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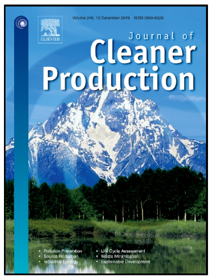

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Comparative life cycle assessment between imported and recovered fly ash for blended cement concrete in the UK

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Abstract

A UK government report released in 2017 indicated that fly ash (FA) production locally is expected to seize after 2021. This means that for the construction industry to meet its continuously increasing demand for an Ordinary Portland Cement (OPC) replacement, FA would probably need to be either imported or recovered from landfills through energy-intensive processes. Recent reports show that companies in the UK have already started importing FA from several countries from which Germany and China were chosen as case studies to exemplify the closest and furthest respectively. The environmental impact associated with the FA transportation raises concerns about the environmental sustainability of the final concrete product. Therefore, this study focuses on using a life cycle assessment (LCA) tool to analyse the environmental impact of importing FA from Germany and China and compare that to recovering landfilled FA in the UK. The study is the first of its kind to investigate the environmental impact of any of the alternatives. Using a Cradle-to-Gate approach and a mix of primary and secondary data, these alternatives were modelled and compared to conventional OPC and currently available locally sources of FA. Results show that the environmental burden from transporting FA from China to the UK will overcome the environmental benefits of it replacing OPC. It is then concluded that the most promising alternative for cleaner production of blended cement concrete is to recover the 50 million tonnes of landfilled FA from the UK using the Dry-processing technique explained in the study. The second best alternative is to import FA from a country within the Europe region to the UK.

1. Introduction

Despite being responsible for more than 5% of the global CO_2 emissions in 2016, the production rate of cement is expected to grow continuously at a rate of 10% annually to reach a historical maximum of around 5000 Mt/Year by 2021 (Andrew, 2018). However, recent research has been directed to meet the “2015 Paris climate conference” guidelines concerning reducing the clinker used in concrete to decrease its environmental impact (Vinuales et al., 2017). Among several options, the most common is partially replacing ordinary Portland cement (OPC) with supplementary cementitious materials of pozzolanic nature such as fly ash (FA) (Rahla et al., 2019). FA is precipitated electrostatically as a by-product from coal burning power plants (Meyer, 2009). China alone produced 700 million tonnes in 2014, making FA the fifth largest raw material available on Earth (Wang et al., 2017). The use of FA as an addition to OPC has been around globally for the past 50 years as it is believed to enhance the 90 days compressive strength and durability of concrete (Assi et al., 2018; Thomas, 2007). Besides increasing the durability and mechanical properties, the use of waste material instead of cement is intended primarily to decrease the latter’s environmental impacts and avoid the burden from landfilling such waste (Muller et al., 2014). A well-recognized comprehensive method of analysing such environmental impact is Life cycle assessment (LCA) (Knoeri et al., 2013). Using LCA, it was argued that replacing 35% of the OPC in a concrete mix could reduce the global warming potential (GWP) up to 30% (Tait and Cheung, 2016). The same conclusion was found when recycled aggregates were used along with 30% OPC replacement with FA (Turk et al., 2015). The use of higher volume of FA (60% and 65% respectively) yielded even more reduction in GWP equivalent to almost 50% (Kurda et al., 2018; Marinković et al., 2017).

In the UK, the use of FA is established in many sectors of the construction market. According to a report by the UK Quality Ash Association (UKQAA), FA is added directly to clinker in cement factories, added partially to OPC in precast concrete and concrete blocks as well as being used in soil stabilization (UKQAA, 2015). In 2014, out of 4 million tonnes of FA produced, more than 2 million tonnes were utilized in the concrete industry in the aforementioned applications (UKQAA, 2014). Several cement manufacturers such as Hanson Heidelberg Cement Group produce ready blended cement packages with 35% FA replacement to OPC (Tait and Cheung, 2016). Contractors have been encouraged to utilize FA in construction due to the presence of different standards as EN 450 and BS 8500. However, although the demand for FA appears to be increasing, the future concerning the availability of local supply is not promising. The reason is that the UK government is opting to close down all coal operated power plants after 2021 according to a governmental report published in 2017 (BEIS, 2017). Starting 2013, the production of coal has already been decreasing in the UK and will continue to decline till it nullifies by 2021 as discussed (BEIS, 2013). Hence, the report proposes two solutions to make FA available beyond the seizure of coal production namely, importing FA from abroad and restoring landfilled FA.

