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Research article

A life cycle assessment of cardboard waste in low stress grade concrete applications

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ABSTRACT

Utilising cardboard waste for the partial substitution of cement within concrete has the potential to yield significant sustainability benefits. Cardboard waste is abundantly available, and a significant proportion of this material is disposed of in landfill. However, conversion of waste cardboard into kraft fibres (KFs) for concrete implementation can be utilised in the building and construction industry. Therefore, identification of sustainability variables associated with cardboard waste in concrete is vital. In this study, two KF composites satisfied the criteria for low stress grade concrete and were subsequently evaluated. SFKF5 mix design contained 5% KFs and SFKF105 contained 10% KFs with 5% metakaolin (MK). Both composites had silica fume (SF) as a fibre modification technique for durability purposes. A life cycle assessment (LCA) determined the environmental effect of waste cardboard integration. A Monte-Carlo simulation was utilised as the sensitivity analysis to investigate transportation and energy manufacturing greenhouse gas (GHG) emission variables. LCA results of SFKF105 had a savings of 11%, 8%, 4% and 1% for terrestrial acidification potential, global warming potential (GWP), terrestrial ecotoxicity potential (TEP) and human toxicity potential, respectively. SFKF5 revealed savings of 3%, 2% and 4% for GWP, TEP and marine eutrophication potential, respectively. The additional travel requirements of KFs and MK to the cement batching plant for composite production did not surpass the embodied energy and travel emissions of the control. However, this was negated due to the additional energy requirements to manufacture KFs. The control, SFKF5, and SFKF105 had an average total of 572, 1023 and 997 $kgCO_2$-eq/m^3, respectively.

1. Introduction

Concrete is the most consumed resource on earth following water (Global_cement_and_concrete_association, 2022). A key constituent material in concrete is cement, and the global production of cement contributes to 5–8% of total carbon dioxide (CO_2) emissions (Kajaste et al., 2016). In 2021, the global consumption rate of cement was estimated to be 4.42 billion tons worldwide (Market_Research, 2022). This is a 33% increase of cement consumption over the last decade (Global_cement, 2022). Cement production requires significant energy demands from extraction to transportation. During the production of cement, fifty percent of CO_2 emissions are due to the combustion of fossil fuels and the remaining emissions are caused by the calcination process of limestone (Petek Gursel et al., 2014). The combination of these processes approximately equates to a 0.77 ton of CO_2 emissions released for every one ton of cement clinker produced (Cement_Industry_Federation, 2021). However, this value is dependent on the location, manufacturing equipment, energy sources and production efficiency during each stage of manufacturing (Zhang et al., 2017). Developed countries are continuously investing heavily into infrastructure projects, therefore the demand for cement-based concretes is expected to consistently increase over the next decade (PWC, 2022). The current consumption rate and requirement of virgin materials in concrete is creating mineral resource deficits in countries such as Hong Kong, Germany and the Netherlands. These countries are now importing basic constituent materials for concrete production (The_Observatory_of_Economic_Complexity, 2022; Morley et al., 2022). Therefore, there is an urgent requirement to identify alternative materials to supplement traditional constituent materials in concrete while also reducing greenhouse gas (GHG) emissions and energy consumption. To achieve this, alternative processes in concrete production, resource consumption and waste management systems must be reviewed (Hossain et al., 2017; Haigh, 2023).

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For many decades researchers have experimented with the partial substitution of cement in concrete with industrial waste materials such as fly ash (FA), silica fume (SF), ground blast furnace slag (GBFS) and glass powder (Sandanayake et al., 2020a; Alsaif, 2021; Zhang et al., 2021; Kalakada et al., 2020). These materials are also known as supplementary cementitious materials (SCM)s and can be mechanically beneficial in concrete due to their pozzolanic properties (Mohr et al., 2007). Other SCM materials such as metakaolin (MK) are also seen as a sustainable option to cement due to the reduced energy requirements when processing (Ramli et al., 2016; Haw et al., 2020). Researchers have introduced glass and plastics within cementitious materials due to their pozzolanic reactivity with other constituent materials (Sandanayake et al., 2020a). Waste plastics and glass are becoming popular fillers within road base infrastructure, however, packaging waste materials such as cardboard remain seldom considered (Haigh et al., 2021). This method of integrating common waste materials can assist the drive toward the circular economy framework (Mostert et al., 2021). Although there are promotion difficulties to utilise waste materials in concrete due to a reduction in mechanical strength characteristics (Haigh et al., 2022a). There are opportunities to utilise waste as a constituent material in concrete for low-stress grade applications (Sandanayake et al., 2018, 2020a). The use of low stress grade concrete can include; screeding and slab infill, driveways, footpaths, and various concrete landscaping systems (Base_Concrete, 2022; The_Constructor, 2022). Currently, the building and construction industry promotes the use of waste plastics and glass in infrastructure projects (Jiang et al., 2019; Mondal et al., 2019). Table 1 depicts common waste materials in low stress grade concrete. As shown in Table 1, plastics are the dominant waste material being utilised in low stress grade concrete materials. This is further showcased with the use of plastics becoming a common material in civil construction works. However, minimum research has been conducted on the alternative uses of cardboard waste. Despite many experimental investigations, studies have seldom considered benchmarking total environmental impacts of integrating waste materials in concrete. There are environmental benefits when supplementing high GHG emission producing materials in concrete. However, the additional energy requirements of processing and transport requirements can affect the total environmental benefit initially established. Moreover, solely integrating waste materials does not ensure bespoke concrete is sustainable. Key factors to consider of waste integration are the local availability and material abundance. Due to the wide application of cardboard across many industries and 5.92 million tonnes of cardboard waste produced annually in Australia (Joe Pickin et al., 2020). This research will focus on the integration of cardboard waste in concrete materials to further promote sustainable practices among industry. Researchers (Haigh et al., 2022a, 2022b; Khorami et al., 2017; Ahmad et al., 2021) have focused on utilising kraft fibres (KFs) derived from waste cardboard within cement composites to demonstrate the mechanical and physical characteristics. MK and SF have also been integrated to enhance fibre durability. However, the environmental impact has not been benchmarked when integrating these materials.

Table 1
Waste materials in low stress grade concrete.

