

A comparative cradle-to-gate life cycle assessment of three concrete mix designs

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Abstract

Purpose The concrete industry faces challenges to create concrete mix designs that reduce negative environmental impacts but also maintain high performance. This has led to ‘greener’ cementitious materials being developed which can decrease the use of traditional Portland cement (PC). This study intended to carry out a ‘cradle-to-gate’ life cycle assessment (LCA) on concrete mix designs containing different cementitious blends.

Methods The aim of this study was to obtain the overall environmental impact, with a particular focus on carbon dioxide (CO₂) emissions of three concrete mix designs: CEM I (100 % PC content), CEM II/B-V (65 % PC content, 35 % Fly Ash (FA) content) and CEM III/B (30 % PC content, 70 % ground granulated blast furnace slag (GGBS) content). Evaluations of the three concrete mixes were performed using ‘SimaPro 8’ LCA software. A comparative cradle-to-gate LCA of these mixes has not currently been explored and could present a new insight into improving the environmental impact of concrete with the use of secondary materials. Recommendations from this work would help the industry make key decisions about concrete mix designs.

Results and discussion Results show that Mix 2 (CEM II/B-V) and Mix 3 (CEM III/B) could potentially be taken forwards to improve their environmental impacts of concrete production. With respect to optimum mix design, it is strongly recommended that GGBS is selected as the addition of choice for reducing CO₂ emissions. FA does still considerably improve sustainability when compared to PC, but this work proved that inclusion of GGBS environmentally optimises the mix design even further. Advantages of using GGBS include lower CO₂ emissions, a substantial reduction of environmental impacts and an increased scope for sustainability due to the higher PC replacement levels that are permitted for GGBS. Due to mix designs enabling a higher contribution of GGBS additions, it would also indicate an increased positive effect regarding waste scenarios.

Conclusions and recommendations The main contribution of this work demonstrated that concrete can be produced without loss of performance whilst significantly reducing the negative environmental impacts incurred in its production. The results obtained from this work would help to define the available options for optimising concrete mix design. The only material variations in each mix were the different cementitious blends. So, by determining the best option, a platform to make recommendations can be established based upon cementitious materials.

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Keywords CO₂ emissions · Concrete production · Construction industry · Concrete mix designs · LCA

Abbreviations

AALCA Advanced attributional LCA
CEM I Cement classification of Portland cement without any main addition

CEM II/A-L	Cement classification of Portland limestone cement containing 6–20 % Limestone
CEM II/B-L	Cement classification of Portland limestone cement containing 21–35 % Limestone
CEM II/B-V	Cement classification of Portland-fly ash cement containing 21–35 % Fly Ash
CEM III/B	Cement classification of blast furnace cement containing 66–80 % ground granulated blast furnace slag
CO ₂	Carbon dioxide
CO ₂ e	Carbon dioxide equivalent
EIO-LCA	Economic input–output LCA
EPD	Environmental product declarations
FA	Fly ash
GGBS	Ground granulated blast-furnace slag
GPP	Green public procurement
HMA	Hot-mix asphalt
ISO	International Organization for Standardization
LCA	Life cycle assessment
MCD	Multiple-criteria decision making
PC	Portland cement
PLC	Portland-limestone cement
SCM	Secondary cementitious material
S-LCA	Social LCA
TBL-EIO	Triple bottom line-EIO
WMA	Warm-mix asphalt

1 Introduction

Concrete is the most widely used construction material on the planet (Henry and Kato 2014; Flower and Sanjayan 2007), and concrete production is believed to be responsible for up to 8 % of all CO₂ emissions worldwide (Pade and Guimaraes 2007; Huntzinger and Eatmon 2009), 2.5 % of all UK CO₂ emissions and the third largest source of CO₂ emissions in the USA (Habert and Roussel 2009; Huntzinger and Eatmon 2009). The manufacture of cementitious products is largely to blame for these emissions. Furthermore, cement manufactures commit about 5 % of global and 2 % of UK CO₂ emissions (Pade and Guimaraes 2007). Therefore, any modifications to concrete mixes are substantial when attempting to reduce negative environmental impacts and increase its sustainability. Sustainability consists of three main pillars: environmental, economic and social. However, only the environmental pillar has a set of indicators for concrete products (García-Segura et al. 2014). In order to achieve sustainability, it is essential to uphold a certain level of quality and performance to meet the standards on concrete. Furthermore, environmental performance has extended into all phases of a product's life cycle and always comes at a cost (Cheung et al. 2015; Cheung and Pachisia 2015). These costs can be reduced

through careful consideration at the early stages, for instance, material selection and mix design in concrete production.

Sustainability is becoming more commonly controlled in construction by regulations to prevent the risk of not having a competitive advantage over traditional options (Lewandowska et al. 2015); however, regulations occasionally constrain sustainability; this is because some standards limit the use of alternative materials for various concrete constituents. This gives producers little scope for sustainability and deters them from exploring other potential options. A combination of life cycle assessment (LCA) with optimisation techniques can be utilised to satisfy both economic and environmental criteria which encourages more sustainable performance of a product system over the entire life cycle (Guinee et al. 2010; Azapagic and Clift. 1999). In concrete products, this can reduce the reluctance from producers to explore potential options in sustainable concrete production (Hayes et al. 2015). Portland cement (PC) is currently the only economic concrete binder, without any main addition, that matches the requirements for durability and performance (Zhang et al. 2014; Li et al. 2015) PC is composed primarily of calcium silicate minerals (Huntzinger and Eatmon 2009) and was found to be the primary source of CO₂ emissions generated by typical commercially produced concrete mixes, being responsible for 74 to 81 % of total CO₂ emissions (Flower and Sanjayan 2007). For example, CEM I concrete utilises PC as its only binder and it produces around 1 t of CO₂ for every tonne that is manufactured (Imbabi et al. 2012). PC can however be blended with other cementitious additions without compromising durability and performance, giving the potential opportunity to reduce the associated environmental impacts. Cementitious materials that are currently available for use in the UK are PC, ground granulated blast-furnace slag (GGBS), fly ash (FA) and limestone. GGBS, FA and limestone are additions that can be used in combination with PC at the concrete works in accordance with the British Standard for Concrete, BS 8500-2 (MPA. 2013).

1.1 Sustainable concrete production

Eisa (2014) states that concrete and global warming are strongly linked, which is a major problem for today's infrastructures. Richardson (2013) outlines how the consumption of concrete has risen from 1500 million tons in 1995 to a projected 3500 million tons by 2020. Concrete production has demonstrated some efforts through production and the supply chain to reduce energy use (Sustainable Concrete Forum 2012). Kawai et al. (2005) proposed that environmental impacts of concrete must be assessed equally alongside mechanical properties, serviceability, safety and durability. Since concrete structures usually last between 50 and 100 years, and that concrete (and especially cement)

production is highly energy intensive, it means that sustainability is paramount (Müller et al. 2014).

1.2 Concrete mix design

Clear (2013) indicates that sustainable construction is supported by a widening range of materials deemed as being suitable for concrete. This provides scope for introducing new materials into the mix design for the process of producing concrete. Livesy (1996) states that the use of these secondary materials have significant environmental impacts through the reduction of energy input into cement, landfill use and also the emission of combustion gases. Black (2014) also indicates that there is little scope for reducing CO₂ emissions without an increased use of secondary cementitious materials (SCMs) (FA/GGBS), and that current clinker replacement levels in the UK are just over 13 %. The potential to increase this figure is demonstrated with a target of 30 % replacement levels by 2050.

GGBS is the by-product from blast furnaces that are used in the manufacture of iron for steel making (Higgins 2006). FA is fine powder resulted from burning of coal in power stations; the composition can vary widely and depends principally on the type of coal burnt and the furnace firing conditions. FA is a pozzolanic material, whereas GGBS has partially inherent cementitious properties. FA contains little calcium; meaning that it is not very reactive as a cementitious material (UKQAA 2008). Sear (2002) explains that FA can reduce the need for natural aggregates and can be used in a wide range of applications, making it ideal for reducing CO₂ emissions. For LCA of mixes containing either GGBS or FA, only emissions from processing are allocated to the materials (Heath and Paine 2014). This is because CO₂ emissions in the blast furnace are normally associated with the production of iron rather than the by-product GGBS, and emissions from power generation are not considered as an environmental burden on FA (UKQAA 2008). This gives PC a disadvantage, as this material is specific to the production of concrete so all CO₂ emissions are relevant.

