A new framework for assessing the environmental impacts of circular economy friendly soil waste-based geopolymer cements

A new framework for assessing the environmental impacts of circular economy friendly soil waste-based geopolymer cements

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ABSTRACT

Portland cement is one of the principal constituents used as a building material and is responsible for high energy consumption and greenhouse gas (GHG)GHGemissions. Any attempt to reduce cement usage would make savings in energy usage and GHGGHG emissions. A case study of Portland cement (CEM-I) replacement using alkali activated soil filter cake as a geopolymer mortar is presented to demonstrate application of a three-stage GHG emission estimation and comparison methodology using a process-based life cycle assessment (LCA) study, with a focus on benchmarking environmental sustainability. Results indicate that the alkali activated soil filter cake reduced total GHG emissions by 31 % compared with CEM-I, which equates to 110 kgCO_2-eq/m^3. Transportation by rail was found to be more sustainable compared with by road, with an overall higher GHG emission reduction of between 5-10%. For road transport, heavy goods vehicles (HGV) of between 3.5t and 5.7t recorded the highest GHGGHG emissions whilst articulated lorries recorded the lowest GHG emissions. Furthermore, the results also demonstrated that a bulk carrier is the most environmentally sustainable option for overseas raw material transportation. Monte-Carlo simulations signified the likelihood of achieving lowered GHG emissions when considering commercial production and inventory changes across different countries varies from 18% to 71%. These results highlight the importance of critical analysis of several factors which contribute towards overall environmental sustainability, prior to decision making on sustainable materials. Further research is encouraged on developing processes and methodologies to prioritize selection of sustainable materials to optimize sustainable benefits.

Keywords: *GHGGreenhouse gas, Geopolymer, Cement binders, Life Cycle Assessment, Sustainability*

1. Introduction

Concrete is a key material that is extensively used in the construction industry, which in the United Kingdom (UK) typically comprises fly ash-blended Portland cement (CEM-II), aggregates, superplasticisers and water. Concrete manufacture is responsible for significant virgin materials consumption and represents a major source of greenhouse gas (GHG) emissions [1]. Early studies report that one tonne of GHG dioxide (CO_2) is produced per tonne of concrete production, which with the introduction of improved processes and cleaner energies this has reduced 0.6 to 0.8 tonnes [2]. CEM-I clinker production requires extensive energy consumption and is responsible for approximately 10% of global CO_2 emissions [3, 4]. With many countries around the world investing heavily in infrastructure development such as the High Speed 2 railway in the UK and Sydney Metro in Australia, the demand for Portland cement-based concretes is expected to continue increasing over the next decade. Based on the construction industry's current consumption rates of traditional virgin materials such as limestone for Portland cement clinker manufacture, sand and gravel aggregates, these mineral resources are at risk of exhaustion and presents an environmental sustainability problem. Therefore, there is an urgent need to identify new alternative materials that can replace the traditionally used virgin materials in CEM-II-based concretes, which have longevity in supply and serve as a sustainable solution for reducing both GHG emissions and energy consumption in concrete production. Over the past three decades, the replacement of Portland cements in concrete has gained widespread research interest across the globe [5-12]. Industrial waste materials such as pulverised fly ash (PFA), ground granulated blast furnace slag (GGBS), glass powder amongst other pozzolanic materials have been extensively assessed as partial replacements [4, 9, 10]. Presented in Table 1 is a classification summary of European cements according to EN 197-1 [13].

Table 1 Overview of European cements [13, 14]

Cement class	Description	Notation	Composition	
			Clinker (%)	Secondary components (%)
Type 1	Portland cement	CEM-I	95 – 100	-
Type 2	Portland clinker + silica fume	CEM-II	90 – 94	6 – 10
	Portland clinker + GGBS		65 – 94	6 – 35
	Portland clinker + pozzolana			
	Portland clinker + PFA			
	Portland clinker + burnt shale			
	Portland clinker + limestone			

Type 3	Blast furnace cement	CEM-III	5 – 64	36 – 95
Type 4	Pozzolanic cement	CEM-IV	45 – 89	11 – 55
Type 5	Composite cement	CEM-V	20 – 64	36 – 80

However, despite the continuous introduction of innovative cement replacement materials, the necessity for environmentally sustainable replacement materials for cement that have longevity in supply and are circular economy friendly is ever growing to cater for the exponential demand within the construction industry [15, 16]. Whilst pozzolanic wastes such as PFA and GGBS are well understood and produce excellent engineering performances in CEM-II-based concretes and geopolymers, they are in high demand by the UK construction industry with supply chain issues. PFA availability is critically low as coal is no longer being mined or burned to generate electricity in the UK. GGBS supplies are also low, given that the UK's iron and steel industry has rapidly declined over the past 10-20 years. This has promoted research into identifying new mineral waste streams that have longevity in supply and ideally possess pozzolanic properties. One of the most desirable waste streams to investigate is soil and mineral waste, whereby approximately 130 million tonnes were produced in the UK in 2016 [17]. Reusing these materials in construction rather than sending to landfill would enhance the circular economy, valorise the waste and make a valuable contribution towards deGHGising the construction sector.

Systematic analysis, comparison and interpretation of the environmental benefits are key steps in benchmarking suitable sustainable materials. Life cycle assessment (LCA) is a well-defined methodology that can evaluate the environmental impacts of a product or process across different life cycle stages [18-21]. This can be achieved through compiling inventories for the desired product, evaluating potential environmental impacts and interpreting the results according to the objectives of the study [22-28]. Several studies have undertaken LCA on new materials as sustainable alternatives to CEM-I, which focus on GHG emissions associated with their production and manufacturing processes [29-33].

Despite CEM-I replacement by using alkali-activated waste materials, a handful of studies have highlighted a GHG emission increase due to the use of alkali activators in the mix design [4, 34-36]. This often reduces the collective embodied GHG emission savings and in certain cases could result in increased GHG emissions compared with Portland clinker-based binders [37]. Moreover, other external factors such as the energy source used for fuel production, transportation of raw materials and resource optimisation for material procurement also contribute significantly towards the total GHG emissions. A number of studies have investigated the local availability and transportation effects on the life cycle emissions of sustainable materials [27, 38, 39]. These studies have mainly attempted to benchmark the use of local sustainable materials by highlighting the potential emission savings. However, most of these comparative emission studies were designed based on laboratory scale production and lack of commercial scale results to facilitate effective comparisons. These observations highlight the importance of performing an in-depth sustainability assessment considering local effects as well as life cycle effects.

The case study presented in this paper aims to benchmark fine-grained construction soil waste which has been processed through a soil washing plant and compare potential GHG emission savings against CEM-I. The waste has cementitious properties through thermal and alkali activation and has the potential to act as a Portland cement replacement material. To compare total GHG emissions and benchmark the overall sustainable benefits of using the waste as a commercial product, a systematic process-based LCA methodology has been adopted. The study focus is only concentrated on benchmarking the commercial level production and the effect of emission inventories on the sustainable production.