Waste material	Partial replacement	Strength (MPa)	Reference
Fly Ash	Cement	25	Afroz et al. (2022)
Ground blast furnace slag	Cement	17	Afroz et al. (2022)
Concrete	Coarse aggregate	22	Allujami et al. (2022)
Glass	Fine aggregate	12–23	Al-Awabdeh et al. (2022)
Glass	Coarse aggregate	17–22.5	Al-Awabdeh et al. (2022)
Polypropylene (e-waste)	Coarse aggregate	5–30	Anand and Hamdan (2022)
Acrylonitrile butadiene styrene (e-waste)	Coarse aggregate	10–51	Anand and Hamdan (2022)
Crumb rubber	Fine aggregate	20–41	Valizadeh et al. (2020)
Ceramic	Fine aggregate	23–28	Ray et al. (2021)
Ceramic	Coarse aggregate	24–26	Ray et al. (2021)
Polyethylene terephthalate	Fine aggregate	21–37	Choi et al. (2005)
Polyethylene terephthalate	Coarse aggregate	9–18	Hossain et al. (2016)
Polyvinyl chloride	Coarse aggregates	16–46	Mohammed et al. (2019)

Hence, the current study focused to analyse and quantify the environmental sustainability of partial cement substitution with KFs in concrete. A life cycle assessment is widely employed to assess the environmental impacts associated with a product or procedure over its life cycle (Sandanayake et al., 2022). The LCA provides a substantial evaluation of the environmental impacts, energy requirements and emission reduction opportunities in various systems and processes. The LCA outcome can assist with making critical decisions toward policies and sustainable investment opportunities (Hossain et al., 2017). Promotion of novel materials require benchmarking of the associated environmental benefits. However, among the previous LCA studies conducted on concrete materials (Liu et al., 2022; Cheng et al., 2022; Duan et al., 2022; Patrisia et al., 2022), few have focused on the integration of waste materials that reside in the residential and commercial sector. In addition, no LCA study has been presented with KF integration in concrete materials. To measure the environmental impact of low-stress grade concrete, three strategies will be implemented in the LCA. First, the optimal KF concrete compressive strength is determined of the novel composites via SF fibre and MK matrix modifications. Secondly, LCA impact categories are selected and measured. Finally, a sensitivity analysis of the bespoke composites is conducted to reduce the parameter variables of concrete production. This paper aims to demonstrate the viability of waste cardboard integration and outlining the environmental affect when integrated within concrete.

2. Research significance and methodology

The detrimental impacts on the environment from various industries are becoming increasingly criticised due to globally accepted climate change reduction targets and the construction industry is no exception. Comprehensively quantifying the environmental impacts of building and construction materials over the whole life cycle is an effective method to benchmark sustainability benefits. Nowadays, the search for locally available alternative materials to replace energy-intensive virgin resources is a popular and an effective approach to achieve sustainable material products that contribute to circular economy (Mostert et al., 2021). Use of abundant waste materials as a supplementary virgin material can both solve the issues of excessive resource depletion and significant landfills due to extreme waste generation. Use of waste materials in concrete to replace cement and aggregates have been a prominent research focus over the past decade with included materials such as masonry, plastics, glass, FA and GBFS (Al-Awabdeh et al., 2022; Anand and Hamdan, 2022; Krishnaraj et al., 2020; Apithanyasai et al., 2020; Guo et al., 2020). However, research is still exploring the possibility of using novel waste materials in concrete otherwise would end-up in landfills. The world business council for sustainable development (WBCSD) created a cement technology roadmap to identify opportunities of CO_2 emission reductions by 2050. The WBCSD identified four fundamental areas that the cement industry must adopt to achieve emission targets worldwide. These include a source of alternative fuels, energy efficiency, clinker substitutions, carbon capture and storage (sustainable_developments, 2021). Moreover, the integration of alternative waste materials in concrete can ensure the building and construction industry aligns common construction methods with positive environmental change. Therefore, LCA investigations can promote the use of alternative methods based on environmentally positive sustainable results, before large economic investments are required for further development. The use of kraft fibres derived from waste cardboard in concrete materials has not been environmentally benchmarked. Therefore, this research will investigate the mechanical strength characteristics of KFs with a potential application. This will determine the acceptable KF concrete mix design to assess for their environmental characteristics. Moreover, an in-depth sustainability analysis is required to comprehensively determine the effect of sensitivity factors. Fig. 1 illustrates this research methodology.

3. Assessment methodology

3.1. Experimental mechanical testing

Compressive strength testing was conducted on the Matest C088-11 N Servo-Plus evolution testing machine and Cyber-Plus evolution data acquisition system. The constituent materials were mixed via a mortar mixer in accordance with AS/NZS 1012.2 (AS/NZS-1012.2, 2014). SF was applied to the fibres as a modification technique conforming with AS/NZS 3582.3 (AS/NZS-3582.3, 2016). Matrix modification using MK was used in accordance with ASTM C-618 (ASTM-C-618, 2019), Class N specifications for natural pozzolans. Fine and coarse aggregates were sourced in accordance with AS/NZS 1141.5 (AS/NZS-1141.5, 2000) and AS/NZS 1141.6.2 (AS/NZS-1141.6.2, 1996), respectively. General purpose cement was the main pozzolanic constituent material conforming with AS/NZS 3972 (AS/NZS-3972, 2010). The composition of the cement is shown in Table 2. Regular potable water was used throughout all mix designs. All samples were created in a laboratory environmental in accordance with AS/NZS 1012.8.2 (AS/NZS-1012.8.2, 2014). The specimens created are to demonstrate viability of the materials being used among industry practices. The processing technique is demonstrated in Fig. 2.

Table 2
Composition of general-purpose cement (Independent_Cement, 2017).

Material	Formula	Proportion
Portland cement clinker	NA	>92%
Lime stone	$CaCO_3$	0–7.5%
Gypsum	$CaSO_4.2H_2O$	3–8%
Clinker Kiln dust	NA	0–2.5%
Chromium (VI) hexavalent	Cr^{6+}	Trace

3.2. Life cycle assessment

To compare the environmental impacts of concrete prepared with the selected waste material, the LCA approach is required. This study utilised OpenLCA as the primary software in conjunction with Ecoinvent 38 database (Ecoinvent, 2022; OpenLCA, 2022). The methodology of the current LCA study presented was in accordance with the ISO 14044 (Organisation_for_Standardisation_ISO_14044 and I, 2006). According to the ISO 14044, the LCA methodology has four primary requirements including scope definition, inventory analysis, impact assessment and interpretation.

3.2.1. Scope functional unit, and system boundary

Previous LCA studies have been conducted to compare environmental benefits of integrating various waste materials within cementitious composites, demonstrating their environmental impacts (Sandanayake et al., 2022; Jian et al., 2021; Goh et al., 2022; Nikbin et al., 2022). These studies included coffee cup waste, polyethylene bottles and recycled concrete aggregate waste as a supplementary virgin material in cementitious composites. However, according to the recent review and understanding, the current study is the first attempt to investigate the environmental impacts associated with re-using