1.3 Considerations and limiting factors of concrete mix

Concrete mix designs have to take into account many factors such as performance, environmental impacts, cost, etc. For concrete mixes, the cement combination can contain up to 80 % GGBS or up to 55 % FA (MPA 2013). These figures can decrease depending on the requirements of the concrete. One limiting factor for GGBS and FA was highlighted by Heath and Paine (2014); they suggested that availability of these materials could mean they would eventually need to be imported. The issue of importing would be contentious as it would undermine the status of these materials as wastes or by-products, which would influence their use.

Another limitation is of course cost. Black (2014) states that optimum mix designs in terms of CO₂e per unit strength are not the cheapest. This can heavily deter the industry from exploring sustainable options since cost is a key driver for producing concrete. Although these alternative materials require more development, it is evident that SCMs are making large strides in the right direction. Higgins (2006) mentions that in 2005, the use of GGBS and FA saved the UK 2.5 million metric tons of CO₂ emission, and there still remains considerable potential for increased use of the two materials in this application. Nevertheless “it is necessary to evaluate concrete’s environmental impact properly, especially when developing new ‘green’ concretes” as stated by Van den Heede and De Belie (2012).

1.4 Recent LCA approach and methods

In order to evaluate the potential environmental impacts of three mixed concrete designs, a review of recent LCA research has been conducted. There are different models in performing an LCA such as process-based LCA, economic input–output LCA (EIO-LCA), triple bottom line-EIO (TBL-EIO), hybrid LCA, advanced attributional LCA (AALCA) and social LCA (S-LCA). A few of these recent works are summarised as follows.

Noori et al. (2015) utilised TBL-EIO to assess the social, economic and environmental impacts of four different wind turbines, two onshore and two offshore. They combined Monte Carlo simulation with multiple-criteria decision making (MCDM) to address the best suitable wind energy source for different weights of socioeconomic and environmental impacts. The Carnegie Mellon University Green Design Initiative (Noori et al. (2014a) developed and implemented the EIO-LCA approach in a software form. The aim of the EIO-LCA model is to eliminate the truncation errors in a typical process-based LCA.

Kucukvar et al. (2014) developed a hybrid TBL-LCA method to evaluate the environmental and socioeconomic impacts of pavements constructed with different types of warm-mix asphalt (WMA) mixtures and compared them to conventional hot-mix asphalt (HMA). However, weighting scoring systems are often based on expert judgment and can sometimes be extremely biased. Andrae (2015a) developed the AALCA to measure high eco-environmental impact products such as office computers and personal devices. The approach has improved the attributional LCA method to better understand the comparative ALCA practice. Rowley et al. (2009) applied a hybrid LCA approach to compare with conventional process-based LCA and input–output-based LCA analysis. The comparison was performed using a case study from the water industry and recommended that from an environmental analysis perspective, it would be beneficial to consider the three methodologies in parallel.

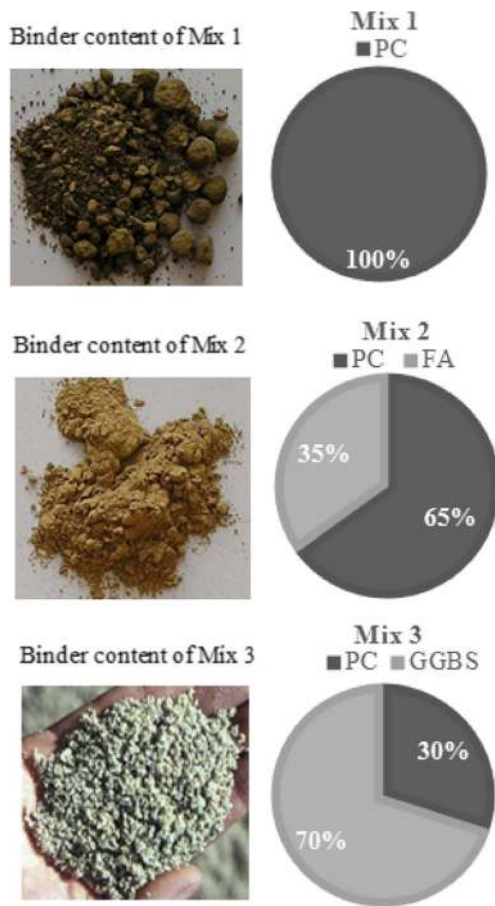


Fig 1 Binder content of each mix (courtesy of Hanson Heidelberg Cement Group of UK)

Huntzinger and Eatmon (2009) conducted a process-based LCA to evaluate the environmental impact of four Portland cement manufacturing processes. Their analysis was based on using SimaPro 6.0 software and shows that blended cements provide the greatest environmental savings. Another process-based LCA evaluation on building materials was carried by

Bribián et al. (2011). They performed an LCA study comparing the most commonly used building materials with eco-materials using three different impact categories such as primary energy demand, water demand and global warming potential. The study proves that the impact of construction products can be significantly reduced by promoting the use of the best techniques available and eco-innovation in production plants, substituting the use of finite natural resources for waste generated in other production processes. Hosseini et al. (2014) developed a quantitative and qualitative tool used in S-LCA. The primary goal of this enhanced S-LCA is to assess and compare socioeconomic impacts of different materials such as concrete and steel for buildings.

The various LCA techniques developed by the researchers have many advantages, but the scope of this study is limited to process-based LCA mainly of data availability issue. The process-based LCA is considered more appropriate for this study, as it aims to include three different cases and because the method used is based on engineering facets, not including those of economic valuation. All environmental data are drawn from the Ecoinvent 3.01 database, allowing this study to compare the cases. This paper is therefore to report a ‘cradle-to-gate’ LCA method on concrete mix designs which have not currently been explored. The contribution of this study is to demonstrate that concrete mixed designs can be produced environmentally friendlier without loss of its performance. The recommended options can potentially be taken forwards to improve the sustainability of concrete production.

2 Methods

2.1 Background of the underlying approach

As seen in Fig. 1, each mix design has a different binder combination; one of the concrete mixes contains traditional PC

Fig. 2 Concrete production system boundary

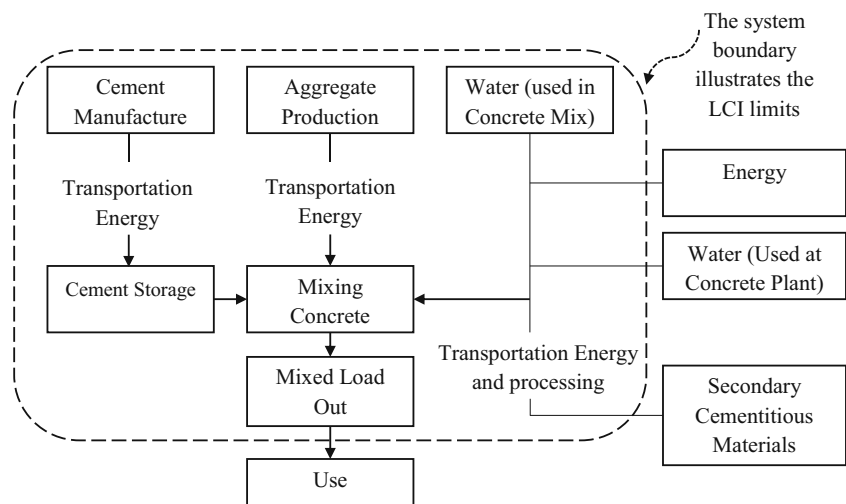


Table 1 Material content of each concrete mix design

Material	Mix 1: CEM I (kg/m ³)	Mix 2: CEM II/B-V (kg/m ³)	Mix 3: CEM III/B (kg/m ³)
PC	380	247	114
GGBS	0	0	266
FA	0	133	0
10/20-mm limestone Aggregate	615	606	610
4/10-mm limestone Aggregate	413	407	410
0–4-mm Fine aggregate	806	794	800
Plasticiser	2	2	2
Water	190	190	190
TOTAL:	2406	2379	2392

(CEM I), another one has a Portland fly ash cement (CEM II/B-V) and the final mix includes a blast furnace cement (CEM III/B). The Intergovernmental Panel on Climate Change (IPCC) states that material substitution could be used to reduce global CO₂ emissions, for example, the addition of by-products or waste materials (GGBS/FA) to clinker (Metz et al. 2007).