2. Production of soil filter cake – case study

The soil 'filter cake' was sourced from Scott Bros Ltd (Teesside, UK), who collect and process mixed soil waste from construction projects (e.g. earthwork excavations, housing developments, land remediation) across the north east of England (UK) including Teesside, North Yorkshire and County Durham). The mixed soil waste is then subjected to a screening process, whereby following initial categorisation, the soil is processed through a soil wash plant in Teesside. This process involves both the cleaning of any contaminated bulk soils and their separation into individual particle sizes (i.e., boulders, cobbles, gravels, sands and fines). Water from the main plant is recycled for washing the soil waste to minimise freshwater usage and thereby promoting sustainable practice. Any water containing contaminants from the soil washing plant is diverted from the washing process to local reed beds for treatment. The coarser grained particle fractions of the washed soil waste have an immediate application for reuse as aggregates in various construction materials such as screeds, concretes and pavements. The fine-grained residue retained on the belt press within the wash plant accumulates to form a 'filter cake'. This consists of highly saturated silt and clay fractions, which currently does not have an immediate application for reuse. Based on the optimised operation frequency and the capacity of the Scott Bros Ltd wash plant, approximately 20 tonnes of soil waste are processed every hour, whereby approximately one third of this volume is represented by fines content.

Thus, an average of 30,000 tonnes of soil waste can be generated per annum on the current wash plant. Based on these statistics, there is a clear justification for investigating the technical prospects of the filter cake as a new readily abundant material for producing a new generation of low GHG cementitious construction materials (i.e. geopolymers).

Figure 1 illustrates the production process of the filter-cake based geopolymer. The process of preparing the geopolymer mortar involved several steps for mechanical activation; using several grindings, pulverizing and crushing techniques to obtain finer particle required to be used as a cement replacement material. The samples were also subjected to thermal and chemical activation prior obtaining the final geopolymer paste, whereby the chemical activation process involved addition of alkalis (including sodium hydroxide, NaOH and sodium silicate, Na_2SiO_4) to activate the cementitious properties of the geopolymer paste. Due to the commercial sensitivity of the geopolymer production process, the authors do not have permission to share the specific information related to the thermal activation process or the quantities of alkalis used in the mix design. The resulting engineering performance of the geopolymer was very impressive, whereby unconfined compressive strength testing (undertaken in accordance with BS1377, BSI 1990) confirmed that samples achieved strengths surpassed 50MPa.

All of these stages in the manufacturing process consume energy, which leads to the generation of GHG emissions. Therefore, the current study aims to evaluate and compare the GHG emissions to benchmark the GHG emission savings of the sustainable material against CEM-I for use in 50MPa concrete or screed obtained at laboratory scale production, compare the key sustainability criteria of local material availability and the transportation effects using case study analysis.

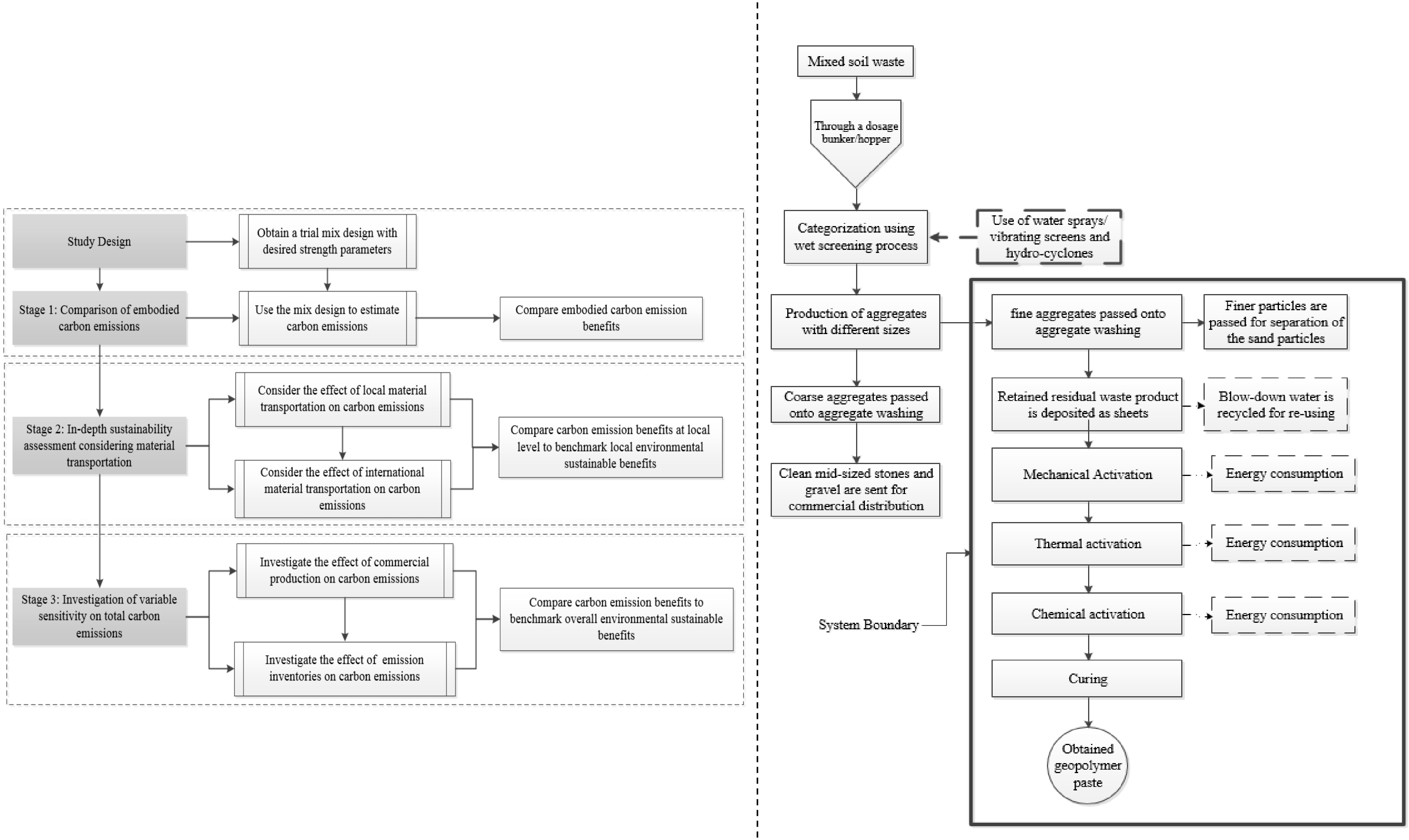


Figure 1 Production process of soil filter cake, system boundary and research methodology

3. Assessment methodology and inventories

3.1 Quantitative approach

LCA can be performed via three major methodologies: 1) input-output, 2) process and 3) hybrid [40-42]. Each method has its own advantages and disadvantages, which differ based on the scope and objective of case specific LCA studies. Their application and accuracy can also vary based on factors such as the purpose, assumptions and data availability. For case study comparisons where ample unit process information is available, the process-based approach will facilitate better comparison options and hence enable more effective interpretation of the results. Hence the current study considers a process based LCA methodology to estimate GHG emissions from material production.

According to ISO 14044, the LCA methodology involves key steps including goal and scope definition, inventory analysis, impact assessment and interpretation [43]. The first phase in the LCA methodology defines the scope and the objectives of the study including the functional unit, system boundary, limitations and assumptions. Inventory analysis and impact assessment is then defined based on the identified goals and scopes for the study, including critical comparison and interpretation. The following section explains the key LCA methodological steps adopted in the current study.