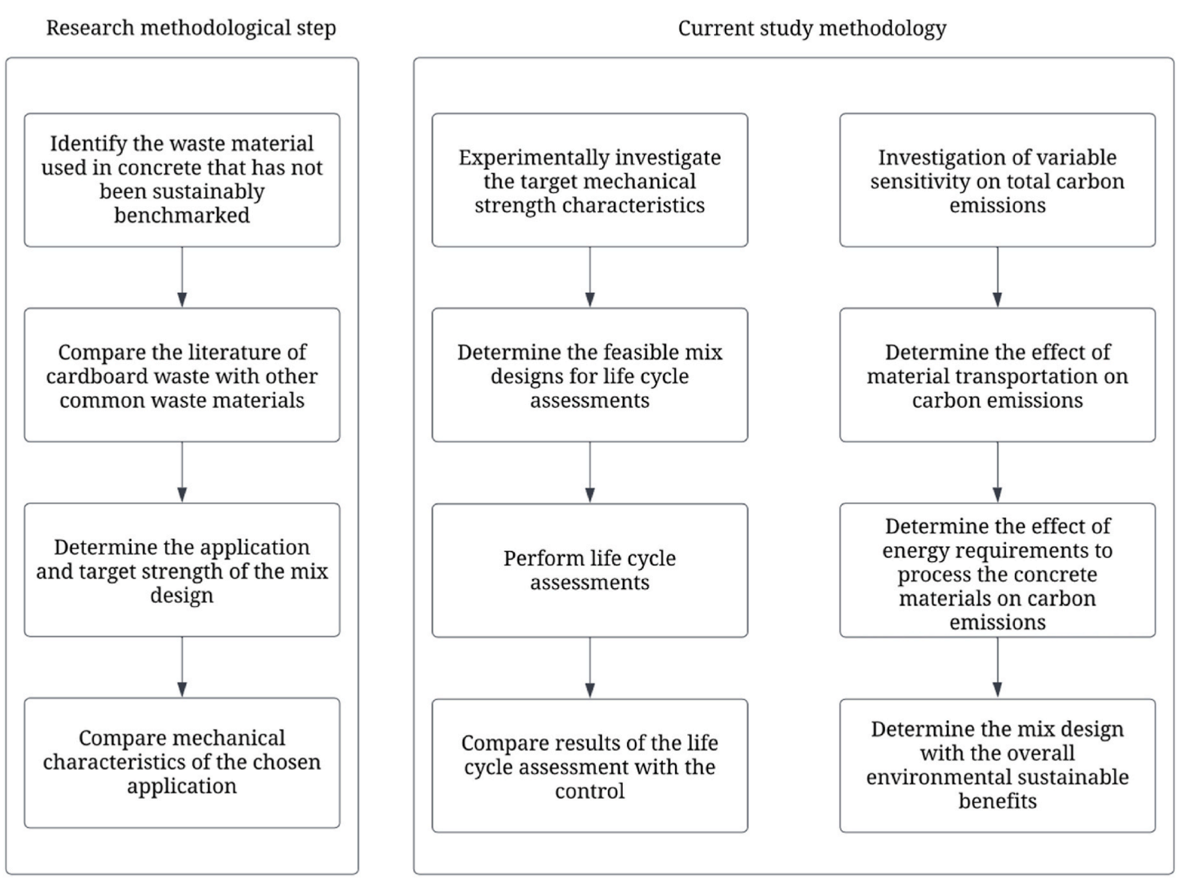

Fig. 1. Research process and methodology.

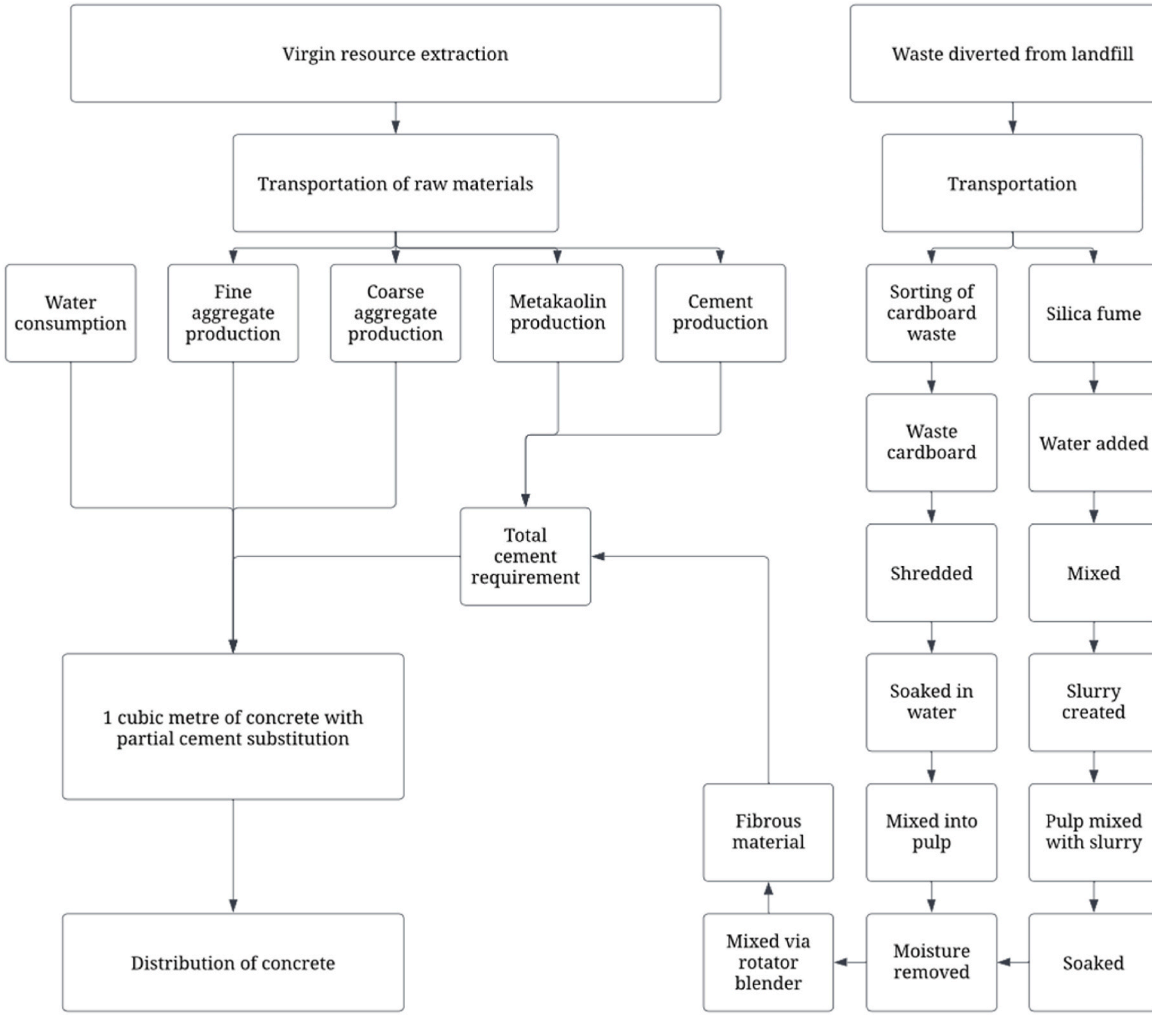

Fig. 2. System boundary for the current study.

cardboard waste materials as a cement replacement material in concrete. Therefore, the current LCA focused on identifying, comparing, and analysing the environmental impacts related to the production of concrete using cardboard waste as a partial cement substitution. The results aim to demonstrate the viability of diverting cardboard waste from landfills and highlight potential environmental benefits associated. Concrete production of all mix designs was created at a laboratory scale to ensure an effective comparison of the novel materials by reducing unknown variables.

The functional unit for concrete in the current LCA study was taken as 1 m^3. The functional unit provides reference to the input and output data and is an important measurement for the final interpretation of the results (Zhang et al., 2019). The study considered a cradle-to-gate system boundary as shown in Fig. 2 to evaluate and compare environmental impacts. The cradle-to-gate process includes the extraction, transportation, production, and distribution of the final concrete materials to a construction site. The maintenance, usage life cycle and final disposal of the various concrete mix designs are assumed to be the same and therefore are excluded from the system boundary.