Looking into the potential for importing FA, two private companies: Power Minerals Co. (Paoli, 2016) and Ecocem Co. (Lambe, 2018) have already started importing FA from Europe (Germany, Italy, Spain, and Portugal) and China respectively. However, this raises concerns on the environmental impact associated with long transportation distances that might end up cancelling the benefits of the imported FA (IFA) replacing OPC. Since FA carries negligible emissions as a product, most of the weight of importing FA could be attributed to its transportation process (O'Brien et al., 2009). An LCA study is needed then to calculate the critical transportation distance of FA beyond which substituting OPC with FA would actually result in higher environmental impact (O'Brien et al., 2009). A similar study concluded that transportation could attribute up to 30% of the environmental impact of the concrete produced depending on the distances travelled by the different concrete constituents (Lopez Gayyare et al., 2015). Nevertheless, increasing transportation distances beyond 20% reduces the environmental benefits of replacing fresh aggregates with recycled ones (Uzzal Husain et al., 2016). A similar research by Gursel et al. (2016) concluded that importing cement from further away China rather than Malaysia, the GWP of concrete in Singapore increases by 11%.

The second alternative proposed by the report is to recover landfilled FA from the UK (BEIS, 2017). Due to variations in the coal quality, only 40-50% of the FA residue could be recycled directly and the rest is simply landfilled (McCarthy et al., 2013). A report by the department for Business, Energy and Industrial Strategy (BEIS, 2017) argue that given suitable recovery technologies are utilized, the current reserve of almost 50 million tonnes of stockpiled FA could be enough to meet decades of demand for use in concrete in the UK. Several technologies were found in the literature attempting the recovery of FA using lab based processes such as the "mechanical processing" technique developed in the centre for Applied Energy Research at the University of Kentucky (Robl et al., 2006). The process involves characterization of the landfilled FA followed by hydraulic classification (Robl et al., 2006). Another technique is the "Triboelectrostatic beneficiation" in which FA particles are pumped into a copper tube that causes an active charge that separates the FA particles and recovers the fine particles suitable for use (Bultras et al., 2015). In addition, the "Dry-processing" technique developed in the University of Dundee, which was reported to successfully recover 90% of random samples of FA, was found to include some energy consumption data (McCarthy et al., 2018). Similar to the importing alternative, further investigation of the associated environmental impacts of the recovery techniques is needed. The energy needed and the resulting emissions from the recovery process of the FA could end up causing negative environmental impacts that surpass that of OPC. This would render the replacement process useless in terms of environmental sustainability.

It is now clear that starting 2022, concrete producers and users in the UK will be facing a challenge sourcing FA. Although there appears to be alternatives, it is necessary to quantify and evaluate the environmental impact of them and compare it to OPC and locally sourced FA. This study is the first of its kind to look into such a critical matter. In order to reach a decision of whether FA is to be imported as opposed to recovering the landfilled FA, an LCA will be carried out on each of the proposed alternatives. The primary data from local UK news about the importing scenario were not used before in any of the studied literature. Also, this is the first study to evaluate the environmental impact of a FA recovery process.

2. Methods

A LCA consists of 4 main stages: (i) Scope and goal definition, (ii) Defining the inventory for the life cycle processes, iii) characterising and measuring the life cycle impact (ISO, 2006) and iv) the interpretation of results. First, the main decision in the scope stage is to decide on the system boundaries and functional unit (Habert et al., 2011). A system boundary of a concrete product could be "Cradle-to-Gate" which spans until the production of its different constituents or "Cradle-to-Grave" which includes the "Use" and "End-of-Life" phases. Many LCA studies opt for a Cradle-to-Gate system boundary due to the large uncertainties present in the remaining phases (Wu et al., 2014). A functional unit is the basis for quantifying the inputs and outputs between alternatives. Hence, its selection needs to be reflective of the nature of the LCA subjects (Panesar et al., 2017). Mass based functional units are found to be the most common when comparing the process of producing binders such as: Lime, FA and OPC (Panesar et al., 2017). The next LCA stage includes collecting the data of energy and emissions associated with the aforementioned scope. The data needed for standard processes can mostly be found in databases such as Ecoinvent, Swiss input/output and ELCD (Sagastume Gutierrez et al., 2017). Another important parameter to decide at this stage is the allocation, which is basically portioning the environmental burden of the original process to the product under study (Marinkovic et al., 2017). According to the EU directive 2008, FA is considered a by-product not a waste and thus ought to be allocated a percentage of the environmental burden of its original production process, which is coal combustion (Anastasiou et al., 2015). The first scenario is "Mass allocation" where the percentage allocation is based on the relative mass between the waste material as a by-product and the mass of the total (the effective mass of electricity + the mass of FA). The second scenario is "Economic allocation" in which the percentage allocated is based on the relative market value between the final product, which is FA and electricity (Chen et al., 2010). LCA studies on Green concrete tend to use economic allocation for FA since it is usually a lower number, which allows the results to be positive relative to OPC, but the fluctuation of market prices brings in uncertainties to the calculations (Marinkovic et al., 2017). The final stage of an LCA is to calculate the environmental impact of the studied product. This is performed by adding up the individual impacts of all the associated processes as per ISO 14040:2006 to calculate an environmental impact indicator; a number that makes the output of the impact assessment study more understandable to the user (Goedkoop et al., 2001). According to Menoufi (2011), there are two main types of indicators: Mid-point indicators, which correlate the calculated impact to a specific change in the environment such as GWP and End-point indicators which correlate the same increase to a further on damage in the cause-effect change such as human health. The significance of this differentiation is that the same comparison between products or processes could result in different scores if looked upon by a Mid-point or an End-point indicator, due to the exaggeration of damage that happens to reach the latter (Maia de Souza et al., 2016). Mid-point indicators are then known to be more accurate given that the user knows which indicator best suits the description of the assessment, but End-point ones are easier to interpret since it is just a single score (Sayyagh et al., 2010).

