of the blocks for PB and conventional CMU were identical. Meanwhile, there was no reliable and practicable data for PB installation, use and disposal. Therefore, it is assumed that the follow-up processes (after installation) will not differ significantly, the consumption and emissions were approximately equivalent.

Overall, the completed production system for manufacturing 1 m^3 CMU included two sections in this study, CMU production, and WPF disposal, namely accounting for the cradle to construction site prepared for installation and the expanded boundary caused by WPF disposal. Figure 3 illustrated PB production combining WPF disposal, the avoided conventional disposal of WPF in the highlighted after waste sorting processes. The raw materials production, transportation, WPF disposal and CMU production phases were marked. There were four scenarios established

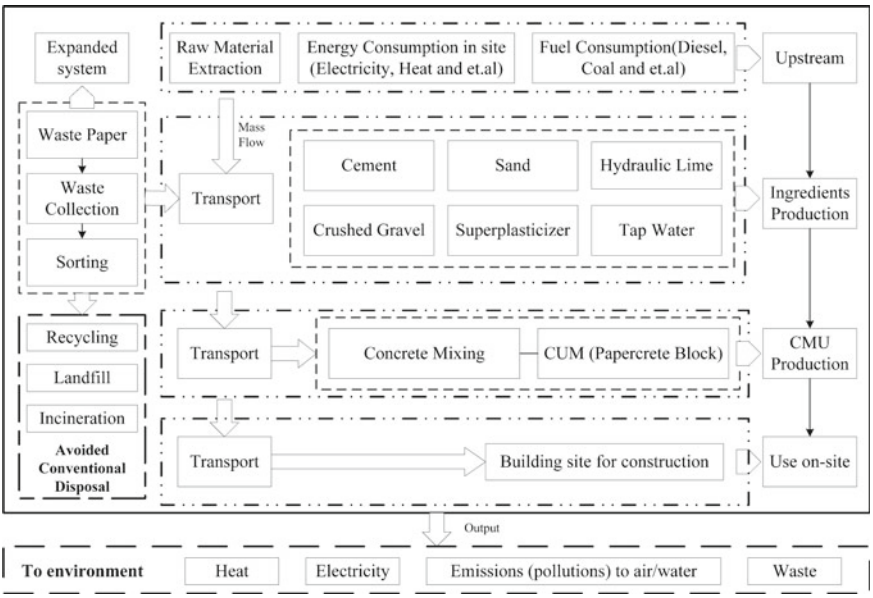


Fig. 3 System boundaries of PB production combining waste paper disposal (cradle to the construction site)

according to the different treatments for WPF. The differences of scenarios were described as following: scenario-1 to 3 contained the conventional CMU production. Scenario-1 involved the incineration of WPF; Scenario-2 involved the landfill of WPF; Scenario-3 involved the manufacture of recycled paper using WPF; Scenario-4 was a completed papercrete production procedure.

3.2 Life Cycle Inventory

It is required to clarify the inputs and outputs' allocation, including mass flow in and out of the processes, the specific substance of emissions, and types of energy consumptions, during the LCI stage. In this study, openLCA 1.9 software (Ortiz et al. 2009) developed in Germany was selected to calculate, evaluate, and interpret the established production system based on the LCI allocation.

The specific source and representative geographical code quoted of inventory data were listed in Table 5. Raw materials production and other consumed materials such

Table 5 Data source and region of LCI for major unit processes in the system

Processes	Geographical code
Raw material production	
– Portland Cement (Kellenberger et al. 2007; Hedrick and James 2010; Boesch and Hellweg 2010)	RoW
– Gravel and Sand (Kellenberger et al. 2007; Künniger et al. 2001)	
– NHL (Kellenberger et al. 2007; Prusinski et al. 2004)	
– Superplasticizer (Althaus et al. 2007)	GLO and RoW
Concrete mixing plant (Marceau et al. 2012; Marceau and Nisbet 2007)	
– Mixing	RoW
– CMU production	
– Concrete mixing factory	GLO
Transportation (Borken-Kleefeld and Weidema 2013)	
– Transport model as the market	GLO
– Transport by truck	
Disposal	
– Waste paper for incineration (Doka 2013)	Row
– Waste paper for landfill (Doka 2007)	
– Waste paper for recycling (Association E-EA 2008; Hischier 2007; Rentz et al. 1999)	
– WPF production (Treichel 2012)	