3.2.2. *Life cycle inventory analysis*

Laboratory process similar to an industry production was used to enable the successful integration of cardboard waste within concrete composites (Coutts, 2005). The cardboard used in this study were extracted from common packaging materials ready to be sent to the material recovery centre. Cardboard waste was subjected to a composition transformation to be used as a constituent material in concrete which included reducing materials to a pulp. It was then transferred into a fibrous material via thermal and blending techniques and the resulting fibres extracted from waste cardboard were called as kraft fibres (KF). In this study, LCA are conducted on three mix designs to compare the environmental impacts for potential use in low stress industry applications such as concrete driveways, screeding and slab infill, footpaths, and various concrete landscaping systems. The mix design compositions are presented in Table 3. The samples included the control, SF modified KFs, and a combination of matrix and fibre modified specimens. It is important to note that surface modification is applied using SF on the KFs at a maximum of 2% loading of the total amount of KFs. This has been shown to be sufficient as a fibre modification technique to enhance the durability of the fibres in high alkaline environments (Haigh et al., 2023a). Moreover, the application of SF can also improve the mechanical strength of cementitious composites, reduce permeability and thermal cracking (Haigh et al., 2023b).

In addition to fibre modified concrete samples, matrix modification

Table 3
Composition of various mix design specimens per cubic metre.

Mix designs	Cement	SFKF	MK	Fine aggregate	Coarse aggregate	Water
Control	355.9			733.6	1100.5	210
SFKF5	338.1	17.79		733.6	1100.5	210
SFKF105	302.52	35.58	17.79	733.6	1100.5	210

using metakaolin was integrated at a 5% cement replacement rate. Metakaolin is a highly reactive pozzolanic material obtained by the calcination of kaolin clay. The calcination process involves heating the kaolin clay between 600 and 850 °C. This process transforms the mineral kaolinite into a material with different properties known as metakaolin (Harikaran et al., 2023). The use of metakaolin as SCM is seen to be a sustainable alternative to cement as the energy required is significantly less (Haw et al., 2020). The energy requirements and sources of all constituent materials such as fine aggregate, coarse aggregate, MK, and general-purpose cement are shown in Table 4. It is important to note that the energy requirements and sources for the conversion of cardboard waste into KFs are detailed in 4.3.2 Energy emissions.

The concrete mix designs were based on a target compressive strength target of 25 MPa. There are additional energy and transportation requirements for the processing and integration of KFs. However, all other materials are assumed to be transported to a one batching plant for concrete production. The mix design code correlates to “SF”- silica fume, “KF”- kraft fibre, the initial number of ‘10’ represents the fibre percentage and the final number ‘5’ representing the amount of MK within the mix design.

3.2.3. *Life cycle impact assessment*

There are three elements of a life cycle impact assessment (LCIA). This is the selection of impact categories; classification of the categories and calculation of the category indicator results. This section quantifies the environmental impacts. The problem-orientated method is adopted for this research and is also known as the “midpoint method”. The midpoint method correlates to the environmental categories for which this study will identify, compare, and analyse. Based on the current global environment, the following seven impact categories were selected. Terrestrial acidification potential (TAP100 in $KgSO_2$-eq), global warming potential (GWP100 in $kgCO_2$-eq), terrestrial ecotoxicity potential (TEP100 in Kg 1, 4-DCB-eq), marine eutrophication potential (MEP100 in Kg-N-eq), human carcinogenic toxicity potential (HTP100 Kg 1, 4-DCB-eq), stratospheric ozone layer depletion potential (ODP100 Kg CFC-11-eq) and mineral resource scarcity potential (MRS in Kg Cu-eq). The normalisation factors for each of the impact categories is summarised in Table 5. The ReCipe hierarchist (h) Midpoint method was used which combines the eco-indicator 99 and CML baselines. OpenLCA software using the Ecoinvent 38 database was used to model material and energy flows for the system boundary considered.

3.2.4. *Limitations and assumptions*

The scope, and system boundaries of LCA studies retain limitations and assumptions due to the research direction and desired objectives. The current study has the following assumptions and limitations.

- The study did not consider end of life behaviours with assumption that all the mix designs will have similar end-of-life considerations
- The study assumed the lifespan of the bespoke mix designs equalled that of the control
- The supply of processed waste cardboard is assumed to be locally available in abundance
- Where emission inventories are not available, emission factors are adopted from published literature
- Waste cardboard conversion into fibrous material was assumed to be conducted at the waste recovery centre
- An equal transportation distance of 36 km was used to transport fine, coarse and cement materials to the concrete batching plant
- The mortar mixer used 4 kWh to create 1 cubic metre of concrete
- Medium voltage power supply is used for the mixing of concrete, drying of fibres and blending of cardboard materials
- Conventional treatment of potable water was assumed, and the corresponding emission inventories were adopted from existing databases

Table 5
Impact categories and normalisation factors.

Impact category	Normalisation factors		
	Unit	Value	Reference
Terrestrial acidification potential	$KgSO_2$-eq	4.10E+01	(Ecoinvent, 2022; OpenLCA, 2022)
Global warming potential	GWP100 in Kg CO_2-eq	7.99E+03	(Ecoinvent, 2022; OpenLCA, 2022)
Terrestrial ecotoxicity potential	Kg 1, 4-DCB-eq	1.04E+03	(Ecoinvent, 2022; OpenLCA, 2022)
Marine eutrophication potential	Kg-N-eq	4.61E+00	(Ecoinvent, 2022; OpenLCA, 2022)
Human carcinogenic toxicity potential	Kg 1, 4-DCB-eq	2.77E+00	(Ecoinvent, 2022; OpenLCA, 2022)
Stratospheric ozone layer depletion potential	Kg CFC-11-eq	5.90E-02	(Ecoinvent, 2022; OpenLCA, 2022)
Mineral resource scarcity	Kg Cu-eq	1.20E+05	(Ecoinvent, 2022; OpenLCA, 2022)

3.3. *Sensitivity analysis*

A Monte-Carlo (MC) simulation is a sampling method to perform an uncertainty analysis of the parameter variables and investigate its influence on the total output (Jafarikia et al., 2022). The MC simulation is a technique used in mathematical model that captures the variability of data in a system using probability distribution (Ita-Nagy et al., 2020). In this study, material transport and energy requirements to produce the novel concrete composite materials can be considered uncertain. The scope of the study is to measure the environmental effect of the various mix designs and therefore the sensitivity analysis using the MC simulation will focus on the GHG emissions created. Table 6 demonstrates the GHG emission factors from transportation and energy sources. In this study, the MC simulation utilises the triangular probability distribution. This is a continuous probability used to represent uncertain variables to which values fall within a specific range. It is triangular when plotted on a graph and defined by three parameters (within the range).

- The minimum value
- The maximum value
- The most likely value

The use of the triangular probability distribution is used in this study

Table 4
Energy inputs for material production (megajoules per kilogram).