Portland-limestone cements (PLCs) have not been included in this study because a limestone content of 21–35 % (CEM II/B-L) is currently not permitted for PLCs in the UK. Secondly, BS 8500-2 only permits a limestone content of 6–20 % (CEM II/A-L) in PLCs. Limestone fines (Chen et al. 2014) would also have relevant environmental burdens arising from quarrying, drying and grinding. This means that there is less scope for achieving sustainability. The potential for PLC is also significantly reduced as it cannot be used with other additions such as GGBS or FA. This means batching plants require additional

silos storage capacity which will not provide cost effectiveness or be practical in terms of space for many urban plants.

Concrete mix designs can be optimised with different cementitious blends within their composition to enhance sustainability and reduce the negative environmental impacts that are associated with the concrete construction industry. This work addressed the CO₂ emissions from the production of three concrete mix designs: CEM I (100 % PC content), CEM II/B-V (65 % PC content, 35 % FA content) and CEM III/B (30 % PC content, 70 % GGBS content). A comparative cradle-to-gate LCA of these mixes has not currently been explored and will present a new insight into improving concrete sustainability with the use of secondary materials. Recommendations from this work will help the industry make key decisions about concrete mix designs. Evaluations of the three concrete mixes were performed using the SimaPro 8

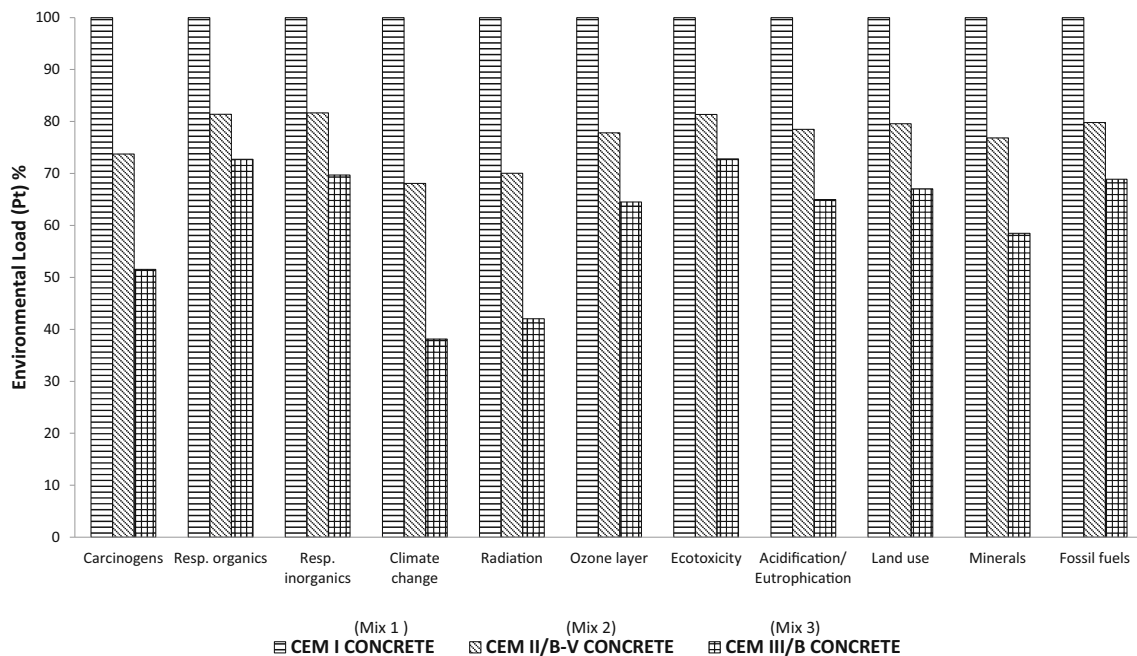


Fig. 3 Eco-indicator 99 impact assessment: characterisation

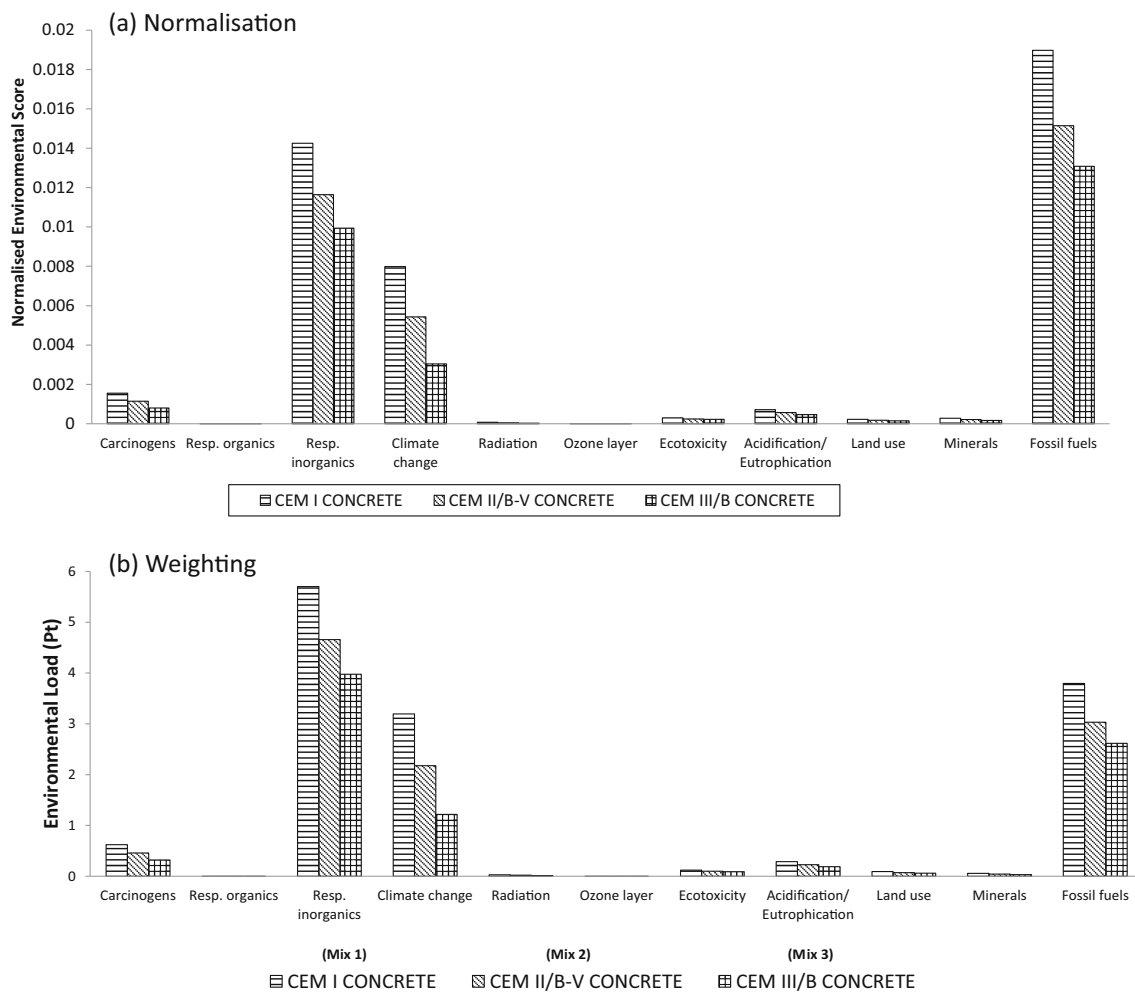


Fig 4 Eco-indicator 99 impact assessment

LCA software. LCA is the most suitable tool available for such evaluation (Josa et al. 2007). The outcome of this work is to make recommendations for optimum concrete mixes with respect to a solution for increased sustainability and reducing environmental impacts. This will provide a methodology for achieving lower CO₂ emissions in the construction industry whilst still attaining effective considerations regarding cost and technical performance. Mitigating associative CO₂ emissions within the construction sector now has a larger emphasis than ever, and activities are now being regulated in terms of the quantity of CO₂ emissions, embedded energy and environmental impacts (Glasser 2014). The methodology proposed by this work can be utilised by designers, producers and also end users in the decision making processes within concrete construction.