2.1 LCA scope definition

The first stage of the LCA study is to decide on the boundaries and the scope. As agreed, it is best descriptive of this kind of comparison between binders to have a Cradle-to-Gate scope. The processes examined are hence only those involved up until the production of the following products: ordinary Portland cement (OPC), current locally sourced UK FA (LFA), IFA and recovered FA (RFA). The functional unit is selected as 1 kg of mass. To reflect the fact that only 90% of the landfilled FA is reported to be recyclable according to McCarthy et al. (2018), the functional united selected for RFA is 1.11. The boundaries of the Cradle-to-Gate scope for all the materials modelled in the LCA are found in Figures 1 and 2. Although the FA studied are intended for use as partial replacements to OPC in concrete, it is out of scope to study the further processes concerned with concrete production, use, and end-of-life. The reason behind this is that beyond the production processes included in this study, all the FA types are assumed to be conforming to the specifications by BS EN 450-1 standard shown below in Table 1, which ensures a fair comparison. The selected countries of origin for the IFA are China and Germany. These exemplify the largest and smallest transportation distance out of all the examined countries from the literature. IFA is hence sub-divided into IFA/C and IFA/G to indicate FA imported from China and Germany, respectively. The selected transportation means is by sea freight and the selected ports from UK, China and Germany were Newcastle, Hong Kong and Bremen, respectively. The calculated freight distances, which are assumed to be only for a single trip considering that other products are transported back on the same carrier, can be found in Table 2. It is assumed that the transportation from the port to the concrete batch plant is the same as the distance from the nearest OPC factory as well as the nearest coal-fired power station where LFA and

RFA are sourced. Hence, the energy and emissions related to the transportation of any of the products to the concrete batch plant is considered as equal. Out of the three recovery techniques found in the literature (Robl et al., 2006; Bultras et al., 2015; McCarthy et al., 2018), the Dry-processing technique was the one selected for the scope of this study. The reason is that the process is well explained in a way that allowed for the calculation of the energy and emissions that was input in the modelling scenario.

Table 1: BS EN 450-1 requirements for FA to replace cement based on Carroll (2015)

Property	Limits
Activity Index	≥ 75% @28 days, ≥ 85% @90 days
Loss On Ignition (LOI)	Category A ≤ 5%, Category B ≤ 7%, Category C ≤ 9%
Particle density	± 200 kg/m^3
Fineness (45 μm)	Category N ≤ 40%, Category S ≤ 12%
Free Calcium Oxide	≤ 1.5%
Reactive Calcium Oxide	≤ 10%
Sulphate Content	≤ 3%
Alkalis	≤ 5%
Magnesium Oxide	≤ 4%
Soluble Phosphate	≤ 100 mg/kg
Total Phosphate	≤ 5%
Reactive SiO_2	≥ 25%

Table 2: The country of origin and transportation distances for the materials included in the study

Symbol	Material	Scope	Origin	Sea Freight (tkm)
OPC	Ordinary Portland Cement	Production	UK	-
LFA	Local fly ash	Production	UK	-
RFA	Recovered fly ash	Dry-processing	UK	-
IFA/C	Imported fly ash from China	Production, Transportation	China	9.0
IFA/G	Imported fly ash from Germany	Production, Transportation	Germany	1.4