Materials	Brown coal	Black coal	Crude oil	Geothermal	Solar energy	Water power	Wind power	Natural gas	Ref
Cement	11.9	26.3	1506.27	5.18	0.24	2.07	0.30	44.1	(Ecoinvent, 2022; Ecoinvent_ecoquery, 2023a)
MK	11.9	26.3	42.3	–	–	–	–	44.1	(Ecoinvent, 2022; Ecoinvent_ecoquery. Kaolin production, 2023)
Fine aggregate	11.9	26.3	42.3	0.00003	–	–	–	44.1	(Ecoinvent, 2022; Ecoinvent_ecoquery, 2023b)
Coarse aggregate	11.9	26.3	42.3	0.00011	–	–	–	44.1	(Ecoinvent, 2022; Ecoinvent_ecoquery. Gravel production, 2023)

Table 6
Input variables used for Monte-Carlo simulation.

Variable parameter	Minimum	Maximum	Probability distribution	Reference
Transportation truck emissions	0.161	0.307	Triangular	(Institute_for_global_environmental_strategies, 2022; IEA, 2022; Protection_Agency. and E, 2022)
Coal (black and brown) emissions	0.63	1.63	Triangular	(Institute_for_global_environmental_strategies, 2022; IEA, 2022; Protection_Agency. and E, 2022)
Gas emissions	0.27	0.9	Triangular	(Institute_for_global_environmental_strategies, 2022; IEA, 2022; Protection_Agency. and E, 2022)
Renewable energy emissions	0.03	0.09	Triangular	(Institute_for_global_environmental_strategies, 2022; IEA, 2022; Protection_Agency. and E, 2022)
Construction site distance (km)	10	150	Triangular	(Lin et al., 2010; Tzanetos et al., 2023; Maghrebi et al., 2015)
Production time (minutes)	60	300	Triangular	(Ghafoori et al., 2018; DIY_Questions_and_Answers, 2023; ScrewFix, 2018)
Capacity of cement mixer (kWh)	0.8	1.1	Triangular	(Edisons, 2023a; Forestwest, 2023; Sales, 2023)
Capacity of rotator mixer (kWh)	1.2	1.6	Triangular	(Pro_Plaster_Products, 2023; Edisons, 2023b; BricoINN, 2023)
Capacity of rotator blender (kWh)	1.1	1.5	Triangular	(Mytopia, 2023; DHGate, 2023; NISBETS, 2023)
Capacity of oven (kWh)	0.5	1.8	Triangular	(LabFriend, 2023; LabDirect, 2023; Across_International, 2023)
Capacity of cardboard shredder (kWh)	0.6	1.4	Triangular	(Brentwood_Recycling_Systems, 2021; Recycling. Cardboard Shredders, 2023; Protective_Packaging, 2023)

due to the minimum and maximum values known for energy consumption, with the output of the simulation providing the most likely. This approach assists when assessing the possible range of outcomes and their probabilities, providing valuable insights into the behaviour of complex systems affected by uncertain variables.

4. Results and discussion

4.1. Experimental results

The compressive results of the various mix designs are graphically depicted in Fig. 3. The standard deviation is shown via error bars in Fig. 3. Two KF composites were chosen that achieved the desired compressive strength of low stress grade concrete. The workability of the composite was not compromised with fibre integration. The results in Fig. 3 demonstrate that fibre integration lowered the desired compressive strength. Integrating fibrous materials can create additional voids in the concrete matrix, resulting with a lower mechanical strength when under implied stress. However, the SF content (silicon dioxide) on the fibre walls consumes calcium hydroxide ($Ca(OH)_2$) which can mitigate degradation on the fibres. This has shown to enhance the composite compressive strength and enabled the two samples shown in Fig. 3 to be acceptable in this study. SFKF5 and SFKF105 had 20 and 21 MPa at 28-days. The strength of the material was deemed compatible for low-stress concrete applications and therefore a comparison of the material for LCA was deemed appropriate. Fig. 4 illustrates the SFKFs used in this study. As can be observed, the fibre content varies in size from approximately 10-36 μm. This is due to the variation of natural fibrous materials that undergo thermal and chemical treatments during the pulping process.

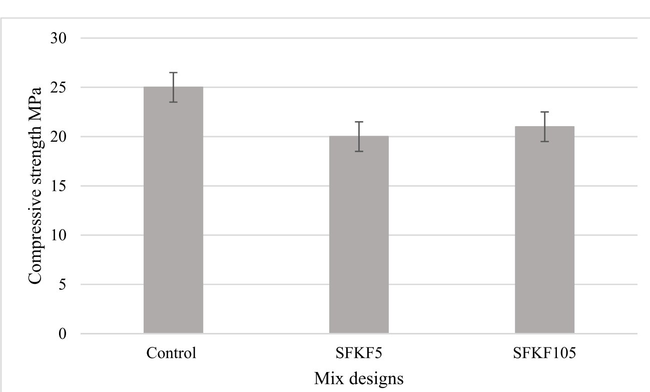

Fig. 3. Compressive strength results.

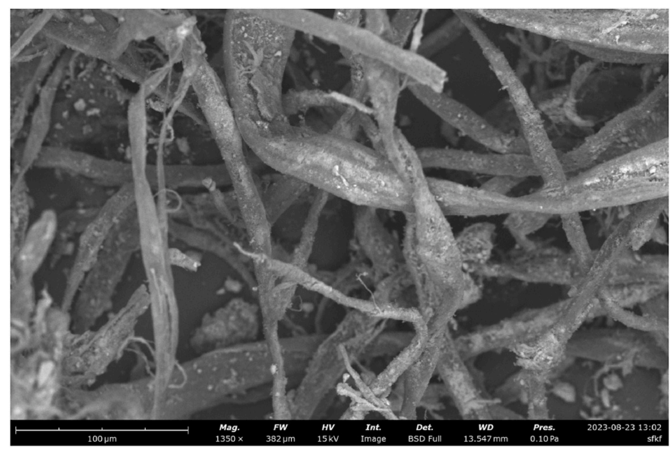

Fig. 4. SEM image of SFKFs.

4.2. LCA findings

The LCA primary objective was to compare the disparity of results against the environmental categories when integrating waste cardboard as a partial cement substitute in concrete materials. The initial LCA findings included transportation of materials to the concrete batching plant. This study included the city of Melbourne, Australia as a case study to exemplify the findings. Waste cardboard materials were sourced from a local resource recovery centre located 37 Km from a

Table 7
LCA results of mix designs.