2.2 The LCA approach of three concrete mixed designs

Borghi (2012) suggests LCA has evolved into a key tool for use as a basis to communicate the overall environmental performance of products. Life cycle studies are based on the fact that decisions taken in one phase should always be set against

the background of the consequences for the following phases (Janssen and Hendriks 2002). In order to compare concrete mix designs, it is important that a cradle-to-gate LCA approach is applied.

An LCA approach is drawn upon to comparatively identify associated negative environmental impacts of three concrete mix designs from cradle-to-gate. The independent variables for this study are the three mix designs. Each selected mix has been designed to produce structural concrete to BS 8500-2, all having a fixed cementitious content of 380 kg/m³. This content includes varying levels of SCMs, in order to demonstrate a trend that higher PC replacement levels can be achieved to proportionally reduce environmental impacts. The hypothesis of this work is that a reduction of negative impacts would occur when higher amounts of constituent SCM were contained in the binder combination of each mix design. The outlines of the LCA on the three concrete mixed designs are as follows:

- Goal and scope definition*—Determine the functional unit and system boundary. In this assessment, the

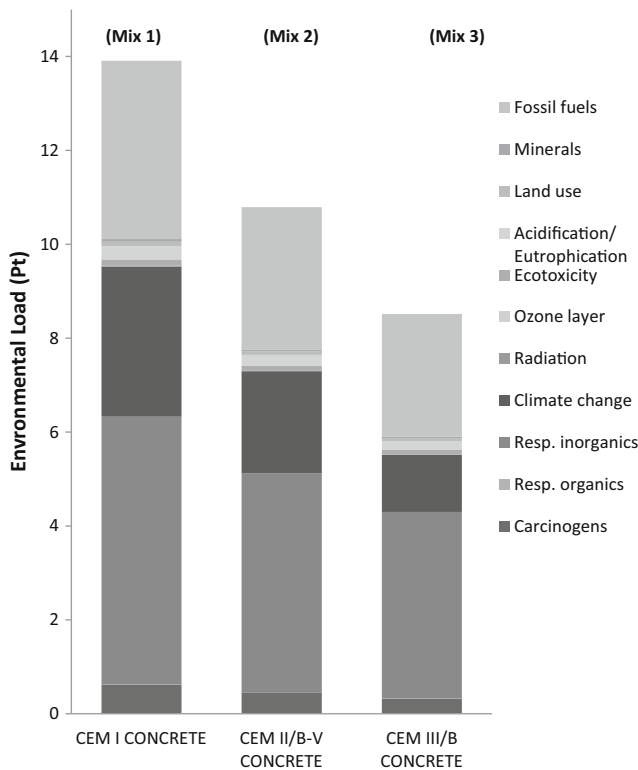


Fig. 5 Eco-indicator 99 impact assessment: single score

software is focused on CO₂ emissions as well as other environmental impact categories relevant to producing a cubic metre of concrete (because concrete is sold on a volumetric basis).

ii. *Inventory analysis*

- Compile and quantify the inputs and outputs throughout the life cycle of each concrete mix design.
- Feed data into the software for each mix design. This should include all materials and processes that have been outlined in the system boundary.
- Calculate tabulated numerical values showing inputs and outputs with respect to the environment for various processes. Inventory tables are extensive and can contain thousands of items.

iii. *Impact assessment*—Understand and evaluate the magnitude and significance of the environmental impacts for each mix design throughout its life cycle, focusing particularly on CO₂ emissions. Determine the importance of data and how they affect different impact categories.

iv. *Interpretation*—Concrete mix designs will be compared in terms of CO₂ emissions and other environmental impacts. The best options regarding sustainability in the industry will be highlighted and other relevant deductions can be made.

2.3 Preparing test cases

To prepare the test cases, the first mix design is a traditional CEM I concrete and the other two are for more novel CEM II/B-V and CEM III/B concretes containing 35 % FA and 70 %

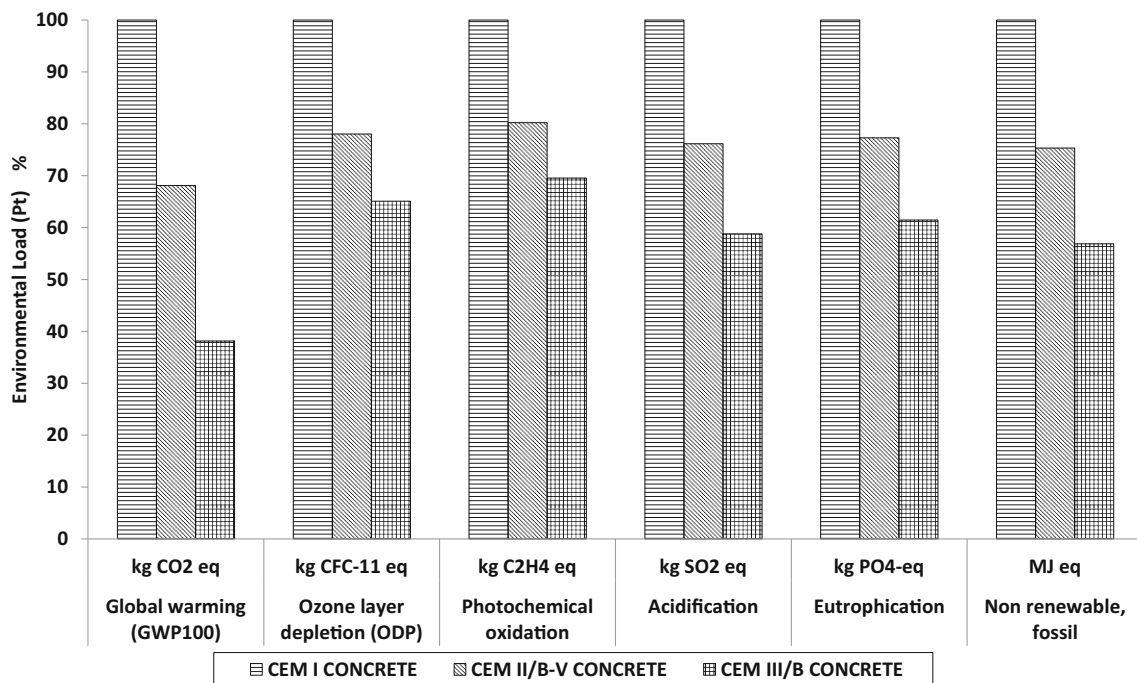


Fig. 6 EPD 2008 impact assessment: characterisation

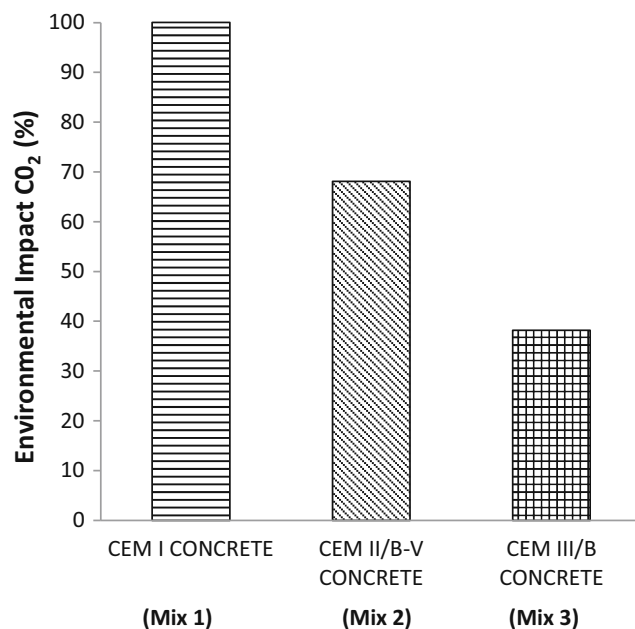
Table 2 EPD 2008 impact assessment table: characterisation

Impact category	Unit	CEM I concrete	CEM II/B-V concrete	CEM III/B concrete
Global warming (GWP100)	kg CO ₂ eq.	339	227	127
Ozone layer depletion (ODP)	kg CFC-11 eq.	1.04E-05	8.10E-06	6.76E-06
Photochemical oxidation	kg C ₂ H ₄ eq.	0.1113	0.0893	0.0774
Acidification	kg SO ₂ eq.	0.5437	0.4134	0.3191
Eutrophication	kg PO ₄ ⁻ eq.	0.1377	0.1064	0.0846
Non renewable, fossil	MJ eq.	1761	1328	1003

GGBS, respectively. The content of these additions are designed to be within the permitted range. The three mix designs produce concretes that have the designation RC32/40 and have the consistence class S3 (wet mix) in accordance with BS 8500-1. Each mix has been designed for concrete that was placed by pump (rather than by skip, chute, etc.); therefore, they are all cohesive and within a specific grading envelope.