Notes RoW and GLO are the rest of the world and global data, where GLO is the average data for all countries globally, while RoW (Rest-of -the-World) is the GLO-based data and adjusted with considering the uncertainty as fuel and energy were obtained from Wernet et al. (2016). The manufacture of CMUs involved all typical concrete block manufacture processes, including forming a mould, air-dry, and package. The transports and infrastructure during this process were included as well. However, the LCI of PB mixing and production, which is not available in existing literature or database, was established based on ingredients. A comparable inventory of typical concrete mixing (25–30 MPa) and CMUs production was selected from the Ecoinvent database with relevance to the RoW geographical context. All manufacturing procedures (material treatment and mixing), energy, fuel, and relevant infrastructure were involved.

Meanwhile, the fresh concrete mixing and block fabrication were considered as a whole. The transportation between papercrete production and block manufacture was ignored. The activities of this production started from the reception of raw ingredients at the concrete batching plant gate. The end of the activities was ready-prepared products at the construction site before the delivery.

The inventory data of waste paper disposal was used from the database, only considering the newspaper. The internal transportation of each activity has been included in the raw materials production phases. The defined transportation phases only involved the carriage between different stages with various modes of transportation, and the default transport distance was adopted according to regional statistical data.

3.3 Life Cycle Impact Assessment

To interpret the life cycle inventories based on these numerous impact data and types, LCIA was preformed to classify categories of environmental impact to specific indicators based on quantitative data of LCI, to explain the influence on the environment or human.

ReCiPe method integrated with the Ecoinvent v3.6 database contains the midpoint approach and the endpoint approach. Several representative indexes of LCA in the ReCiPe midpoint method are adopted to support the product decision through summarised assessment. Totally 18 different environmental impact categories are evaluated: agricultural land occupation ($ALOP$, m^2a), climate change (GWP, kg, $CO_2\,eq$), fossil depletion (FDP, kg, $oil\,eq$), freshwater ecotoxicity ($FETP$, kg, 1, 4_DCB eq), freshwater eutrophication (FEP, kg, $P\,eq$), human toxicity (HTP, kg, 1, 4_DCB eq), ionising radiation (IRP_HE, kg, $U235\,eq$), marine ecotoxicity ($METP$, kg, 1, $4\_DCB\,eq$), marine eutrophication (MEP, kg, $N\,eq$), metal depletion (MDP, kg, $Fe\,eq$), natural land transformation ($NLTP$, m^2), ozone depletion (ODP, kg, $CFC\_11\,eq$), particulate matter formation ($PMFP$, kg, $PM_{10}\,eq$), photochemical oxidant formation ($POFP$, kg, $NMVOC\,eq$), terrestrial acidification ($TAP100$, kg, $SO_2\,eq$), terrestrial ecotoxicity ($TETP$, kg, 1, 4_DCB eq), urban land occupation

($ULOP$, m^2a) and water depletion (WDP, m^3). Further, the after characterisation, ReCiPe endpoint provides the normalisation and weighting standards to convert the characterised impact indicators to be three specified categories for comparison.

4 Discussions

4.1 LCI Results and Interpretation

Table 6 summarises the characterised impact of four concrete block production scenarios through the Recipe Midpoint (H) method to investigate the given functional unit's environmental benefit. Compared to the conventional concrete with the incineration of WPF, there is no remarkable improvement of PB production in terms of the life cycle perspective. Most impact indicators of Scenario-3 achieve an acceptable level, indicating that paper recycling is still the most appropriate treatment, demonstrated by several studies (Corcelli et al. 2018; Schmidt et al. 2007).