Impact category	Unit	Control	SFKF5	SFKF105
Terrestrial acidification potential	Kg SO_2-eq	7.62E-01	7.80E-01	6.84E-01
Global warming potential	KgCO_2-eq	3.70E+02	3.60E+02	3.43E+02
Terrestrial ecotoxicity potential	Kg 1, 4-DCB-eq	6.58E+02	6.48E+02	6.38E+02
Marine eutrophication potential	Kg-N-eq	5.06E-03	5.17E-03	5.13E-03
Human carcinogenic toxicity potential	Kg 1, 4-DCB-eq	5.61E+00	5.64E+00	5.53E+00
Stratospheric ozone layer depletion potential	Kg CFC-11-eq	6.30E-05	6.20E-05	8.48E-05
Mineral resource scarcity	Kg Cu eq	1.26 + 00	1.42E+00	1.37E+00

concrete batching plant. All other constituent materials for concrete production were sourced 36 Km from the nearest quarry. Table 7 demonstrate the results of the various mix designs against the impact categories. Table 8 demonstrates the difference of impact categories between the various mix designs and the control. 5% waste cardboard material integrated within concrete materials demonstrate a negative effect on TAP100. This is shown with SFKF5 having a 0.018075 kg. It is important to note that the integration of 5% MK improves the TAP100. All fibre integrated mix designs demonstrated an improved GWP100. This shows integrating cardboard waste materials in concrete can inherently reduce the GWP by reducing cement requirements. The highest contributor toward TEP100 was the control with 658 kg 1, 4-DCB-eq. Again, the higher the percentage of cardboard waste reduced the negative effect of TEP100. The MEP100 was varied marginally compared to the control and fibre mix designs. HTP100 increased with 5% fibre integration. This is due to the extra processing requirement undertaken when converging waste cardboard into a fibrous product ready for composite integration. However, increasing fibre percentage from 5 to 10% reduces this negative impact marginally. ODP100 increases as the fibre percentage increases. This is primarily due to the increased processing requirements like the negative effect of HTP100. MRS improves when fibre is integrated at all levels compared to the control. However, when MK is utilised as a SCM, the negative effect increases past that of the control. This is because MK is dehydroxylated form of the clay mineral kaolinite (Wei et al., 2017). Although abundant in some areas, limestone is still a more common material to source for cement production. Hence, the MRS is higher when MK is integrated in the composite design.

Fig. 5 graphically depicts the GHG emissions produced from the various constituent materials in the three mix designs. The emissions are of resource extraction and constituent material manufacturing ready for concrete integration but do not include the production or transportation of the novel concrete composites. As shown, the highest GHG emission producer is cement. The control had the highest percentage of cement and resulted in 335.8 kgCO_2-eq/m^3. SFKF5 and SFKF105 emitted 319.01 and 285.43 kgCO_2-eq/m^3, respectively. As the percentage of cement is reduced, the overall GHG emission is reduced. Cement attributes 90, 89 and 86% of total material GHG emissions for the control, SFKF5 and SFKF105 samples. The high percentage represents an opportunity to potentially reduce GHG emissions with just one constituent material. KFs have not been included in Fig. 5 due to the uncertainty factors when producing the material for concrete application. The following section will demonstrate these material variables. 5% MK integration demonstrated 5.77 kgCO_2-eq/m^3. This is significantly less than 16.79 kgCO_2-eq/m^3 for 5% cement integration. Although MK can only be partially substituted for cement due to the reduction of mechanical properties, the material demonstrates environmental benefits, nonetheless.

Table 8
Potential environmental savings using KF in concrete.

Impact category	Unit	SFKF5	SFKF105
Terrestrial acidification potential	Kg SO_2-eq	−1.81E-02	7.74E-02
Global warming potential	KgCO_2-eq	1.00E+01	2.65E+01
Terrestrial ecotoxicity potential	Kg 1, 4-DCB-eq	9.75E+00	2.05E+01
Marine eutrophication potential	Kg-N-eq	−1.04E-04	−6.49E-05
Human carcinogenic toxicity potential	Kg 1, 4-DCB-eq	−3.35E-02	7.73E-02
Stratospheric ozone layer depletion potential	Kg CFC-11-eq	1.01E-06	−2.18E-05
Mineral resource scarcity	Kg Cu eq	5.34E-02	−1.04E-01

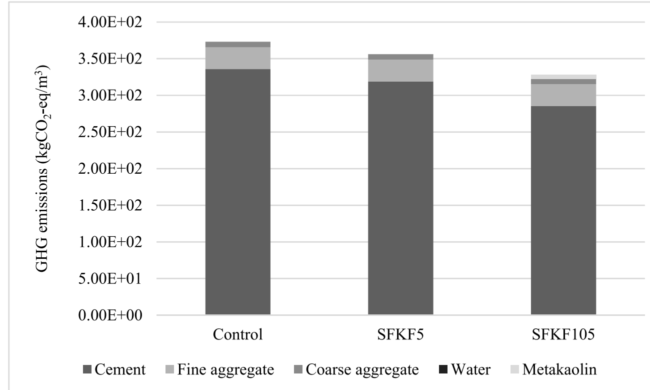

Fig. 5. GHG emissions of concrete composites (1 m^3).

4.3. Monte-Carlo simulation results

4.3.1. Transport emissions

The pre-production transportation is generally considered as a sensitive factor in the LCAs due to the high variable of possible distances and individual transport emissions (Jian et al., 2021). Due to the uncertainty of this factor in future case studies, a MC simulation was conducted to analyse the influence of input parameters on the LCA outcomes. The probability simulation graphically depicted in Fig. 6 demonstrates the calculations of the variable emission factor of a concrete truck transporting the raw materials to the concrete batching plant with a distance of 10–150 km. Fig. 7 illustrates the location of the raw materials to the concrete batching plant in Melbourne, Australia. The associated transportation emissions are shown in Table 6, with the maximum and minimum values accounted for during the triangular distribution to produce the most likely outcome. The MC simulation performed 10,000 iterations with a confidence level of 0.05. The lower and upper quartile limits of each box is represented on each side of the mean with the minimum and maximum values shown outside of the box. These values are then compared against each mix design to ascertain the GHG emission value that transportation has on the novel composite materials. It is important to note that the material emissions value has remained a constant to ascertain the true emission variability of transportation. For the MC simulation, 1 m^3 was kept desirable to transport as the value would only increase at the same incremental interval. As graphically depicted in Fig. 6, the control demonstrates the highest GHG emission value compared to all fibre composites. This is primarily due to the higher cement percentage which has a higher total sample material emission value. The average travel and material emission range of the control, SFKF5 and SFKF105 are 375.28, 362.16 and 339.24 kgCO_2-eq/m^3.

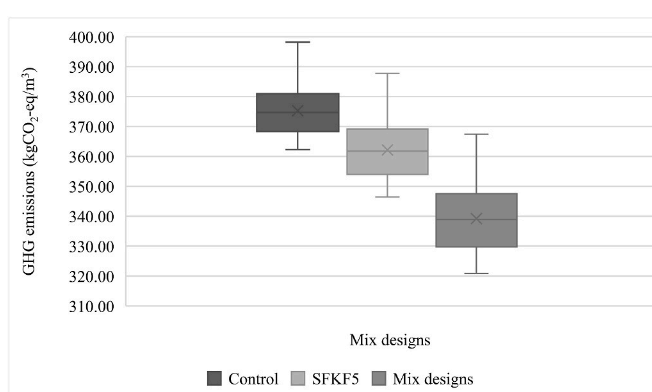

Fig. 6. Transportation and material GHG emissions of 1 m^3 concrete materials.