3.2 Scope of the study

Assessment of all the environmental impacts for a product or process is critical to benchmarking their performance [23, 44]. However, the majority of previous studies have considered energy performance and GHG emissions of construction materials due to their large quantities and elevated environmental significance [45-48]. Hence, this study presents a simple framework for comparing GHG emissions and the identification of significant sources of GHG emissions for geopolymer screeds against those traditionally made from CEM-I, with a view to facilitating the environmental optimisation of their procurement and usage.

According to the Kyoto Protocol, six major GHG emission substances are defined, namely GHG dioxide (CO_2), Methane (CH_4), Nitrous oxide (N_2O), HydrofluoroGHGs (HFCs), PerfluoroGHGs (PFCs), and Sulphur hexafluoride (SF_6) [49]. However, GHG emissions in the current study are principally due to fossil fuel or electricity consumption. Hence CO_2, CH_4 and N_2O are the predominantly significant factors. These major emissions were converted to CO_2 equivalents of GHG emissions using characterisation factors of 1, 24 and 310 for GHG dioxide (CO_2), Methane (CH_4) and Nitrous oxide (N_2O) respectively [31, 32, 50, 51].

3.3 System boundary and research methodology

The system boundary corresponding to the embodied GHG emissions comparison is presented in Figure 1. The manufacturing stages after the soil filter cake was obtained from the filter belt were considered for assessment as it is a waste material and was acquired from the main soil washing process for producing recycled coarse- and fine-grained aggregates. Therefore, the energy consumption and GHG emissions associated with the upstream processes in the cycle were not considered for the current study. Moreover, the objective of the study is to estimate and compare the GHG emissions variation as a result of replacing CEM-I with the activated filter cake geopolymer. Thus, all the energy consumption activities following the acquisition of the wet soil filter cake to the production of the geopolymer are considered in the system boundary for the analysis.

The second stage of this study aims to investigate transportation and local availability effects in using the soil filter cake geopolymer as a construction material. For this case, a cradle to gate system boundary is considered for comparing GHG emissions. Therefore, embodied GHG emissions from: 1) materials due to extraction and production, 2) transportation and 3) construction equipment were considered for the study. Figure 1 provides a clear representation of the proposed research methodology with the intended outcomes at each stage.

3.4 Function and the functional unit

As per ISO14044 definition of functional unit is critical to conducting a comprehensive assessment and comparison [52]. Since the primary objective of this study is to compare the GHG emissions of using soil filter cake geopolymer as a replacement material for CEM-I, a functional unit of cubic metre of cement mortar is considered.

3.5 Quantitative models

3.5.1 *Total embodied GHG emissions from materials*

The total embodied GHG emissions are quantified by collating the GHG emissions associated with the manufacture of raw materials including cement replacement material (soil filter cake geopolymer), fine aggregate and cement.

$$E_{tot} = \sum E_m * Q_m \qquad (1)$$

E_{tot} is the total embodied GHG emissions in $kgCO_2$-eq/m^3 of cement paste, E_m is GHG emission factor for corresponding material m in $kgCO_2$/unit weight and Q_m is the weight of the material in type ‘m’ in the same unit considered.

3.5.2 *GHG emissions from machine operation*

GHG emissions from machine operation are mainly from electricity usage or fossil fuel consumption. The following equation expresses the GHG emissions calculation procedure for equipment based on fuel type.

$$(E_{eq})_{el} = \sum E_{el} * P_{el} * h * r_c$$
$$(E_{eq})_{ff} = \sum E_{ff} * F_{ff}(1+\alpha) * h \quad (2)$$

Where; $(E_{eq})_{el}$ and $(E_{eq})_{ff}$ are the GHG emissions from electric and fossil fuel operated equipment respectively in $kgCO_2$-eq/m^3 of cement paste. E_{el} and E_{ff} are the GHG emission factors for electricity and fossil fuel type in $kgCO_2$-eq/kWh and $kgCO_2$-eq/litre, h is the hour of usage, P_{el} and F_{ff} are the power of the machine and fuel consumption of the machine in kW and litres/hour respectively and α is the idle time factor for the machine.

3.5.3 *GHG emissions from transport vehicles*

GHG emissions from transport vehicles is a function of the distance travelled and the type of fuel consumed by the vehicle. The following equation is used to determine GHG emissions from transportation.

$$(E_t)_z = \sum E_z * d_t * (w_t + w) \quad (3)$$

Where; $(E_t)_z$ is the GHG emissions from transport vehicle t for the fuel type 'z', E_z is GHG emission factor in $kgCO_2$-eq/ton-km, w_t dead weight of the vehicle t in tonnes w is the material weight in tonnes and w is the distance in km.

3.6 Emission inventories

3.6.1 *Emission factors for other raw materials*

Sodium silicate (Na_2SiO_3) was a key alkali activator material that was added to activate the cementitious properties of the filter cake geopolymer paste. The production of Na_2SiO_3 is an energy intensive process and results in significant GHG emissions due to elevated temperature levels during production. Using energy consumption details obtained from published literature and local suppliers, the GHG emission factor for Na_2SiO_3 in the UK was estimated to be 0.35 $kgCO_2$-eq/kg. This value is significantly lower compared with many other countries due to the renewable energy sources used for electricity generation in [4]. The sodium hydroxide (NaOH) component of the geopolymer mortar was another alkali activator used to activate the cementitious properties of the filter cake. NaOH is a by-product of chlorine production and is often produced through electrolysis of brine solutions. This process is energy intensive and can lead to high energy utilisation if not managed effectively during the manufacturing process. Based on the extraction to production process, the GHG emission factor was estimated as 1.06 $kgCO_2$-eq/kg. This emission factor was modelled using energy consumption details and machine usage obtained from local suppliers. This value is comparatively low as compared to some of the previously published literature (1.12 to 1.35 $kgCO_2$-eq/kg) mainly due to the clean electricity used in the UK

GHG emissions due to CEM-I manufacture can vary based on factors such as the limestone composition, configuration and operating temperatures of calcination equipment, energy sources used for production and the pattern of energy consumption. Based on these variables, GHG emission factors vary from 0.7 to 1.0 $kgCO_2$-eq/kg [5]. Based on the energy sources used for electricity generation and fossil fuel usage, the GHG emission factor for CEM-I production in the UK was determined as 0.78 $kgCO_2$-eq/kg. GHG emission factors for sand manufacture and water processing were used as 0.0048 $kgCO_2$-eq/kg and 0.344 $kgCO_2$-eq/m^3 respectively [53, 54].

3.6.2 *Emission factors for transportation*

Different modes of transportation were considered in the current study to investigate their effects on GHG emissions and facilitate comparisons. These include rail, road using different types of heavy goods vehicles and sea using different cargo ship sizes. For all of the cases considered, as summarised in Table 2, an average GHG emission factor was used to determine transportation GHG emissions. The analysis only considered one-way transportation, based on the assumption that regardless of the mode of transportation, the return journey is used to transport different material from destination to origin. Discrete values of GHG emission factors for transportation vehicles were considered for the analysis to investigate the effect of laden vehicle weight on the total GHG emissions.