Table 6 Recipe Midpoint (H) characterised impacts calculated for all scenarios, referred to as a functional unit of 1 m^3 of concrete block

Impact Indicators	Unit	PB	CMU		
		Scenario-4	Scenario-1	Scenario-2	Scenario-3
ALOP	m^2a	9.580E + 01	4.462E + 01	1.793E + 01	5.061E + 01
GWP100	kg CO_2-Eq	4.713E + 02	4.776E + 02	4.724E + 02	4.949E + 02
FDP	kg oil-Eq	9.809E + 01	9.515E + 01	9.506E + 01	9.680E + 01
FETP	kg 1,4-DCB-Eq	3.839E + 00	3.599E + 00	3.516E + 00	3.772E + 00
FEP	kg P-Eq	1.345E-01	1.128E-01	1.188E-01	1.217E-01
HTP	kg 1,4-DCB-Eq	1.575E + 02	1.406E + 02	1.410E + 02	1.486E + 02
IRP_HE	kg U235-Eq	1.275E + 01	1.391E + 01	1.216E + 01	1.375E + 01
METP	kg 1,4-DCB-Eq	3.654E + 00	3.442E + 00	3.356E + 00	3.609E + 00
MEP	kg N-Eq	4.127E-01	4.128E-01	4.053E-01	4.402E-01
MDP	kg Fe-Eq	5.000E + 01	5.419E + 01	5.390E + 01	5.423E + 01
NLTP	m^2	1.868E-01	2.058E-01	2.064E-01	2.057E-01
ODP	kg CFC-11-Eq	2.020E-05	2.270E-05	2.230E-05	2.280E-05
PMFP	kg PM10-Eq	8.167E-01	7.731E-01	7.636E-01	7.842E-01
POFP	kg NMVOC	9.899E-01	1.283E + 00	1.270E + 00	1.310E + 00
TAP100	kg SO_2-Eq	1.181E + 00	1.098E + 00	1.101E + 00	1.134E + 00
TETP	kg 1,4-DCB-Eq	1.006E-01	1.083E-01	2.648E-01	1.086E-01
ULOP	m^2a	9.725E + 00	9.620E + 00	9.577E + 00	9.744E + 00
WDP	m^3	2.186E + 00	2.206E + 00	2.245E + 00	2.223E + 00

GWP100, MDP, NLTP, ODP, POFP, TETP, and WDP of Scenario-1 achieved a slight reduction compared to the other three scenarios. The main reasons causing the decrease of environmental indicators include: The consumption of natural aggregate is reduced slightly. Remarkably, there is a significant increase of ALOP for Scenario-4, compared to the minimum ALOP obtained in scenario-3 (expanded system of recycling paper production), increasing fourfold. The increase of land occupation is reasonable, considering the upstream of WPF production, a set of factories are required to be constructed, such as sorting and fibre production plant.

Compared to Scenario-3, there is no remarkable improvement in environmental impact for the utilisation of WPF, contrary there is a slightly negative effect on the part of environmental indicators. Overall the midpoint indicators of Scenario-4 presented comparable results to scenario-1 (incineration scheme), and better than Scenario-2. Except for ALOP increasing, GWP100, HTP, MEP, MDP, NLTP, ODP, POFP, TETP and WDP decreased by 4.8%, 7.3%, 6.3%, 7.8%, 9.2%, 11.1%, 24.2%, 7.4% and 1.6%, respectively. The partly reduction of carbon dioxide emissions is due to NHL's utilisation replacing cement content, as discussed in the literature review section, compared with cement production, energy consumption, and carbon dioxide emissions during NHL production saved.

Cement production makes a significant contribution to most environmental impact except for MDP, ULOP and WDP. Compared to Scenario-1–3, cement production contributes to each environmental impact decreases in Scenario-4 due to cement usage reduction. The indicators including IRP_He, ODP, and POFP during PB production obtain the environmental credits, the reduction caused by waste paper sorting and transportation processes (Galán-Marín et al. 2015; Treichel, 2012). The possible reasons are the utilisation of methane and avoided incineration. However, these credits are unapparent in the whole system.

Additionally, due to reducing the weight of concrete, the contamination caused by transport has a reduction (however this aspect is not remarkable and affected by distance and carrying capacity). The energy consumption in Scenario-4 is generated from WPF production (WPF collection, sorting and fabrication). However, the recovery of paper is a credit of positive environmental influent.

4.2 Sensitivity Analysis

To access the effect of mixed proportion change on the environmental impact, since the environmental impact of NHL in cement is clarified previously, only WPF-C and WPF-A are modified. Table 7 shows the mix WPF replacement ratio in papercrete, the 28-day compressive strength with these mix proportion is comparable, around 8 MPa.