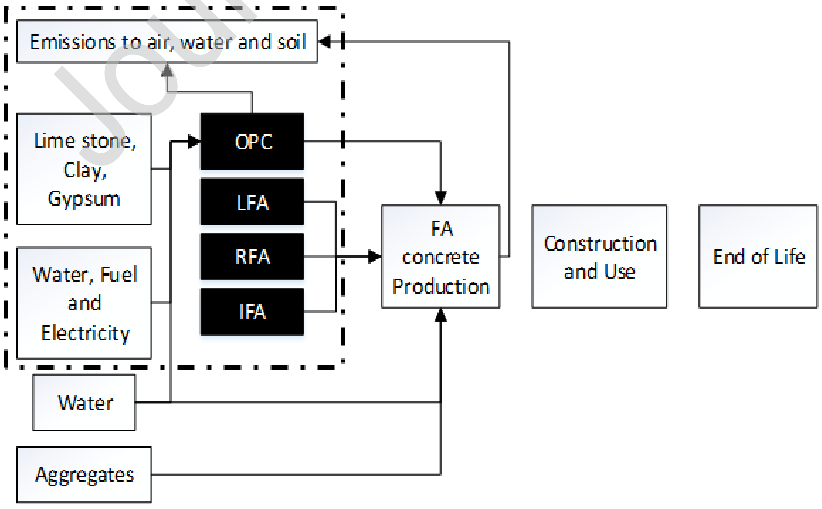

Figure 1: The boundary of the LCA study and OPC production process

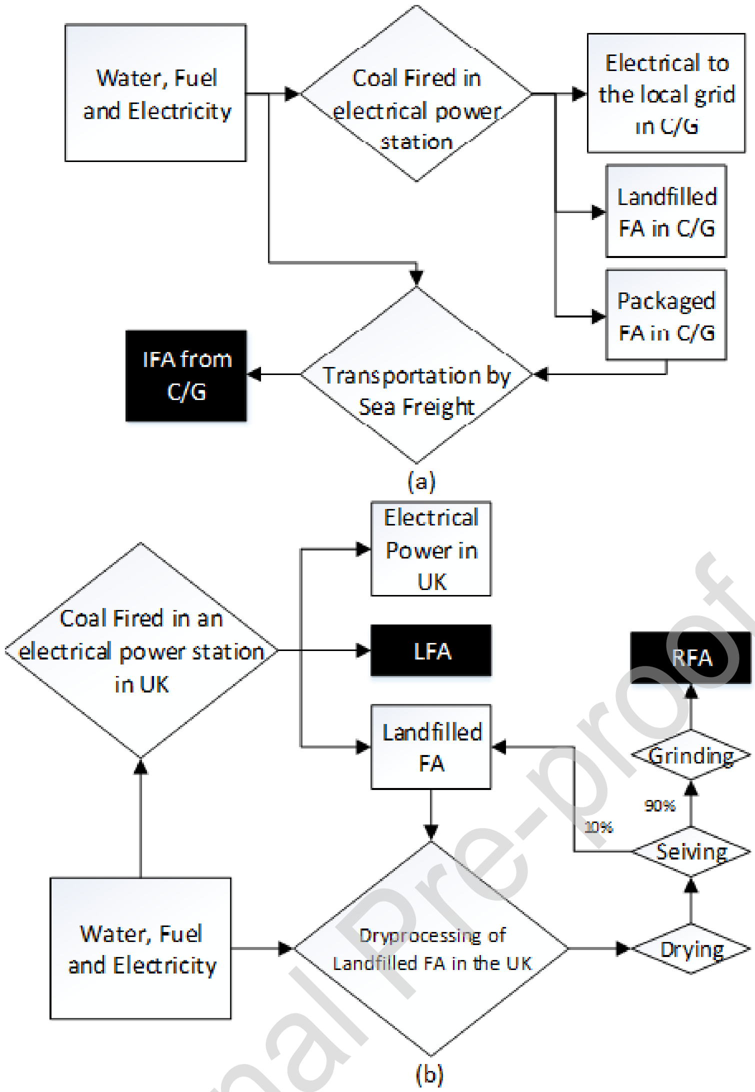

Figure 2: The boundary of the production process of (a) IFA, and (b) locally sourced and RFA

2.2 Life Cycle Inventory Analysis

The data necessary for this LCA can be categorized into two groups: the first is related to calculating the energy and emissions related to OPC as well as these related to the IFA including the production process in the country of origin and the transportation to the UK. These were found as a secondary data from the Ecoinvent data base using SimaPro 8. The second group, which include the primary data that calculate the energy required for the Dry-processing recovery of landfilled FA and the calculations necessary for the allocation scenario of FA, were developed using primary data.

In order to calculate the allocation scenario for FA; the difference in prices of FA relative to electricity in both countries were surveyed. In China, the cost of electricity and FA was found to be 0.11 €/kWh (CEIC, 2018) and 10 €/tonne (Alibaba, 2019; Wang et al., 2016) respectively, while the electricity price in Germany was 0.29 €/kWh (Statista, 2018). Due to the absence of any commercially available data around the price of FA in Germany, it was assumed to be the same as that in the UK, which is 50 €/tonne (Alberici et al., 2017). Assuming both countries use the same coal combustion techniques, 2689 kWh of electricity and 80 kg of FA can be produced from burning one tonne of coal (Seto et al., 2017). Hence according to Equation 1 (Chen et al., 2010), the economic allocation for the IFA from China and Germany is calculated to be 0.25% and 0.50%, respectively. Using the same assumption for the LFA, since the price of the electricity in the UK was found to be 0.16 €/kWh (UKPower, 2019), the economic allocation percentage was calculated to be 0.11%. The mass allocation was calculated as 9.3% using Equation 2 according to Seto et al. (2017). A summary of the allocation percentages for all alternatives could be found in Table 3. It should be noted that the three economic allocation percentages are fairly lower than the ones in the literature (4% in Seto et al., 2017 and 1% in Chen et al., 2010). This could be attributed to discrepancies in the primary data used. Regarding the RFA, it being already landfilled waste, no original burden is allocated to it.