Table 2 Average GHG emission factors for different transport

Vehicle type	Transport method	GHG emission factor ($kgCO_2$-eq/ tonne.km)	Reference/s
Bulk Carrier	Sea	0.00354	[53, 55]
General Cargo	Sea	0.01323	[53, 55]
Container ship	Sea	0.01614	[53, 55]
Heavy Goods Vehicle (HGV)	Road	0.10650	[53, 55]

Rigid (btw 3.5 - 7.5 t)	Road	0.52043	[53, 55]
Rigid (btw 7.5 t - 17 t)	Road	0.36835	[53, 55]
Rigid (>17 tonnes)	Road	0.18306	[53, 55]
Articulated (btw 3.5t - 33t)	Road	0.14179	[53, 55]
Articulated (>33t)	Road	0.07773	[53, 55]
Freight train	Rail	0.02556	[53, 55]

4. Sustainability assessment

To maximise the commercial potential of soil-based geopolymers in the UK, raw soil wastes will need to be locally sourced and transported to other locations within the UK. Furthermore, to benchmark the overall assessment, it is important to assess the sustainability benefits when the raw material is exported to different countries for production. Therefore, the sustainability assessment in the following analysis aims to investigate the effect of transportation in benchmarking the sustainability criteria.

4.1 Case 1 – Effect of transportation (within UK and Ireland)

For this case, 6 major cities across the UK and Ireland as shown in Figure 2 are considered to investigate the effect of material transportation between these different geographical locations on total GHG emissions. Rail transportation and a standard HGV were considered for transporting the raw filter cake material from the reference city (R1), Middlesbrough to the selected cities. For Dublin, total transportation includes either a combination of rail and sea, or road and sea transportation using average transportation emission factors for the corresponding mode of transport [53, 55].

Transportation emissions are dependent on the type and weight of vehicle used for transportation [56-59]. Therefore, it is important to investigate the effect of vehicle type and weight on the total transportation emissions. Two cases corresponding to 50% laden and 100% laden for each vehicle were considered for the analysis, as shown in Table 3. The outputs of this analysis are important for selecting the most appropriate vehicle and capacity to minimise GHG emissions. The analysis used discrete values of GHG emissions representing available truck types with different loading capacities to investigate the effect of real-time material transportation.

Table 3 Description of types of vehicles used for material transportation

Section No	Type of vehicle	Capacity	Fuel type

1	Rigid HGV	<3.5 tonnes	Diesel
2	Rigid HGV	Between 3.5 – 7.5 tonnes	Diesel
3	Rigid HGV	>17.5 tonnes	Diesel
4	Heavy rigid HGV	>35tonnes	Diesel
5	Articulated HGV	Between 3.5 – 33 tonnes	Diesel
6	Articulated HGV	>33 tonnes	Diesel
7	Normal Lorry	<20 tonnes	Diesel

Figure 2 Local transportation considered within the United Kingdom and Ireland

4.2 Case 2 – Effect of local availability of materials (export to other countries)

In this case, raw material exportation to a selection of major international destinations are considered to compare GHG emission savings of using soil filter cake material, rather than CEM-I. The investigation of GHG emissions due to material transportation will highlight the potential commercial possibilities of the material as a sustainable alternative to CEM-I. Sea transportation is considered over road freight transportation due to the observed lower GHG emissions. The corresponding sea transportation distances from Teesport in the UK to 5 major international ports are shown in Table 4.

Table 4 Sea transportation distances from Teesport (UK) for material importation

Destination	Distance (Nautical Miles)	Distance (km)
New York, USA	3,344.00	6,193.09
Shanghai, China	10,668.00	19,757.14
Melbourne, Australia	11,254.00	20,842.41
Calais, France	280.00	518.56
Singapore	8,421.00	15,595.69

4.3 Sensitivity analysis using Monte-Carlo Simulation

Monte-Carlo simulation is a frequently used sampling method to perform parameter uncertainty analysis [60]. In the current study, several input factors such as material quantities for the production of both the filter cake geopolymer cement and CEM-I mortar can be considered as uncertain. However, the scope of the current study is to estimate and compare the GHG emission associated with the filter cake geopolymer mortar production and the market development of the product. Commercial level production and the influence of GHG emissions due to electricity generation are two major factors that will define the promotion of the sustainable geopolymer as a commercially viable product in the construction market. Therefore, these two factors are considered as the two major inputs (scenario 1 and 2) for the sensitivity analysis. Resulting total GHG emissions per m^3 of cement mortar (output) were then compared to investigate the influence of each variable on the output.

Scenario 1 (SC1): Investigation of emission variations due to commercial level production

The current emission analysis is undertaken based on energy consumption details related to laboratory scale production. However, for commercial-scale production, the scale of energy consumption is different due to the usage of heavy and complex machinery including heavy duty crushers, mills and ovens. Furthermore, these pieces of equipment have large capacities which must be accounted for in calculating the power consumption when making comparisons with lab-scale manufacture. Therefore, the following equation was used to adjust the power usage of the industry scale equipment to suit the power consumption of mass production:

$$P_{adj} = \frac{C_l}{C_i} * P_i \qquad (4)$$

Where P_{adj} is the adjusted power of the industry scale machine in kW, P_i is the power of the industry scale equipment in kW and $\frac{C_l}{C_i}$ is the ratio between capacity of the laboratory and industry scale equipment. Using the above adjustment, SC1 will evaluate GHG emission variations due to the mass scale production. This will facilitate the benchmarking process of the emission savings at implementation level. The power outputs for different pieces of equipment were obtained from various suppliers across the globe, whereby the mean and standard deviation were determined from the inventory of information. An adjusted random power value was generated within the minimum and maximum values as shown in Table 5. These adjusted values were obtained by multiplying the laboratory scale with the capacity ratio as shown in equation (4). Using a curve-fitting exercise, several datasets of power values were simulated into a probability distribution. Monte-Carlo simulations were then performed with 10,000 iterations to explore variations in GHG emissions due to commercial production with a statistical significance of 0.05 [60].

Table 5 Power variation of commercial level production equipment

Equipment	Adjusted power in kW			Standard	Probability
	Mean	Max	Minimum	deviation	distribution
Ovens – drying/ curing	0.36	0.74	0.10	0.17	Triangular
Furnaces	1.23	3.68	0.65	0.78	Triangular
Disc mills	4	6.8	0.71	1.8	Triangular
Grinder/pulveriser	4.25	7.80	0.55	2.92	Triangular

Scenario 2 (SC2): Investigating the effect of emission inventories

GHG emissions for production of 1 m^3 soil filter cake geopolymer was estimated using average electricity emission factors in the UK and Ireland. However, based on the power source of electricity generation, the GHG emission factors can change significantly. Therefore, the current scenario aims to investigate the effect of electricity generation emissions on the geopolymer production in different regions of the globe. Based on the numerous electricity emission inventories in Europe, Asia and the USA were selected as inputs and probability distribution were determined using a curve fitting exercise. Table 7 summarises the determined electricity emission factor inventory, with values for the mean, maximum, minimum and standard deviation. The variation is primarily due to the varying power sources used to generate electricity across different countries and states. Similar to the previous scenario, Monte-Carlo simulations were conducted by generating a random variable using the boundary conditions shown in Table 7. Using 10,000 iterations, SC2 aimed to investigate the effect of emissions from electricity generation on the GHG emissions of screed production.