Figure 4 indicates the change of environmental indicators based on endpoint method with mixing proportions varying. All indicators of scenario-4 with Mix-2 achieve the lowest level compared to other scenarios. The increase in the replacement

Table 7 Mix proportion for LCA comparison

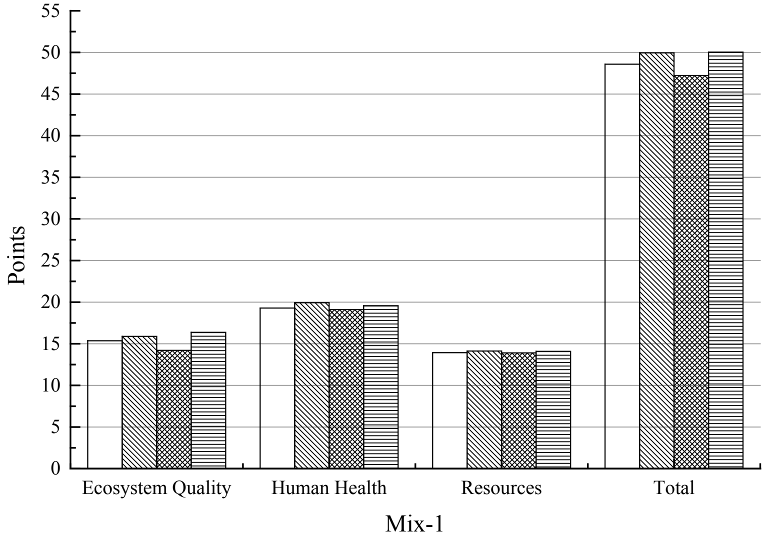
	w/c	NHL ratio	WPF-C	WPF-A
Mix-1	0.48	15	2	2
Mix-2	0.48	15	4	0
Mix-3	0.48	15	0	4

of cement makes a positive effect on the environment. The total point of environmental damage for Scenario-4 with Mix-1 is comparable to Scenario-2, namely the landfill disposal. However, the benefit of increasing WPF-C from 2 to 4% is remarkable. The energy consumption and emissions avoided from cement production, aggregate production, and transport are more significant than those from WPF production. Additionally, the change of scenarios with Mix-3 indicates that WPF production's negative influence is much more considerable than the benefit of avoided aggregates production.

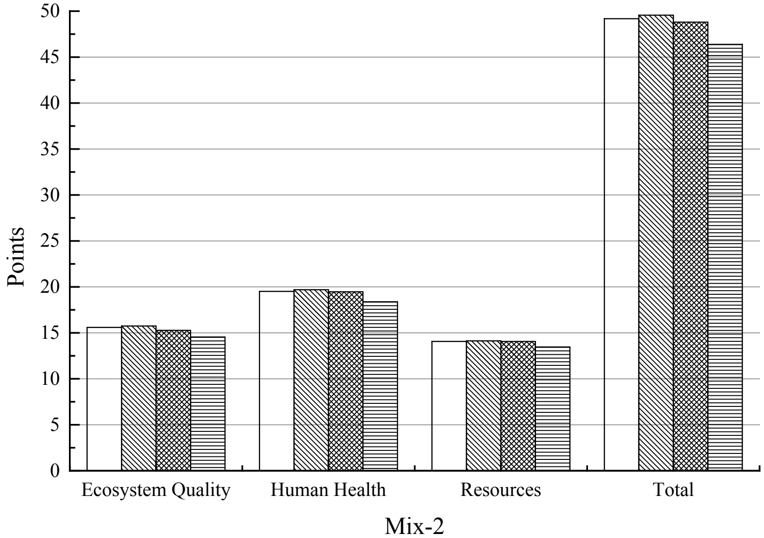
It is predictable for the influence of transport distance on the environmental impact; thus, in this section, only Scenario-3 and Scenario-4 with Mix-1 are selected for comparison. Figure 5 shows that a simulation of transport distances for all transportation activities is conducted, by fixing the distance factor. For the total damage environment indicator, the limiting distance lower is five times. It is essential to mention that the analysis was performed for all impact categories. However, terrestrial ecotoxicity one stood out over the others. However, considering the transportation distance is based on the average of the statistical data in the database, it is a high possibility that the environmental points of Scenario-3 achieve the highest score compared to other scenarios. The total environmental point of Scenario-4 close to Scenario-1 and better than scenario-1 in practice.