$$\text{Economic Allocation} = \frac{(€.\,\mathrm{m})_{\text{by}-\text{product}}}{(€.\,\mathrm{m})_{\text{main product}} + (€.\,\mathrm{m})_{\text{by}-\text{product}}} \tag{1}$$

$$\text{Mass Allocation} = \frac{(\mathrm{m})_{\text{by}-\text{product}}}{(\mathrm{m})_{\text{main product}} + (\mathrm{m})_{\text{by}-\text{product}}} \tag{2}$$

Table 3: A summary of the allocation scenarios for all materials included in the study

Symbol	Local Electricity Price (€/kWh)	Local FA Price (€/tonne)	FA generated/ Coal (Kg/t)	Electricity Generated/ Coal (kWh/t)	Mass Allocation (%)	Economic Allocation (%)
OPC	No Allocation					
RFA	No Allocation					
LFA	0.16	50	80	2689	9.3	0.11
IFA/C	0.11	50	80	2689	9.3	0.25
IFA/G	0.29	10	80	2689	9.3	0.50

2.3 Life Cycle Impact assessment

In this study, two indicators were chosen, the GWP in a 100 years time (GWP 100) calculated using a Mid-point indicator by the Centre of Environmental Studies at Leiden University (CML 2000), and the single score of Eco-indicator 99 (EI-99) which is an End-point indicator. The alternatives for importing FA were modelled using SimaPro 8, then compared to locally sourced FA and OPC while accounting for the allocation scenario. After that the impact of the RFA using Dry-processing was calculated and compared to the rest. Finally, before judging on the best alternative, a sensitivity analysis was performed to measure the impact of changing critical parameters such as transportation distances and allocation percentages.

3. Calculations and discussions

3.1 The impact of the imported fly ash

3.1.1 Using mass allocation scenario

As shown in Figure 3, allocating 9.3% of the original process would mean that IFA products and even locally FA products have a higher environmental impact than OPC. Judging by the EI-99 single point indicator, IFA from Germany, IFA from China and LFA are around 4, 16 and 7 times higher than OPC, respectively. The GWP indicator does not change the ranking, but decreases the relative scores to be 4, 6, 4 and 1 for IFA from Germany, IFA from China, LCA and OPC, respectively.

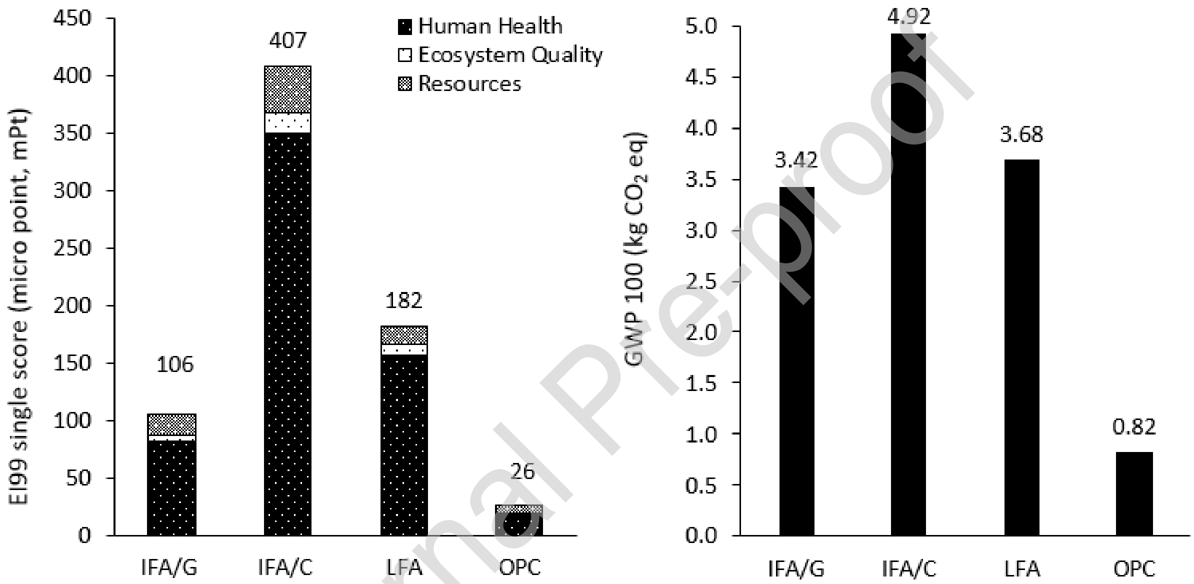

Figure 3: The impact of importing FA using EI-99 (L) and GWP (R) indicators with mass allocation

3.1.2 Using economic allocation scenario

On the other hand, using the economic allocation scenario, the impact assessment results change significantly. Since the environmental burden from the original process is a much less than the mass allocation scenario, all binders seem to have a lower environmental impact than OPC, which is the starting point for considering them as an OPC replacement. However, results differ depending on the indicator used. As shown in Figure 4, the relative scores for the GWP100 of IFA from Germany, IFA from China, LFA are 30%, 88% and 5% compared to OPC, respectively. When using the EI-99 single indicator, the rankings have changed. IFA from China has a higher impact with a relative score of 3.24 compared to OPC, but LFA and IFA from Germany remained less, scoring 8% and 52% respectively compared to OPC.