Table 6 Electricity emission inventories for different regions across the world

Region	Electricity emission factor in $kgCO_2$-eq/kWh	Reference/s

	Mean	Max	Minimum	Standard deviation	Probability distribution	
Europe	0.3529	0.8750	0.0120	0.2241	Normal	[53, 61-63]
America	0.4426	0.9258	0.0303	0.2356	Normal	[64-67]
Asia	0.6672	0.8000	0.4916	0.1236	Normal	[61, 68]

5. Results and Discussions

5.1 Material embodied GHG emissions

The observed GHGGHG emission comparisons for the geopolymer mortar and CEM-I pastes are illustrated in Figure 4. The results show that the alkali activated soil filter cake achieved a total GHGGHG emission reduction of 109.95 kgCO_2-eq/m^3 compared with CEM-I, which equates to approximately 31%. This is mainly due to the benefits of local sourcing of waste materials, along with the replacement of CEM-I and fine aggregates. This reduction can lead to significant savings of GHGGHG emissions when larger quantities are used in construction projects. The use of alkali activators accounts for 79% of the total GHGGHG emissions for the new geopolymer paste. It further contributes to the total reduction of 389kgCO_2-eq/m^3 (84%) achieved through CEM-I replacement, ultimately resulting in a 31% total GHGGHG emission reduction. The error bars correspond to the mix design variations and it is evident that the geopolymer paste can vary to 306 to 385 kgCO_2-eq/m^3.

This estimation is based on local production in Middlesbrough with the use of local GHGGHG emission factors in the UK and under the assumption that the raw materials are locally available for production. While CEM-I as a raw material is often commercially available in major cities, soil filter cake may not be readily available for commercial production. Thus, the GHGGHG emissions due to transportation also need to be considered for the geopolymer mortar production in other cities across the UK and Ireland.

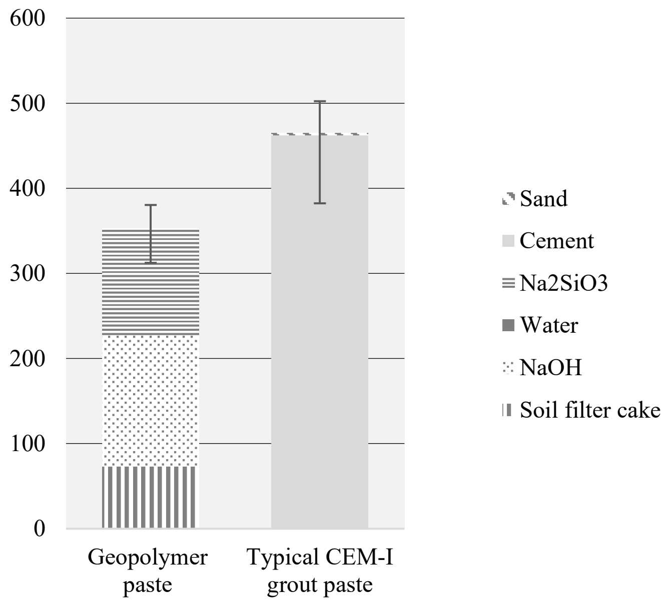


Figure 3 GHG emissions comparison in kgCO_2-eq/m^3 of cement paste

5.2 Sustainability assessment results

5.2.1 *GHG emission considering material transportation within the UK*

The resulting total GHG emissions, which incorporate emissions through different transportation modes are illustrated in Figure 4. Total GHG emissions for the geopolymer mortar was calculated by adding surplus GHG emissions due to material transportation to each city locally, as explained in equation (3). This case considered rail and road transportation using average GHG emission factors, along with raw material transportation from Middlesbrough to six major cities across the UK. The results are compared with GHG emissions from CEM-I mortar manufacture under the assumption that CEM-I is locally available in all six major cities. Thus, the GHG emissions due to transportation was assumed to be negligible for CEM-I mortar manufacture. The resulting comparisons indicate that total GHG emissions including the emissions increase due to raw material transportation do not exceed the GHG emissions of normal CEM-I paste. Dublin has a sea transport component and the total includes a GHG emissions proportion with emissions from sea transportation as well. As expected, rail transportation was more sustainable compared with road transport, whereby an overall lower GHG emission reduction of 5-10% was recorded. The results further signify that the transportation of the raw materials within the UK to produce the geopolymer mortar is environmentally sustainable, with GHG emission savings.

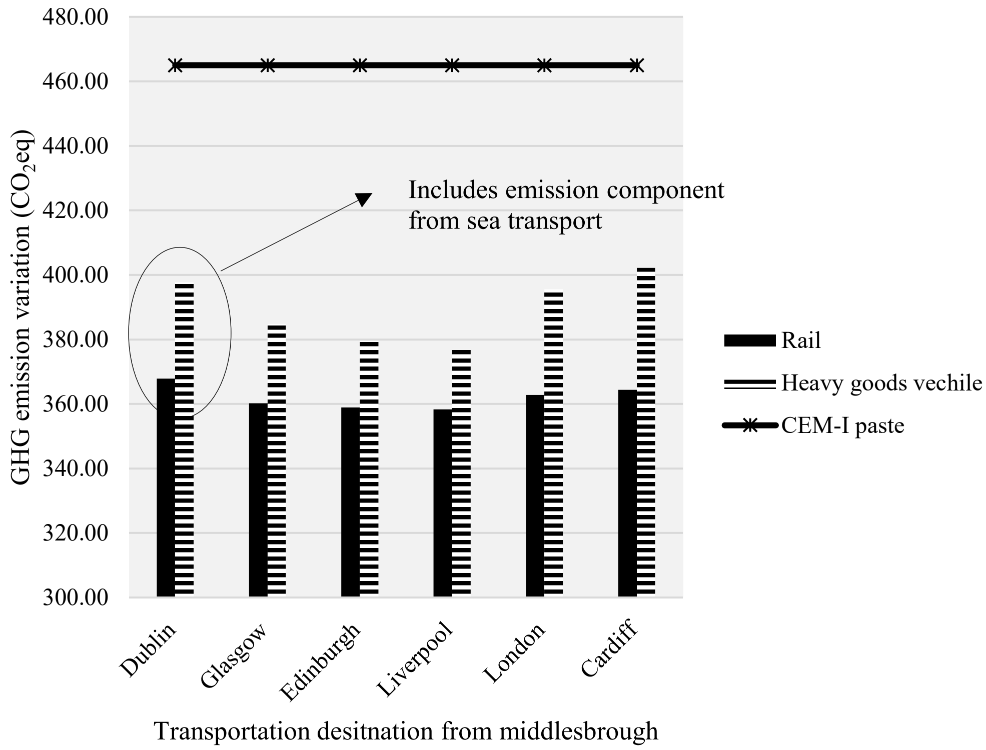


Figure 4 GHG emission variation due to raw material transportation within the UK and Ireland

Figure 5 presents total GHG emission variations based on the type and weight of the heavy goods vehicle (HGV) used for raw material transportation within the UK and Ireland. Since the total GHG emissions are dependent on the weight of the vehicle (as per equation 3), the resulting GHG emissions when the vehicle is fully loaded and half loaded for different vehicle types vary significantly.