2.4 System boundary of the concrete production

The system boundary (Fig. 2) includes all of the necessary inputs for producing concrete, such as extraction and processing of raw materials up to producing the concrete mix. Cement manufacture and aggregate extraction/processing are all operations that fall within the boundary, as are all material transportations. The system boundary does not include SCMs. Energy and water inputs to the concrete mixing plant are also not within the boundary. The assumptions made for the system boundary are justified in the following section.

**Fig. 7** Ecopoints 97 impact assessment: characterisation

2.5 Assumptions

The following assumptions have been taken into account for this LCA:

- A functional unit of 1 m³, i.e., each mixed produces 1 m³.
- All three mix designs are capable of producing concretes of equivalent mechanical performance and durability. It is for this reason that technical performance has not been determined.
- Many concrete production processes are uniform for each mix design and are therefore not relevant to this comparative study. Relevant processing data for materials are included within the LCA system boundary.
- GGBS and FA are by-products; therefore, any emissions allocated to the materials from steel or electricity production are not seen as relevant in terms of concrete production and have not been included inside the system boundary. Only processing and transportation emissions are allocated to the materials for this assessment.
- Average round trip transportation distances to the concrete plant are estimated to be 105 km for aggregate materials, 209 km for PC, 314 km for FA and 439 km for GGBS. Distances are assumed as typical for the UK.
- All transportation is conservatively anticipated to be by road.
- Ninety percent of solid wastes that are generated at the concrete plant are recycled. Under this assumption, it is estimated that the total landfill waste is 16 kg/m³ of concrete.

2.6 Concrete mix designs

The three concrete mix designs undergoing LCA are summarised in Table 1. Mix design LCA inputs can be found in the Electronic Supplementary Material as Appendix A (note: some inputs are not visible, since relevant processes for each material are automatically included).

Table 3 Ecopoints 97 impact assessment table: characterisation

Impact category	Unit	CEM I concrete	CEM II/B-V concrete	CEM III/B concrete
<i>NOx</i>	<i>g</i>	645	510	430
<i>SOx</i>	<i>g SO2 eq.</i>	198	141	91
<i>NMVOC</i>	<i>g</i>	98	80	72
<i>NH3</i>	<i>g</i>	16	12	9
<i>Dust PM10</i>	<i>g</i>	116	101	91
<i>CO2</i>	<i>g CO2 eq.</i>	334,148	227,600	127,635
<i>Ozone layer</i>	<i>g CFC-11</i>	0.0115	0.0090	0.0075
<i>Pb (air)</i>	<i>g</i>	0.0609	0.0437	0.0288
<i>Cd (air)</i>	<i>g</i>	0.0054	0.0038	0.0024
<i>Zn (air)</i>	<i>g</i>	0.0982	0.0779	0.0658
<i>Hg (air)</i>	<i>g</i>	0.0131	0.0089	0.0050
<i>COD</i>	<i>g</i>	276	243	250
<i>P</i>	<i>g</i>	0.0119	0.0108	0.0112
<i>N</i>	<i>g</i>	0.4868	0.3788	0.2978
<i>Cr (water)</i>	<i>g</i>	0.2913	0.2448	0.2308
<i>Zn (water)</i>	<i>g</i>	3.66	2.92	2.52
<i>Cu (water)</i>	<i>g</i>	0.5801	0.4416	0.3261
<i>Cd (water)</i>	<i>g</i>	0.0429	0.0320	0.0229
<i>Hg (water)</i>	<i>g</i>	0.0039	0.0029	0.0020
<i>Pb (water)</i>	<i>g</i>	0.1029	0.0766	0.0543
<i>Ni (water)</i>	<i>g</i>	1.38	1.03	0.73
<i>AOX (water)</i>	<i>g Cl-</i>	0.0008	0.0007	0.0007
<i>Nitrate (soil)</i>	<i>g</i>	0.4584	0.3620	0.3003
<i>Metals (soil)</i>	<i>g Cd eq.</i>	0.0007	0.0007	0.0008
<i>Pesticide soil</i>	<i>g act.subst.</i>	0.0033	0.0031	0.0033
<i>Waste</i>	<i>g</i>	21,724	20,933	20,859
<i>Waste (special)</i>	<i>g</i>	0.9267	0.7798	0.7276
<i>LMRAD</i>	<i>cm3</i>	1.11	0.78	0.47
<i>HRAD</i>	<i>cm3</i>	0.2435	0.1711	0.1038
<i>Energy</i>	<i>MJ LHV</i>	1826	1372	1028

All three concrete mix designs have the following:

- i. A water/cement ratio of 0.50 (the maximum allowable is 0.55);
- ii. An overall binder content of 380 kg/m³ (the minimum allowable is 300 kg/m³);
- iii. An inclusion of PC 42.5. This cement is typically used in construction and is frequently combined with FA and GGBS; and
- iv. Been yield checked in order to ensure that they produce 1 m³ of concrete. There is a slight variation in mass and density across each mix due to material variation and rounding. Each mix achieved this yield within a tolerance of ±1 %, which is generally deemed as acceptable within industry standards. The yield checks for each mix can be found in Appendix B (Electronic Supplementary Material).

3 Life cycle assessment results

Results were obtained in SimaPro LCA software using three different impact assessment methods: Eco-indicator 99, EPD 2008 and Ecopoints 97. These methods are generally accepted and commonly used for demonstrating environmental profiles. Results are presented by impact categories which can be grouped together to form damage categories. Results by damage category can be found in Appendix C (Electronic Supplementary Material). Every impact category shown in Fig. 3 for the Eco-indicator 99 method have the same trend. The characterisation of each category comparatively displays impacts associated with each mix design. It is clear that ‘Mix 3’ demonstrated the lowest impact, with ‘Mix 1’ consistently showing the highest. ‘Mix 2’ revealed improvements compared to Mix 1, but constantly displayed an environmental performance that falls somewhere between the other two mix designs.