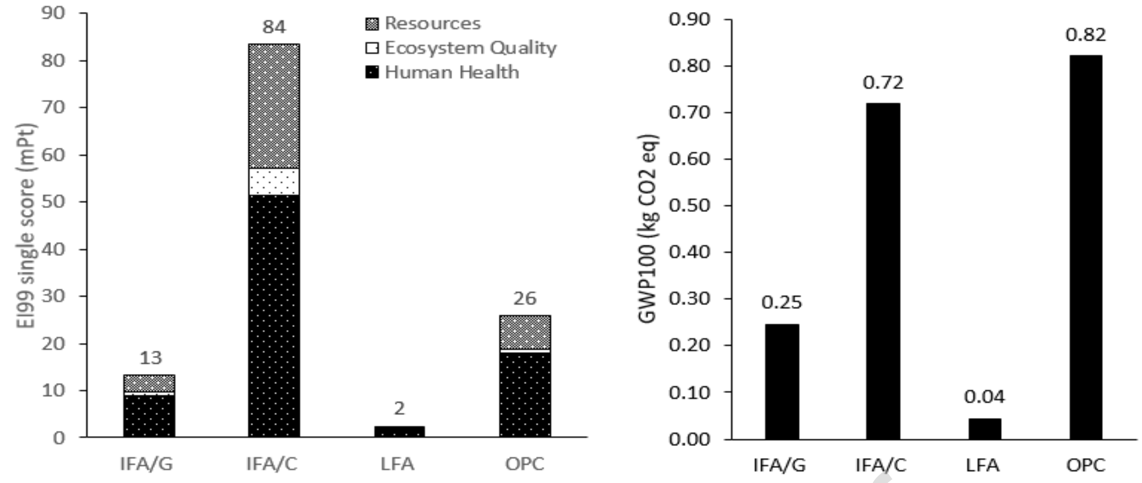

Figure 4: The impact of importing FA using the EI-99 (L) and GWP (R) indicators with economic allocation

The presented results show that the alternative of importing FA from Germany appears to have less environmental impact than that from China. Based on the Mass allocation scenario, IFA/G has 4 and 1.5 times less the relative score of the IFA/C using GWP and EI-99 indicators respectively. The economic allocation scenario model shows that IFA/G has 7 and 3 times less the relative score of the IFA/C using GWP and EI-99 indicators respectively. However, it is noticeable that IFA/C has a differentially higher EI-99 than the rest of the alternatives, which is why the ranking of the alternatives change in Figure 4. This could be contributed to the following factors:

i. The approach followed in this study to simulate the process of producing FA uses the energy mix available in the Ecoinvent database for each of the countries of origin. This was also done by Gursel et al. (2014) when comparing between different sources of cement for a project in Singapore. As shown in Figure 5, the impact of producing electricity (and FA as a by-product) in China is almost three times higher than the same generation process in Germany.

ii. This justifies the increase in the EI-99 indicator of IFA/C than the rest of the indicators. However, the same differential impact is not evident when comparing between the alternatives using GWP, which caused change in the rankings in Figure 4. The reason behind this is that as seen in Figure 5, the largest contributor to the EI-99 score of the electricity generation process in China, which is later on allocated to IFA/C, is 'Human Health'. Human Health, as an End-Point indicator, is calculated based on the following Mid-Point indicator: Ozone Layer Depletion, Human Toxicity, Ionizing Radiation, Photochemical Oxidation and Respiratory Effects (Menoufi, 2011). On the other hand, GWP is a different Mid-Point indicator, which is calculated mainly by adding carbon dioxide, nitrogen dioxide and methane emissions (Menoufi, 2011).