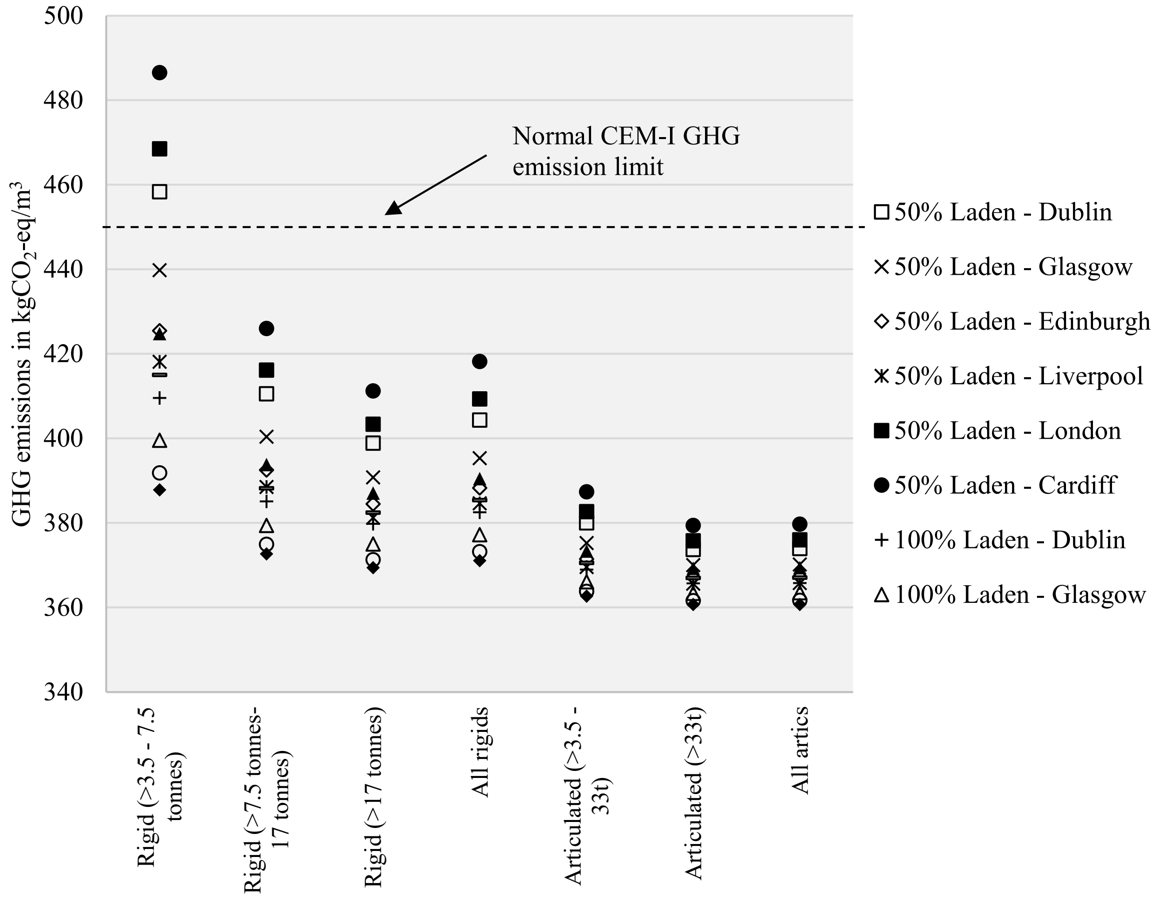


Figure 5 GHG emission variation due to the size and type of the vehicle

Results indicate that material transportation using HGVs between 3.5t and 5.7t recorded the highest GHG emissions, whilst articulated lorries (artic) recorded the lowest GHG emissions. Using HGVs (<7.5t) to transport raw materials to Dublin and London would produce total GHG emissions that exceed those for CEM-I paste, which would make the process environmentally unsustainable. These results signify the importance of carefully selecting the most suitable vehicle for raw material transportation when considering life cycle GHG emissions savings.

5.2.2 *GHG emission distribution considering raw material transportation to other countries*

The resulting GHG emission variations, considering raw material transportation to other major countries are shown in Figure 6. GHG emissions for the filter cake geopolymer mortar was calculated by additionally considering GHG emissions due to material transportation (soil waste) as per equation (3). Each country in the analysis was selected to facilitate an effective comparison representing different regions across the globe. Three types of ships including bulk carrier, general cargo ship and container ship were considered to facilitate the analysis. In each scenario, average GHG emission factors corresponding to each ship type were used to facilitate the comparative analysis. Similar to results from SC1, it was assumed that CEM-I or an equivalent cement is readily available in the countries considered for this analysis.