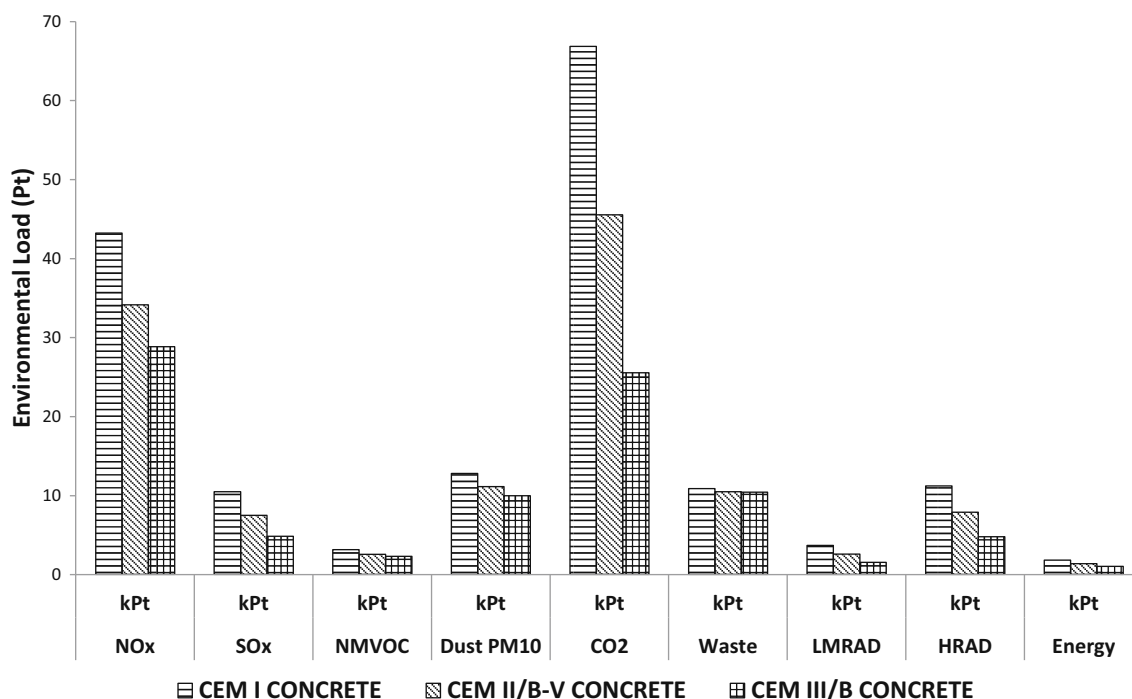


Fig. 8 Ecopoints 97 impact assessment: weighting

The normalisation result shown in Fig. 4a illustrates the relative size of the 11 impact categories. Fossil fuels have the greatest normalised environmental score for each mix design, followed by Resp. inorganics and then climate change. Figure 4b shows the weighting of each impact category. Weighting is the product of normalisation results and weighting factors and displays a relative importance of each impact category. Resp. inorganics, climate change and fossil fuels show the highest importance in terms of impacts.

Figure 5 illustrates that the total single scores from the Eco-indicator 99 method show that Mix 1 has the highest score with 13.9 Pt. The unit ‘Pt’ is regarded as dimensionless and its sole purpose is to compare relative differences between products, which in this case are the three concrete mixes. Mix 2 shows a slight reduction (–23 %) by having a value of 10.8 Pt whilst Mix 3 shows an even further reduction (–40 %) with a value of 8.52 Pt. Single scores were formed from the weighted results and are attributed to each mix. This facilitates an immediate understanding of the overall environmental impacts.

Figure 6 shows the EPD 2008 method that includes the impact category of ‘global warming (GWP100)’ which measures the performance of each product regarding CO₂. This is a key finding and basically reflects that higher PC replacement levels lead directly to a lower amount of associated CO₂ emissions. Table 2 shows unit values in kilogram CO₂ equivalent (‘kg CO₂ eq’) to be 334, 227 and 127 for Mix 1, Mix 2 and Mix 3, respectively. Overall, this means that Mix 1 was accountable for a substantial 32 % increase and a staggering 62 % increase in consequential CO₂ emissions when compared

with Mix 2 and the Mix 3. By comparing Mix 2 and Mix 3, it can be seen that Mix 2 is responsible for 44 % greater amount of equivalent CO₂ emissions, indicating that Mix 3 has by some way showed the strongest reduction in CO₂ emissions.

Figure 7 illustrates the strong negative correlation between the amount of SCM addition and CO₂ emissions in the production of 1 m³ of concrete. The actual values for the CO₂ impact category for this method are given as 3.34×10^5 , 2.28×10^5 and 1.28×10^5 for Mixes 1, 2 and 3, respectively. These values are given in Table 3 and have the unit gram CO₂ equivalent (‘g CO₂ eq’). If these values are converted to kilogram CO₂ equivalent, they become 334, 228 and 128, making them extremely similar (within 1 kg CO₂ eq.) to the corresponding values for global warming (GWP) that are illustrated in Fig. 6 (and Table 2).

The importance of CO₂ emissions is boldly exposed in Fig. 8. It can be seen that CO₂ has the highest weighted contribution to environmental impacts. The three values for CO₂ loads for Mixes 1, 2 and 3 were 66.8, 45.5 and 25.5 kPt. Hence, Mix 3 is 62 and 44 % lower than Mix 1 and Mix 2, respectively. These scores therefore make up the largest chunk of the single scores for each mix as shown in Fig. 9.

The overall pattern of the Ecopoints 97 Single Score results indicate a sizeable decrease in overall environmental load for the mix designs containing SCMs, compared with Mix 1, which reflects all other results. Mix 1 has an overall score of 173 kPt, with Mix 2 and Mix 3 achieving totals of 130 and 94.5 kPt (as shown in Table 4). Hence, Mix 3 is 45 and 27 % lower than Mix 1 and Mix 2, respectively. Some of the

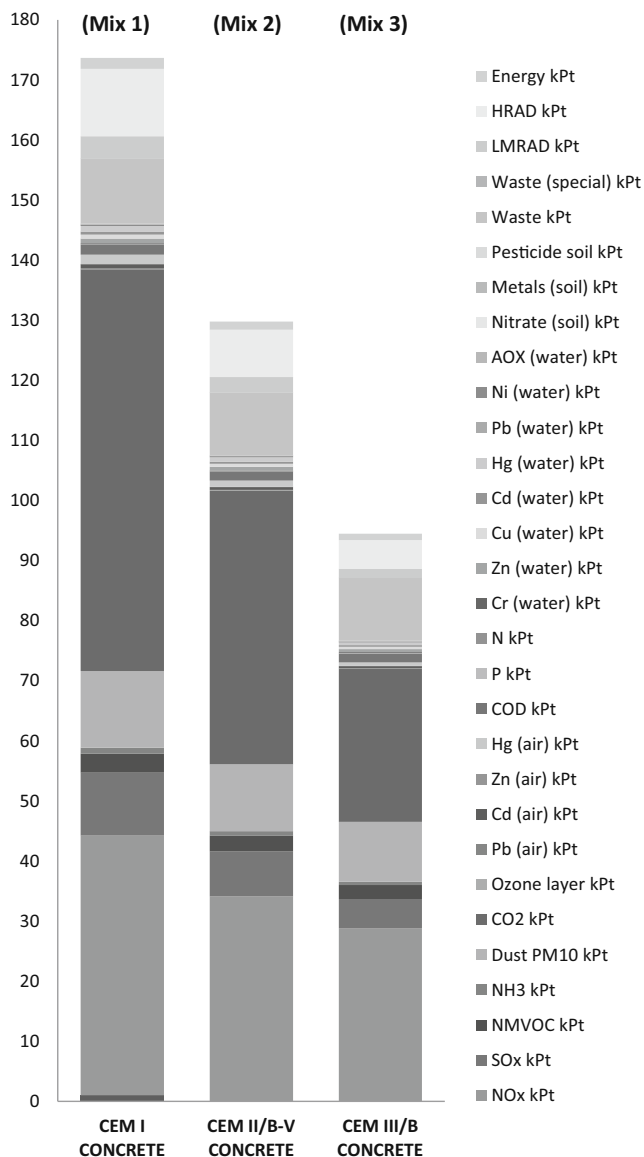


Fig. 9 Ecopoints 97 impact assessment: single score

individual impact categories in Fig. 9 show a slight contradiction than this. The categories COD, P, AOX (water), metals (soil) and pesticide soil do not demonstrate a decrease in values for Mix 2 and Mix 3. This can be seen in more detail in Tables 3 and 4; however, these categories are considered to be inapt in terms of their relativity to this study. This consideration is validated in Fig. 8 where these categories can be seen to have an extremely small or even non-existent weighted impact.

4 Discussion

The results obtained from this work would help define the available options for optimising concrete mix design. In this optioneering process, each mix design is considered to be a different option. The only material variations in each mix are

the different cementitious blends. So, by determining the best option, a platform to make recommendations can be established based upon cementitious materials.

4.1 Mix 1 (CEM I concrete) option

Mix 1 advantages:

- CEM I concrete can be recycled for use in aggregate applications. This has an official designation as recycled Portland cement concrete (RPCCC).
- PC is more readily available than FA/GGBS. PC is manufactured specifically for the purpose of concrete production, so it is made to satisfy demand.
- PC has shorter transportation distances to the concrete plant than SCMs, which implicates reduced environmental impacts and CO₂ emissions for transportation of materials in this mix design.