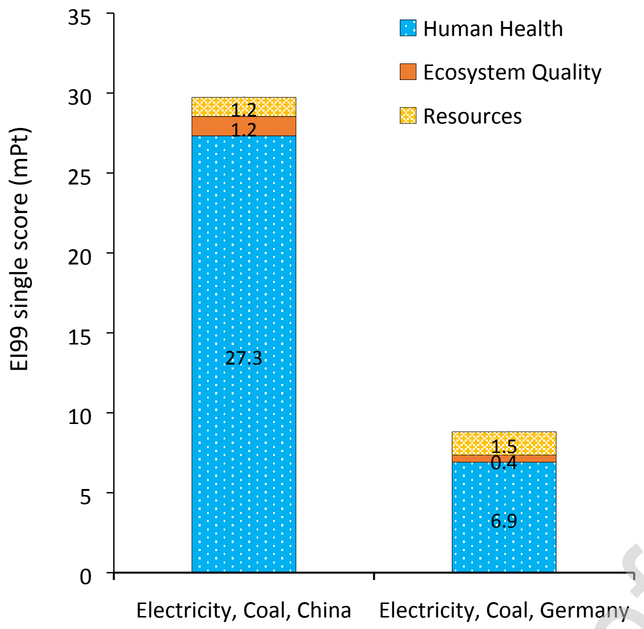

Figure 5: Comparison of the Ecoinvent score for the original production process of FA between Germany and China

3.2 The impact of the recovered fly ash

For the RFA impact assessment, the chosen method was the Dry-processing proposed by McCarthy et al. (2018), which entails that 90% of the FA landfilled are recyclable to conform to BS EN 450-1 through a process of drying, sieving then mechanical grinding. According to Baker et al. (2015), the landfilled FA has an average water content of 15-20% and the energy required to remove it by oven drying at 105°C is around 200 kWh/tonne. McCarthy et al. (2018) states that the mechanical grinding is carried out using a "Fritsch Pulverisette" machine in 500 g batches with 20 minutes of operation each. The machine operates at 110V and 0.5A as per its technical catalogue so the energy demand for the grinding process is estimated at around 300 kWh/tonne. Using these energy inputs for the recovery process, the environmental impact for the RFA was modelled using SimaPro 8 using GWP and EI-99 as indicators. The results of the impact assessment per 1.11 kg of mass of RFA was only compared to 1 kg of OPC, LFA, IFA/C and IFA/G. An economic allocation scenario similar to that in the previous model was selected for LFA, IFA/C and IFA/G, since it was established by the literature as the most realistic scenario to compare to (Chen et al.. 2010; Habert et al., 2011; Seto et al., 2017).

As shown in Figure 6, recovering of FA using the "Dry-processing" method yield a binder that has 50% and 75% less environmental impact compared to OPC when using EI-99's End-point and GWP as indicators, respectively. Nevertheless, RFA has 7 and 6 times less impact that IFA/C using EI-99's single indicator and GWP respectively. Compared to IFA from Germany, RFA only has 10-15% reduction. Finally, the impact of RFA was found to be higher than that of LFA which is believed to seize to be available beyond 2021, which still makes RFA the best alternative considered in this study. The fact that the locally available and imported FA alternatives were allocated only minimal percentages as per the economic allocation scenario means that RFA would have even yielded higher environmental gains had the other FA alternatives been allocated higher percentages as established in 4.1. This could be contributed to the fact that RFA is not allocated any burden from its original production process since it is considered as a waste. Also, the "Dry-processing" method is, as explained by McCarthy et al. (2018), very basic and energy efficient. In addition, the fact that it is already landfilled means that recycling FA has a positive environmental impact, especially for the *Carcinogens, Ecotoxicity* and of course *Land use*.

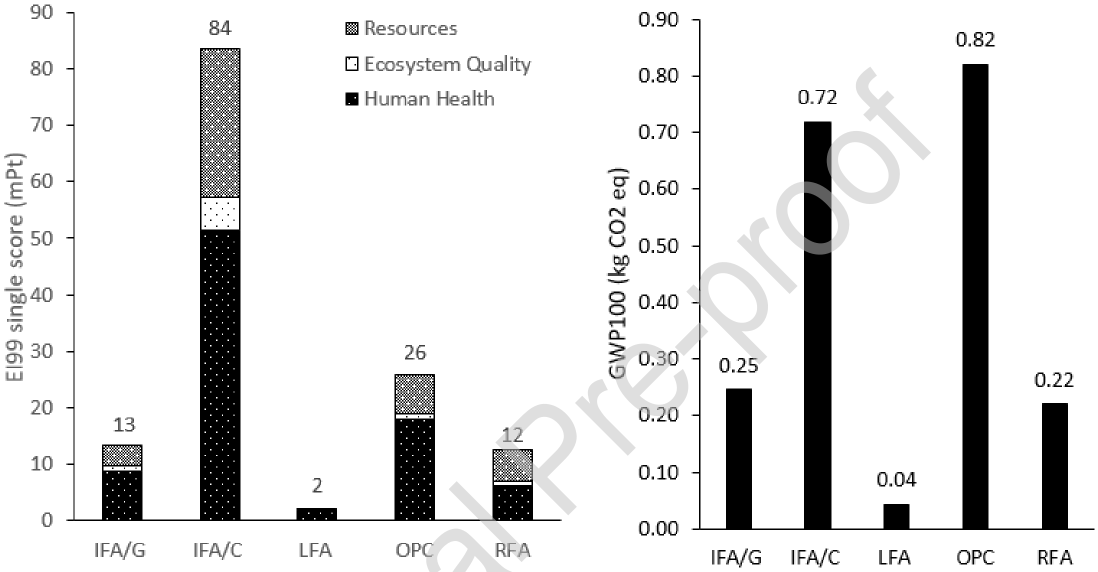

Figure 6: EI-99 Single score indicator (L) and GWP (R) of RFA vs OPC

3.3 Sensitivity Analysis

Before generalizing the judgment on the preferred alternatives to LFA from the 3 proposed ones, the sensitivity of the calculated impact to allocation scenarios, transportation distances, and recovery processes was studied.