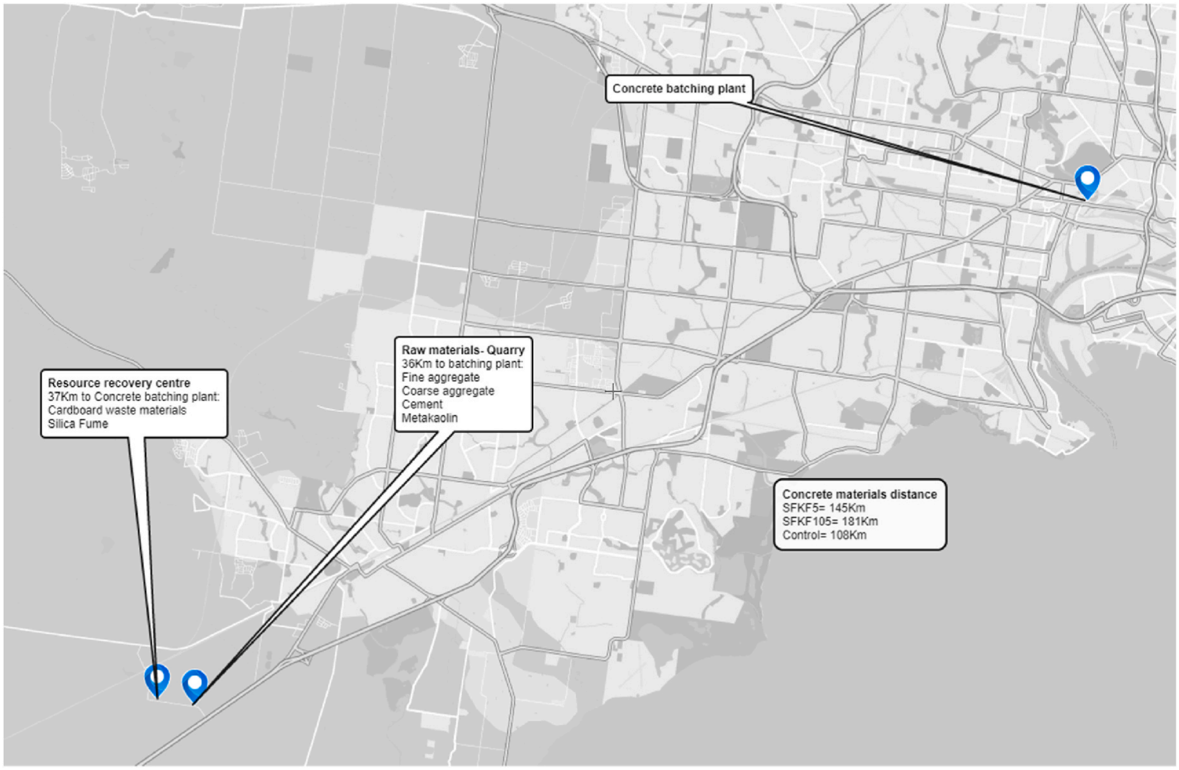

Fig. 7. Travel distances for materials to concrete batching plant.

As illustrated in Fig. 6, there is a larger variable of GHG emissions produced for SFKF105 due to the additional transport requirements of raw materials. For example, the transportation of MK is an additional travel requirement, creating additional emissions. This is shown with a minimum and maximum of 320.89 and 367.44 kgCO_2-eq/m^3, respectively. SFKF5 had an average of 362.16 kgCO_2-eq/m^3, which was similar to the minimum of the control and the upper quartile of SFKF105. The interquartile range of each sample indicates there are smaller values produced from the 10,000 iterations produced from the MC simulation. This is primarily due to the smaller variability of the 10–150 km transport emissions produced and the constant value of material emissions. Although there is only an 9.6% emission reduction once the material arrives at the construction site for SFKF105, this value can be significant when there is a large concrete requirement. Fibre integration within the composite materials require additional transportation services from the materials recovery centre, therefore it is expected that higher emissions will be produced from transportation with these materials. The control, SFKF5 and SFKF105 had a total material transportation of 108, 145 and 181 km, respectively. The additional distance represents the extra materials required for the concrete batching process. However, minimising the cement requirement in composite materials offset the additional GHG emissions produced from transportation. It is important to note that the emissions produced when manufacturing KFs and the mixing of all constituent concrete materials can vary depending on the resources and location of the project.

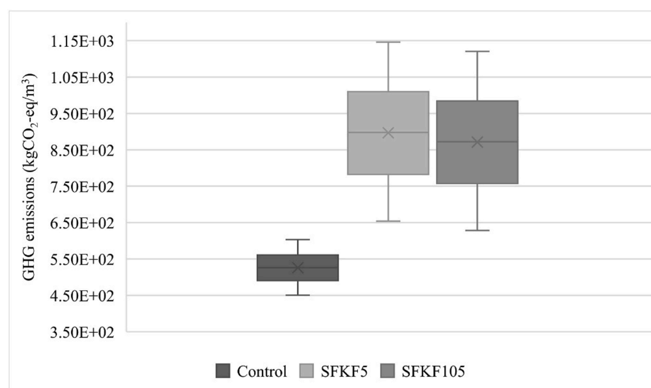

Fig. 8. Material and manufacturing GHG emissions for 1 m^3 concrete.

4.3.2. *Energy emissions*

The energy required to produce concrete materials is considered to be sensitive due to the high variable of energy requirement from different machinery for manufacturing (Sandanayake et al., 2020b). Due to the uncertainty of this factor in future case studies, a MC simulation was conducted to analyse the influence of input parameters on the LCA outcomes. Fig. 8 graphically depicts the variable GHG emissions for the material and the various machinery required to produce the novel composite materials. The MC simulation produced 10,000 iterations with a confidence level of 0.05. Fig. 8 details the emissions produced for each type of machine over a variable of 60–300 min. This is due to the uncertainty of user composite production. The machines selected were based on a laboratory scale of concrete and fibre production in line with the scope of the study. As 1 m^3 is selected as the functional unit, integrating larger commercial machines would significantly alter the outputs conducted by the LCA. Moreover, a 60- 300-min time-period was selected to represent a scalable time measurement. The GHG emissions shown in Fig. 8 is derived from the MC simulation of the emission factors for the three energy sources. Each machine selected is consistent to use 10, 60 and 30% of gas, coal, and renewable energy sources. The findings illustrated in Fig. 8 demonstrate the additional GHG emissions produced to manufacture the composite materials. As shown, there is a significant increase of GHG emissions produced for the novel composite materials when using waste cardboard. The control, SFKF5 and SFKF105 had an average of 525, 897 and 871 kgCO_2-eq/m^3. This represents a GHG emission increase of 42 and 39% for SFKF5 and SFKF105, respectively.

This is due to the additional energy requirement when producing ready-made KFs for constituent material integration.

Fig. 9 illustrates the total GHG emissions produced of all material, transport and energy requirements when manufacturing the composite materials. As shown, waste fibre composites still produce the most GHG emissions within the cradle to gate parameters. The control, SFKF5, and SFKF105 demonstrate an average of 572, 1023 and 997 kgCO$_2$-eq/m^3, respectively. Similar results are produced with the material and manufacturing emissions due to the constant raw material GHG emissions. However, the maximum and minimum values are varied due to the additional transportation requirements. These values extend the scope of the box plot and whisker total data set. SFKF105 has a lower emission value compared to SFKF5. This is due to the reduction of cement when replaced with MK. Despite the additional transportation requirements, small values of cement replacement can demonstrate GHG emission savings.