5 Conclusions

A cradle-to-gate LCA of papercrete combining with the waste paper disposal procedures was conducted to evaluate if using waste paper to replace concrete ingredients. LCA results for 1 m^3 of papercrete demonstrate using waste paper as a construction material is an environmentally friendly scheme. Compared with the waste paper incineration scheme, every environmental indicator improves, which has more than 70% reduction in greenhouse gas emissions. The most significant contribution is attributed to the elimination of incineration and the reduced use of cement. However, when the amount of waste paper used to replace cement and aggregate is comparable, the environmental indicator adopted in this study has a slight improvement compared to conventional concrete production combined with waste paper recycling. The difference of GWP is negligible. However, environmental benefit increases gradually with

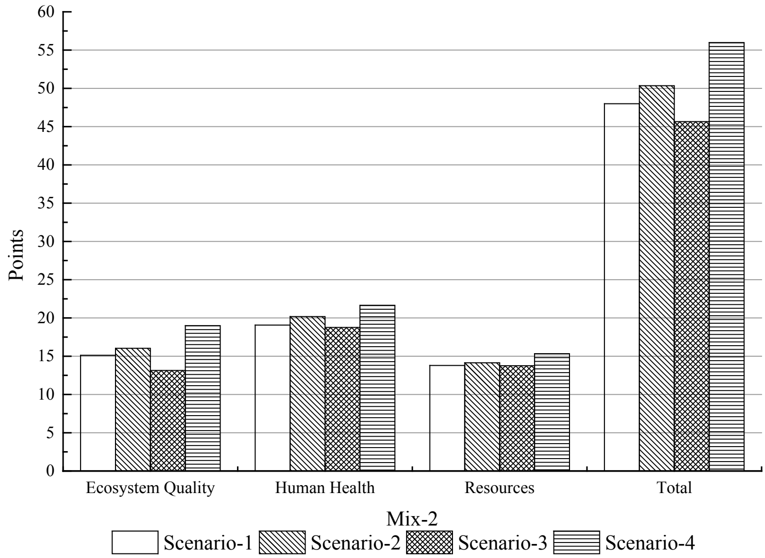


a) Environmental impact points of papercrete with Mix-1



b) Environmental impact points of papercrete with Mix-2

Fig. 4 The environmental indicators of each scenario with the corresponding mix proportion based on endpoint method



c) Environmental impact points of papercrete with Mix-3

Fig. 4 (continued)

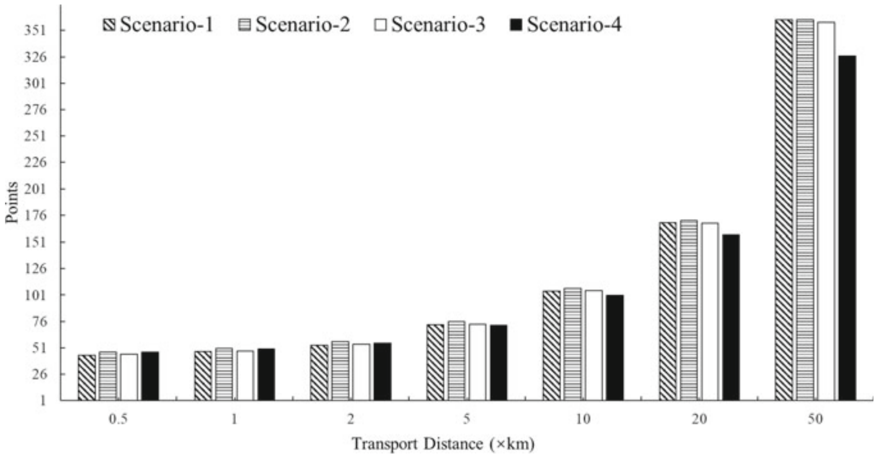


Fig. 5 Sensitivity analysis for all transportation distances, in terms of total damage point

increasing the substitute rate of cement. The environmental impact of WPF production is higher than that of aggregates production. Therefore using WPF to replace the cement content is more beneficial to the environment than using WPF to replace the aggregate content.

Meanwhile, the increase in transportation distance achieves environment credits of PB production. In summary, using waste paper as the concrete ingredient is efficient to relieve the energy consumption and pollution to the environment for both concrete production and paper disposal. The weight reduction is a vital advantage of papercrete, which generates potential environmental benefits in replacing cement.

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