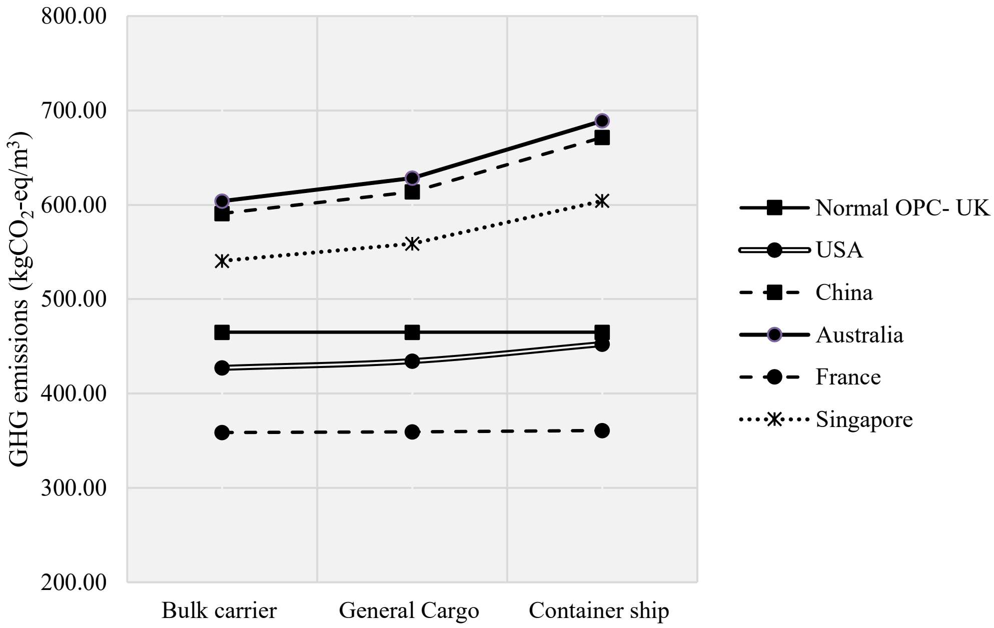
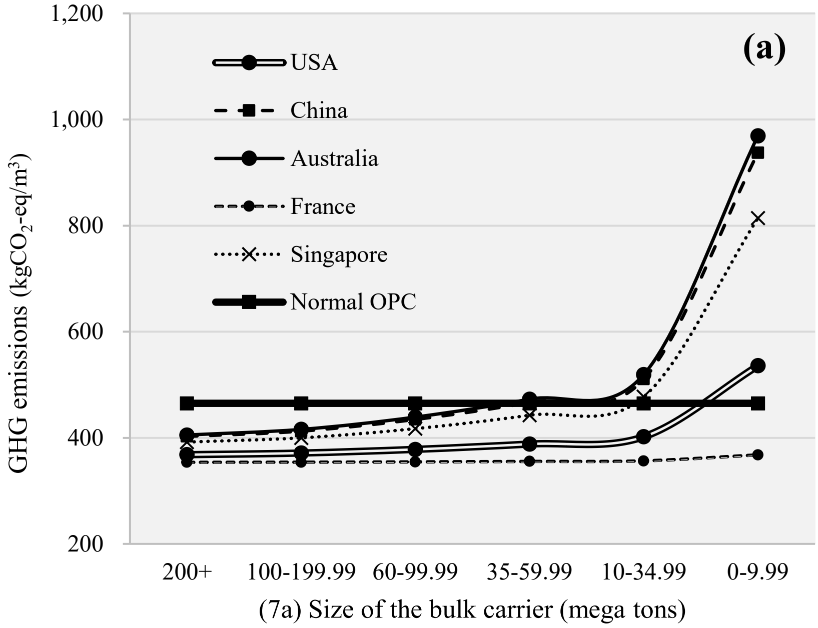
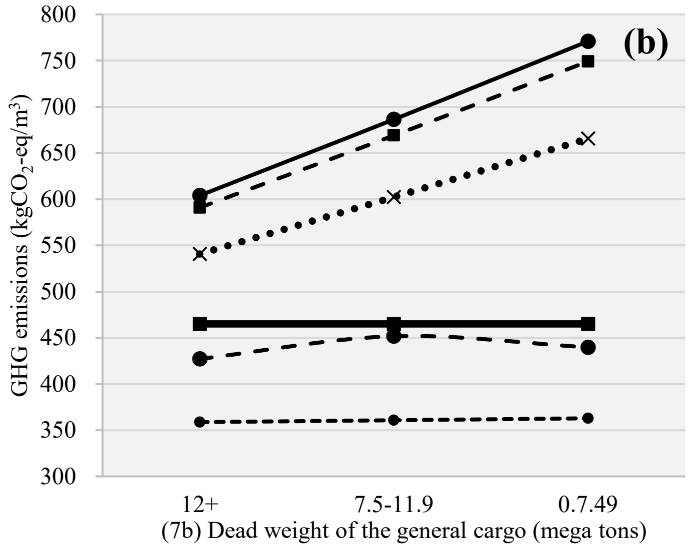


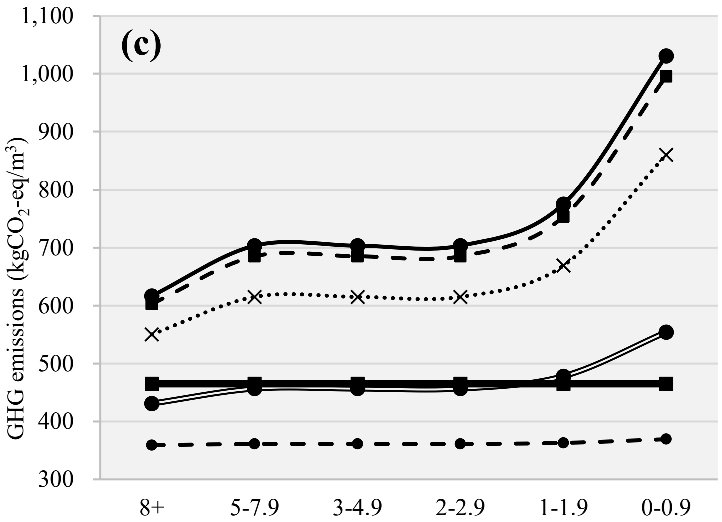
Figure 6 GHG emission variation due to raw material importation to other countries

Results signify that irrespective of the ship type, raw material exportation to USA and France provide GHG savings in geopolymer mortar production compared with CEM-I paste. Moreover, the results also illustrate that using a bulk carrier is the most environmentally sustainable option for raw material transportation to other countries for producing geopolymer pastes. However, the use of waste material to replace CEM-I content in the mortar can be justified in terms of responsible resource usage and therefore can be considered sustainable for exporting to USA.

GHG emission variations based on the weight of different types of ship are shown in Figure 7. Results from Figure 7(a), indicate for the five countries considered, using the heaviest bulk carrier (> 200 megatons) to export raw materials for manufacturing filter cake geopolymer, can achieve greater GHG emission savings compared with the production of CEM-I mortar using virgin materials. Furthermore, using a bulk carrier with a dead weight above 60 megatons can still achieve GHG emission savings. However, when using bulk carriers with weights ranging between 35-59.99 megatons, raw material export to Australia and China becomes environmentally unsustainable in terms of GHG emissions. Use of the lightest bulk carrier (up to 10 megatons) will lead to higher GHG emissions when raw materials are exported to all countries apart from France.


(a)
USA
China
Australia
France
Singapore
Normal OPC
GHG emissions (kgCO2-eq/m3)
1,200
1,000
800
600
400
200
200+
100-199.99
60-99.99
35-59.99
10-34.99
0-9.99
(7a) Size of the bulk carrier (mega tons)


(b)
GHG emissions (kgCO2-eq/m3)
800
750
700
650
600
550
500
450
400
350
300
12+
7.5-11.9
0.7.49
(7b) Dead weight of the general cargo (mega tons)



(7c) Dead weight of the container ship (mega TEU)

Figure 7 GHG emission variation due to the size and type of the transport ship

Comparison of GHG emission patterns for varying sizes of general cargo as per Figure 7(b) and container ship as per Figure 7(c) indicate that filter cake geopolymer mortar production can only achieve GHG emission savings when the material is exported to France . However, in the case of using container ships larger than 8 megatons, geopolymer exportation to USA can achieve GHG emission savings. These findings further signify the importance of carefully considering transportation impacts and procuring raw filter cake materials from local sources.

5.3 GHG emission variation due to electricity emission inventory change

Variance of GHG emission inventories is another major factor that can significantly contribute to variations in the final calculated total GHG emissions. The resulting GHG emission variations due to electricity production in Europe, USA and Asia are shown in Figure 8 – based on 10,000 iterations from Monte-Carlo Simulation. The lower and upper limits of each box represents the first quartile (Q1) and the third quartile (Q3) values respectively, with minimum and maximum values also indicated. These were then compared with CEM-I mortar to determine the probability of total GHG emission variation due to electricity inventory change. Results indicate that Asia has the lowest sensitivity to emission variation, ranging from 434 to 531 $kgCO_2$-eq/m^3. However, due to the higher transportation distances the likelihood of achieving GHG emission savings is only 18%. Therefore, the use of soil filter cake to produce a geopolymer mortar is unlikely to achieve GHG savings. On the other hand, Europe and USA both have higher likelihoods of achieving GHG savings with probabilities of 33% and 8% respectively. However, for USA the maximum GHG emissions can reach up to 571 $kgCO_2$-eq/m^3. This is mainly due to the high variation of energy sources used for electricity production.