Fig. 10 demonstrates the variation of fuel source to create the energy required to operate the machinery. As graphically depicted, the primary source of energy is from fossil fuel sources such as gas, brown and black coal. These sources represent 10, 10 and 50% respectively. However, the emission factor remained the same for the variations of coal and have been combined for graphical representation. There is 30% renewable energy sourced for the power of operational machinery. Although there is still a GHG emission factor, this value is significantly lower, as shown in Table 6. Fig. 11 demonstrates that the cardboard shredder requires the most energy and ultimately produces the most GHG emissions. The interquartile ranges vary significantly for the various machinery due to the overall energy requirement of each machine. The concrete mixer and cardboard shredder require a high voltage power The increase of power supply requirements increase the energy ultimately increasing the GHG emissions produced. The additional processing of waste cardboard increases the energy requirement and therefore increases the GHG emissions produced with an average of 575 kgCO$_2$-eq/m^3 over a 60–300-min time-period. This is significant when the concrete mixer produces an average of 157 kgCO$_2$-eq/m^3. However, the critical factor of the energy required is derived from the energy source. As shown in Fig. 10, fossil fuel energy is the primary source of power. Local governments worldwide are converting power supplies to greener and renewable energy sources (Jankovic et al., 2022). Therefore, as the source changes to a green energy power supply, the additional power requirements of KFs will not demonstrate larger volumes of GHG emissions produced into the atmosphere.

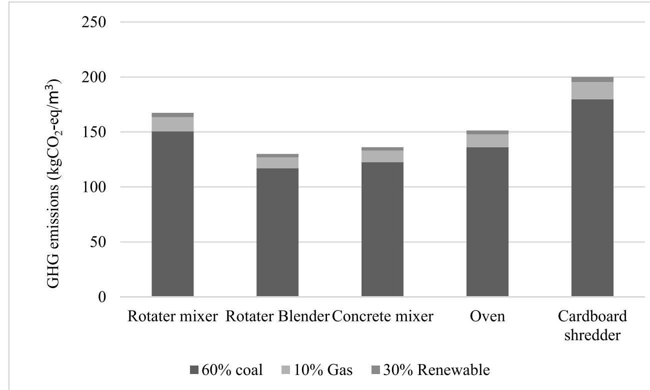

Fig. 10. Variations of energy source and their average GHG emissions for 60-300-min usage.

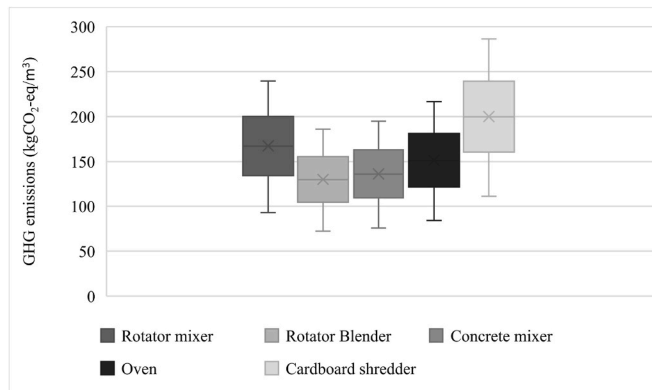

Fig. 11. Equipment variation of GHG emissions produced for 60- 300-min usage.

5. Conclusion

To search for alternative methods of cardboard waste distribution, this study focused on the integration of waste KFs within low-stress grade concrete. This paper presented three key stages of methodology to evaluate the viability and environmental effects of the waste material in concrete. First, the mechanical strength of KFs as a partial cement substitute within concrete materials was analysed. Secondly, the life cycle assessment outputs on key impact categories were identified. Finally, a sensitivity analysis was conducted on the variability of GHG emissions produced from transport and energy usage. The mechanical performance demonstrated comparative compressive strength in low stress grade concrete, with 5% partial cement substitution using SF modified fibres. A matrix modified composite using MK was also deemed satisfactory for its strength characteristics when using 5% MK and 10% SF modified fibres. The life cycle assessment results revealed for 1 m^3 of SFKF105 had savings of 11%, 8%, 4% and 1% for TAP, GWP, TEP and HTP impact categories, respectively. SFKF5 revealed saving results of 3%, 2% and 4% for GWP, TEP and MRS impact categories respectively. The life cycle assessment of SFKF105 also showed increased negative environmental impacts on MRS, ODP and MEP impact categories. However, the negative impact on the environment in these impact categories is marginally different. Although the additional processing of KFs increased the HTP in SFKF5, this was offset in SFKF105 due to the integration of MK and the increased fibre percentage. The Monte-Carlo simulation provided further information on the variability factors when integrating bespoke materials into the mix design. Initially, the extra requirement of transportation for more constituent materials increased the GHG emissions. SFKF105 revealed an average of 29 kgCO$_2$-eq/m^3 for material transportation to the concrete batching plant. Whereas transportation of the control produced 59% less GHG emissions. However, this was mitigated by the material emissions originally produced to batch traditional concrete. Ultimately, SFKF105 demonstrated the lowest GHG emissions from cradle-to-gate and the control produced the

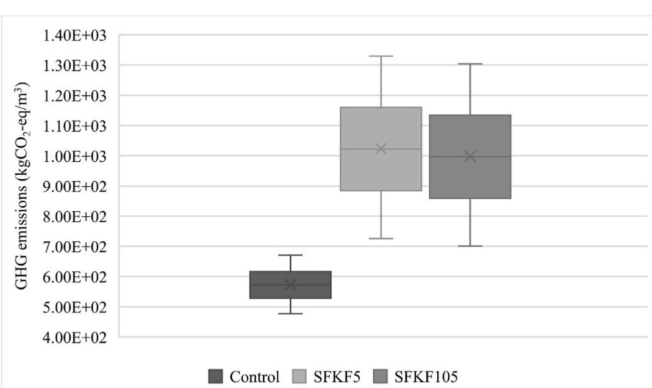

Fig. 9. Total GHG emissions for 1 m^3 concrete.

highest amount of GHG emissions for material and transportation factors. A sensitivity analysis on the energy sources and the operational machinery was also conducted. The results revealed additional energy requirements for the processing of KFs. Due to the additional manufacturing processes to convert waste cardboard into KFs, the original GHG emission material and transportation savings were then eliminated. Moreover, energy sources were compared to see the effect of fossil fuel-based systems and potential GHG emission savings when using renewable energy in the future. This study examined the multiple considerations required when evaluating and classifying what a green material is. The contributions of this study highlight the various considerations required when researching novel materials to be used in cementitious composite systems. As shown, the variability factors can affect what is initially thought to be a sustainable material alternative and potentially create additional negative impacts. However, it is important to note that reducing landfill of waste materials will always be environmentally beneficial. As renewable energy becomes the primary source, opportunities will be more prominent for bespoke materials to be used in the construction industry.

CRediT authorship contribution statement

Robert Haigh: Methodology, Resources, Software. **Malindu Sandanayake:** Conceptualization, Methodology, Resources, Software, Supervision, Validation, Writing – review & editing. **Yanni Bouras:** Methodology, Writing – review & editing. **Zora Vrcelj:** Funding acquisition, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. No Competing interests were identified.

Data availability

Data will be made available on request.

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