Mix 1 disadvantages:

- This mix presented the highest CO₂ emissions; kilogram CO₂ equivalent values are greater than both Mix 2 and Mix 3 by both 107 and 207, respectively. Thus, Mix 1 is 32 % higher than Mix 2 and 62 % more than Mix 3.
- This mix has the highest total single scores in both the Eco-indicator 99 and Ecopoints 97 methods with values of 13.9 and 173 kPt, respectively.

Overall, this option is not feasible and therefore must be discarded.

4.2 Mix 2 (CEM II/B-V concrete) option

Mix 2 advantages:

- Mix 2 does demonstrate considerable CO₂ reductions when compared with Mix 1. According to this study, a 32 % decrease in kilogram CO₂ equivalent would result from using a CEMII/B-V as opposed to a CEM I mix.
- A single score totals from the Eco-indicator 99 and Ecopoints 97 methods, Mix 2 exhibited 3.1 Pt (– 23 %) and 43 kPt (–25 %) reductions when compared with Mix 1, respectively.
- Transport distances for FA to the concrete plant are estimated to be 314 km on average in the UK. This is 123 km less than the value for GGBS.

Mix 2 disadvantages:

- CEMII/B-V mixes can only contain a maximum of 55 % FA addition, but in the UK, this figure rarely rises above a 30 % replacement level. This is not as high when

Table 4 Ecopoints 97 impact assessment table: weighting/single score

Impact category	Unit	CEM I concrete	CEM II/B-V concrete	CEM III/B concrete
<i>Total</i>	<i>kPt</i>	173	130	94
<i>NOx</i>	<i>kPt</i>	43	34	29
<i>SOx</i>	<i>kPt</i>	10.49	7.48	4.84
<i>NMVOc</i>	<i>kPt</i>	3.15	2.57	2.31
<i>NH3</i>	<i>kPt</i>	0.9999	0.7665	0.5455
<i>Dust PM10</i>	<i>kPt</i>	13	11	10
<i>CO2</i>	<i>kPt</i>	67	46	26
<i>Ozone layer</i>	<i>kPt</i>	0.0230	0.0181	0.0151
<i>Pb (air)</i>	<i>kPt</i>	0.1765	0.1268	0.0835
<i>Cd (air)</i>	<i>kPt</i>	0.6469	0.4599	0.2928
<i>Zn (air)</i>	<i>kPt</i>	0.0511	0.0405	0.0342
<i>Hg (air)</i>	<i>kPt</i>	1.57	1.07	0.60
<i>COD</i>	<i>kPt</i>	1.63	1.43	1.48
<i>P</i>	<i>kPt</i>	0.0237	0.0215	0.0224
<i>N</i>	<i>kPt</i>	0.0336	0.0261	0.0205
<i>Cr (water)</i>	<i>kPt</i>	0.1923	0.1615	0.1523
<i>Zn (water)</i>	<i>kPt</i>	0.7695	0.6141	0.5295
<i>Cu (water)</i>	<i>kPt</i>	0.6961	0.5300	0.3913
<i>Cd (water)</i>	<i>kPt</i>	0.4720	0.3517	0.2518
<i>Hg (water)</i>	<i>kPt</i>	0.9461	0.6938	0.4785
<i>Pb (water)</i>	<i>kPt</i>	0.0154	0.0115	0.0081
<i>Ni (water)</i>	<i>kPt</i>	0.2627	0.1951	0.1386
<i>AOX (water)</i>	<i>kPt</i>	0.0003	0.0002	0.0002
<i>Nitrate (soil)</i>	<i>kPt</i>	0.0124	0.0098	0.0081
<i>Metals (soil)</i>	<i>kPt</i>	0.0823	0.0810	0.1007
<i>Pesticide soil</i>	<i>kPt</i>	0.0027	0.0025	0.0027
<i>Waste</i>	<i>kPt</i>	11	10	10
<i>Waste (special)</i>	<i>kPt</i>	0.0222	0.0187	0.0175
<i>LMRAD</i>	<i>kPt</i>	3.68	2.58	1.55
<i>HRAD</i>	<i>kPt</i>	11.20	7.87	4.78
<i>Energy</i>	<i>kPt</i>	1.83	1.37	1.03

compared with replacement levels of other concrete classifications.

- Many coal power stations do not operate constantly, and some are even closing down completely. This affects the availability of FA.

Overall, this option does demonstrate some scope for sustainability and shows clear improvements when compared with Mix 1.

4.3 Mix 3 (CEM III/B concrete) option

Mix 3 advantages:

- CEM III/B mixes can contain up to 80 % GGBS addition. This high PC replacement level offers a larger scope for sustainability than other concrete classifications.

- The results from the LCA show that Mix 3 has the lowest CO₂ emissions with a value of 127 kg CO₂ eq. This is lower than the values of Mix 1 and Mix 2 by a massive 207 and 100 kg CO₂ eq., 62 and 32 % respectively.
- Single score totals from the LCA results are much lower for Mix 3 than for the other two mixes. The single scores from Eco-indicator 99 and Ecopoints 97 are only 8.52 Pt (40 and 27 % lower than Mix 1 and Mix 2) and 94.5 kPt (45 and 27 % lower than Mix 1 and Mix 2), respectively. The EPD 2008 method also indicates that Mix 3 has the smallest value across all of the impact categories.

Mix 3 disadvantages:

- GGBS used within the CEMIII/B mix tends to have the largest transport distance compared to other cementitious materials; this is due to a select amount of locations that

still operate blast furnaces in the UK. Some iron slag is even imported from mainland Europe to maintain the supply.

Overall, the advantages strongly outweigh the disadvantage, meaning that this option is most definitely feasible.

5 Recommendation

As highlighted previously, the only options that display any feasibility are Mix 2 and Mix 3. It is recommended that both of these options could potentially be taken forwards to improve the sustainability of concrete production. With respect to optimum mix design, it is strongly recommended that GGBS is selected as the addition of choice for improving sustainability. FA does still considerably improve sustainability when compared to PC, but the LCA of this work proved that inclusion of GGBS environmentally optimises the mix design even further. Advantages of using GGBS include lower CO₂ emissions, a substantial reduction of environmental impacts and an increased scope for sustainability due to the higher PC replacement levels that are permitted for GGBS. Due to mix designs enabling a higher contribution of GGBS additions (per cubic metre of concrete), it would also indicate an increased positive effect regarding waste scenarios. This is because without being applied to concrete mix designs, both GGBS and FA would be waste materials and would therefore be sent to landfill.

6 Conclusions, limitations and future work

The work demonstrated that significantly ‘greener’ concrete can be produced. This demonstration is largely successful due to the conclusive evidence that the addition of SCMs within mix designs can go a long way to reducing the overall CO₂ emissions and therefore substantially improve sustainability. Of these SCMs, it is also decided that GGBS would provide further benefits than FA for satisfying this objective. Both a cradle-to-gate LCA and an optioneering process delivered an overall resolution that can help designers and specifiers encourage the use of SCMs. Some stumbling blocks are still evident with the use of SCMs; the industry should make use of the obvious advantages with respect to sustainability that these materials have to offer. The identification of these advantages means that this work can be used for key sustainability decisions when it comes to concrete mix designs. The agenda for optimising the mix design also heavily relies on cost and performance implications, which are additional areas that can be explored in the future.

The authors accept that there are limitations in this study. Within this work, the authors excluded uncertainty and sensitivity analysis and focused on the evaluation of environmental

impacts of the three concrete mixed designs. However, uncertainty and sensitivity analysis are important in conducting LCA (Noori et al. 2014b; Andrae 2015b). Uncertainty is one of the characteristics of the real world; including uncertainty and sensitivity analysis can help achieve a more realistic result. Therefore, future work should include the adaptation of AALCA (Andrae 2015a) and different methods such as Monte Carlo or exploratory modelling (Noori et al. 2014b).