Similarly, Europe exhibits a similar variation, with maximum and minimum values of 555 $kgCO_2$-eq/m^3 and 283 $kgCO_2$-eq/m^3, respectively.

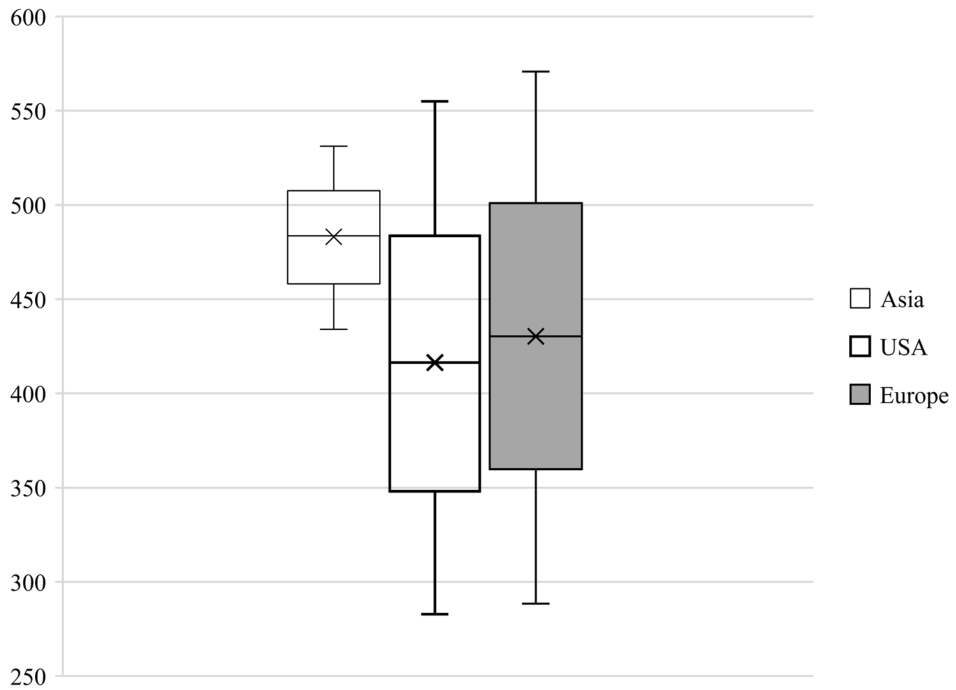


Figure 8 Total GHG emission variation for material production ($kgCO_2$-eq/m^3) due to emission inventory change

5.4 GHG emission variation due to commercial production

GHG emission modelling and results discussed in the current study are based on laboratory scale production and consumption. Therefore, the results do not represent the commercial production levels. Commercial production frequently utilises heavy and large equipment which will influence the emission patterns significantly. Similar to previous analyses, the uncertainty of GHG emission variations was obtained using 10,000 iterations with a confidence level of 0.05. The resulting GHG emission variations indicated that GHG emissions due to commercial production can vary from a minimum of 282 $kgCO_2$-eq/m^3 to a maximum of 572 $kgCO_2$-eq/m^3. The first and third quartile were recorded as 337 and 462 $kgCO_2$-eq/m^3 respectively. The likelihood of total GHG emissions for the filter cake geopolymer being less than that for CEM-I mortar production is recorded aound 71%, as obtained from the Monte-Carlo distribution output. This indicates that despite considering commercial production, there is a high probability that the proposed geopolymer cement mortar will achieve GHG emission savings compared to CEM-I paste.

5.5 Assumptions and limitations

The current study only considered GHG emissions. Future more detailed LCA studies should also consider other environmental impacts, especially when alkali activators are required for manufacturing alternative cementitious materials [69, 70]. The embodied GHG emissions for more sustainable cements are based on process-based energy consumption data obtained in the UK. Moreover, the following general assumptions were also considered in the current analysis.

- GHG emission comparisons are based on the specific UK case study for soil filter cake-based geopolymer production, quality control methods and manufacturing strategies. The results will vary based on the changes in production processes
- Wherever GHG emission factors were not modelled, their values were obtained from previous similar studies. This is due to the lack of access to commercially available LCA inventory databases.
- GHG sequestration and durability aspects of the filter cake geopolymer were not considered in the current study for estimating GHG emissions
- Other effects on the mechanical strength and durability performance of the geopolymer (e.g. GHGation) were not considered due to lack of information. To add a level of conservatism to this study, any beneficial effects from GHGation or other such reactions on the engineering performance of the geopolymer were deemed negligible.
- The emission factors for each material in the geopolymer mortar mix were modelled using the fuel and energy consumption information provided by local manufacturers. These factors may differ based on the energy source and energy consumption patterns.

6. Conclusions and Further Research

The current study presents a three-stage methodology to evaluate GHG emissions for a soil filter cake geopolymer as a sustainable replacement for CEM-I, with a focus on benchmarking environmental sustainability. Stage one compared potential embodied GHG emission savings from the geopolymer at the materials production stage. The second and third stages investigated the use of different modes of transportation and key GHG emission benefits in the production stage, including the effect of commercial production and emission inventories. The following key findings were obtained from the study:

- The addition of alkali activators accounted for around 79% of total GHG emissions for the geopolymer paste.
- Replacement of CEM-I with the filter cake geopolymer resulted in a total GHG emission reduction of 3895 $kgCO_2$-eq/m^3.
- Monte-Carlo simulations indicated that GHG emissions from commercial cement mortar production can vary from 282 - 572 $kgCO_2$-eq/m^3 and the likelihood of this being less than CEM-I is 70.75%
- Sensitivity results on inventory variation revealed that Asia has the lowest sensitivity to emission variation, between 434 to 531 $kgCO_2$-eq/m^3
- Europe and USA regions recorded higher likelihoods of achieving GHG savings compared with Asia, with probabilities of around 33% and 58% respectively

The use of alkali activators has a significant impact on the GHG footprint of geopolymer manufacture, which may even outweigh potential GHG emission savings of cement replacement if suitable optimisation methods are not adopted to minimise their use. Rail was a more sustainable mode of transport compared with road for local raw material transportation within the UK. Results also indicated that using larger ships can potentially lead to GHG emission savings, particularly for material importation.

The results compared GHG emissions related to using filter cake geopolymer mortar as a cementitious material. Further studies should concentrate on evaluating additional environmental impacts of using filter cake geopolymer and performing comparative assessments with more commercially available metakaolin geopolymers. Future research into the optimisation of alkali activator content to produce the most sustainable geopolymer mortar mix design for a given compressive strength. Other studies can also be concentrated on comparison of GHG emissions of geo polymer soil waste cement mortar with other locally available cement replacement materials to compare benefits. Moreover, future research can also be focused on developing processes to optimise the triple bottom pillars of sustainability benefits, i.e. economic, environmental and social.

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Property (IP) arrangements, the authors are unable to provide a detailed summary of process information related to the geopolymer mortar production.

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