Further research work could form a detailed tool to be used by the industry for making decisions regarding SCMs for optimum mix design. In order to achieve this, it is recommended that future work should carry out an in depth cost analysis in order to find a compromise between environmental reduction and cost effectiveness; this should be interesting as FA generally tends to be cheaper as a material than GGBS. Further work should include testing different concretes to measure technical performance, including the acquisition of results for 28-day compressive strength, durability, permeability and so on. This should ensure that correct mechanical properties are selected for specific applications. Future work can also look at the broader scope for sustainability in concrete production and should carry out LCA in order to find potential benefits of other mix design materials other than SCMs, for example, the inclusion of recycled aggregates, alkali-activated binders and the incorporation of water recycling at concrete plants, amongst other potential options.

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References

- Andrae AS (2015a) Method based on market changes for improvement of comparative attributional life cycle assessments. *Int J Life Cycle Assess* 20(2):263–275
- Andrae ASG (2015b) Comparative screening life cycle impact assessment of renewable and fossil power supply for a radio base station site. *Int J Green Technol* 1:21–34
- Azapagic A, Clift R (1999) The application of life cycle assessment to process optimisation. *Comput Chem Eng* 23(10):1509–1526
- Black L (2014) Is carbon pricing a driver in concrete mix design? *ICT Yearbook 2014–2015*, pp 29–33

- Borghesi AD (2012) LCA and communication: environmental product declaration. *Int J Life Cycle Assess* 18(2):293–295
- Bribián IZ, Capilla AV, Usón AA (2011) Life cycle assessment of building materials: comparative analysis of energy and environmental impacts and evaluation of the eco-efficiency improvement potential. *Build Environ* 46(5):1133–1140
- Chen JJ, Kwan AKH, Jiang Y (2014) Adding limestone fines as cement paste replacement to reduce water permeability and sorptivity of concrete. *Const Build Mater* 56:87–93
- Cheung WM, Pachisia V (2015) Facilitating waste paper recycling and repurposing via cost modelling of machine failure, labour availability and waste quantity. *Resour Conserv Recycl* 101:34–41
- Cheung WM, Marsh R, Griffin PW, Newnes LB, Mileham AR, Lanham JD (2015) Towards cleaner production: a roadmap for predicting product end-of-life costs at early design concept. *J Clean Prod* 87:431–441
- Clear CA (2013) Aggregates their role in concrete and the green agenda, institute of concrete technology annual convention symposium 2013—concrete: grey to green. The Institute of Concrete Technology, Surrey, pp 21–35
- Eisa A (2014) Properties of concrete incorporating recycled post-consumer environmental wastes. *Int J Concr Struct Mater* 8(3):251–258
- Flower DJ, Sanjayan JG (2007) Greenhouse gas emissions due to concrete manufacture. *Int J Life Cycle Assess* 12(5):282–288
- García-Segura T, Yepes V, Alcalá J (2014) Life cycle greenhouse gas emissions of blended cement concrete including carbonation and durability. *J Life Cycle Assess* 19(1):3–12
- Glasser FP (2014) Changing perspectives in cement and concrete science. *Proc. 34th Concrete and Cement Science Conference, University of Sheffield*, pp 1–2
- Guinee JB et al (2010) Life cycle assessment: past, present, and future. *Environ Sci Technol* 45(1):90–96
- Habert G, Roussel N (2009) Study of two concrete mix-design strategies to reach carbon mitigation objectives. *Cem Conc Compos* 31(6):397–402
- Hayes JB et al (2015) Evaluation of leaching of trace metals from concrete amended with cement kiln baghouse filter dust. *Resour Conserv Recycl* 94:92–98
- Heath AC, Paine KA (2014) Reducing CO₂: optimum blend of binders in the UK. *Proc. 34th Concrete and Cement Science Conference, University of Sheffield*, pp 15–22
- Henry M, Kato Y (2014) Understanding the regional context of sustainable concrete in Asia: case studies in Mongolia and Singapore. *Resour Conserv Recycl* 82:86–93
- Higgins D (2006) Sustainable concrete: how can additions contribute? The Institute of Concrete Technology: Concrete for a Sustainable Future, Annual Technical Symposium, pp 2–6
- Hosseiniyou SA, Mansour S, Shirazi MA (2014) Social life cycle assessment for material selection: a case study of building materials. *Int J Life Cycle Assess* 19(3):620–645
- Huntzinger DN, Eatmon TD (2009) A life-cycle assessment of Portland cement manufacturing: comparing the traditional process with alternative technologies. *J Clean Prod* 17(7):668–675
- Imbabi MS, Carrigan C, McKenna S (2012) Trends and developments in green cement and concrete technology. *Int J Sustain Build Environ* 1(2):194–216
- Janssen GMT, Hendriks CF (2002) Sustainable use of recycled materials in building construction. *Adv Build Technol* 1399–1406
- Josa A, Aguado A, Cardim A, Byars E (2007) Comparative analysis of the life cycle impact assessment of available cement inventories in the EU. *Cem Concr Res* 37(5):781–788
- Kawai K, Sugimaya T, Kobayashi K, Sano S (2005) A proposal of concrete structure design methods considering environmental performance. *J Adv Concr Technol* 3(1):41–51
- Kucukvar M, Noori M, Egilmez G, Tatari O (2014) Stochastic decision modeling for sustainable pavement designs. *Int J Life Cycle Assess* 19(6):1185–1199
- Lewandowska A, Noskowiak A, Pajchrowski G, Zarebska J (2015) Between full LCA and energy certification methodology—a comparison of six methodological variants of buildings environmental assessment. *Int J Life Cycle Assess* 20(1):9–22
- Li C, Cui S, Nie Z, Gong X, Wang Z, Itsubo N (2015) The LCA of Portland cement production in China. *Int J Life Cycle Assess* 20(1):117–127
- Livesy P (1996) Balancing energy and the environment: the challenge for cement industry. *Concrete*. In: *The service of mankind. Concrete for environment enhancement and protection*, London, pp 321–330
- Metz B, Davidson OR, Bosch P, Dave R, Meyer LA (2007) Contribution of working group III to the fourth assessment report of the intergovernmental panel on climate change, IPCC 4th assessment report. Cambridge University Press, Cambridge
- MPA (2013) Fact sheet 18: embodied CO₂e of UK cement, additions and cementitious material, mineral products association with CSMA and. UKQAA, UK
- Müller HS, Breiner R, Moffatt JS, Haist M (2014) Design and properties of sustainable concrete. *Procedia Eng* 95:290–304
- Noori M, Kucukvar M, Tatari O (2014a) Economic input–output based sustainability analysis of onshore and offshore wind energy systems. *Int J Green Energy* 12(9):939–948
- Noori M, Tatari O, Nam B, Golestani B, Greene J (2014b) A stochastic optimization approach for the selection of reflective cracking mitigation techniques. *Transp Res Part A: Policy Pract* 69:367–378
- Noori M, Kucukvar M, Tatari O (2015) A macro-level decision analysis of wind power as a solution for sustainable energy in the USA. *Int J Sust Energy* 34(10):629–644
- Pade C, Guimaraes M (2007) The CO₂ uptake of concrete in a 100 year perspective. *Cem Concr Res* 37(9):1348–1356
- Richardson A (2013) Reuse of materials and byproducts in construction: waste minimization and recycling. Springer, London, pp 1–4
- Rowley HV, Lundie S, Peters GM (2009) A hybrid life cycle assessment model for comparison with conventional methodologies in Australia. *Int J Life Cycle Assess* 14(6):508–516
- Sear LKA (2002) The environmental benefits of using PFA in cementitious systems, Sustainable Concrete Construction. Thomas Telford Publishing, London, pp 313–322
- Sustainable Concrete Forum (2012) Concrete Industry Sustainability Performance Report – 6th report: 2012 performance data. Available at: <www.sustainableconcrete.org.uk/PDF/Sustainable%20Report%202013_FINAL.pdf>. Accessed October 2014.
- UKQAA (2008) Sustainability using fly ash in concrete, Technical Datasheet 8.2, UK Quality Ash Association
- Van den Heede P, De Belie N (2012) Environmental impact and life cycle assessment (LCA) of traditional and ‘green’ concretes: literature review and theoretical calculations. *Cem Concr Compos* 34(4):431–442
- Zhang J, Cheng JC, Lo IM (2014) Life cycle carbon footprint measurement of Portland cement and ready mix concrete for a city with local scarcity of resources like Hong Kong. *Int J Life Cycle Assess* 19(4):745–757