3.3.1 Sensitivity to Allocation Scenario

In order to assess the sensitivity of the calculated environmental impact of the two proposed importing alternatives to locally available FA and OPC, the graph in Figure 7 was plotted between the GWP100 indicator used and difference allocation percentages (0-15%) of all three alternatives. Generally, the results in Figure 7 show that the environmental impact of IFA is very sensitive to the selected allocation scenario with a common slope of almost 0.4 kg CO_2 eq per 1% change in allocation. Had the scope of this study included FA as a part of a concrete product, which means reducing its contribution to the FA content in concrete (around 10%), the results would have been less sensitive to change. The same conclusion was found in the literature (Gursel et al., 2014; Seto et al., 2017). As shown in the results, the calculated environmental burden of FA was a 6 to 8 times less when an economic allocation scenario was chosen compared to mass allocation. The critical allocation scenario for the IFA to have less GWP100 than OPC was calculated to be 2.5%. The graph also shows that the sensitivity of FA to allocation scenarios studies by Chen et al. (2010) is almost identical to the one calculated for the FA imported from Germany in this study. Accordingly, researchers tend to rely more on economic allocation, although dependant on electricity and FA prices, to encourage the use of supplementary cementitious materials in the construction industry (Marinković et al., 2017). This means that it is up to the user to determine the most indicative allocation scenario regarding the intended purpose until a consensus is reached on the most accurate method for allocation (Mohammadi et al., 2017).

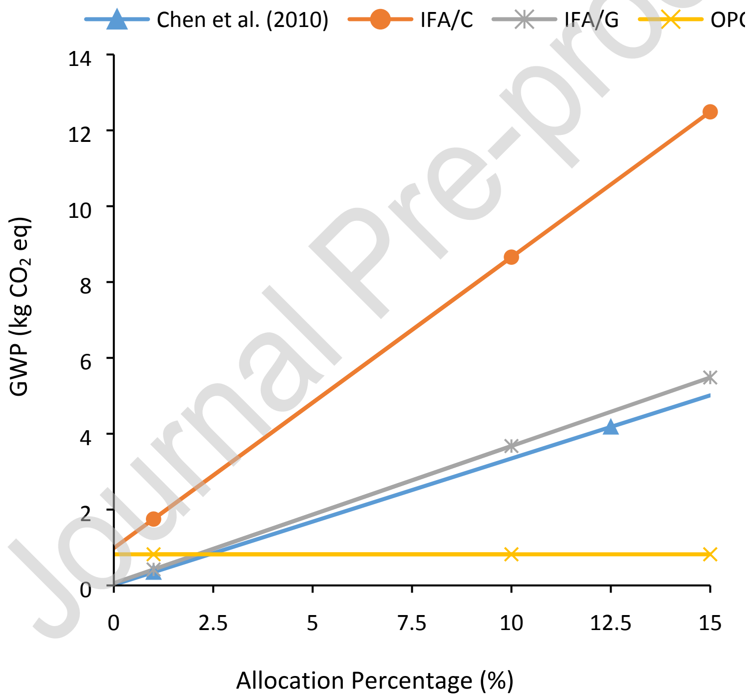

Figure 7: Sensitivity analysis of the allocation of different FA materials compared to OPC

It is also shown that importing FA from China has a higher environmental impact than locally available FA regardless of the allocation scenario. This could be contributed to the large transportation distance between China and the UK (calculated as 9 tkm) compared to that between Germany and the UK (1.4 tkm only). It is also established that the original process of FA generation as a by-product in electricity power plants has a much higher impact in China compared to than in Germany. Given the aforementioned assumptions, importing FA to the UK from anywhere with the same power generation process and the transportation distance as Germany will reduce the environmental impact compared to OPC. The condition is that the allocation scenario selected attributes ≤2.5%.

It is worth noting that environmental impact is not the only parameter to consider when comparing alternatives in the construction industry. It is agreed from the literature that economic feasibility of the solution might have even a bigger weight depending on the stakeholders (Garcia-Segura et al., 2013; Ignacio Navarro et al., 2018; Tucker et al., 2018). The primary data used in this study indicate that the price of FA imported from China (10 €/tonne) is five times less that its selling price in Europe (Alberici et al., 2017; Wang et al., 2016). This means that from the perspective of concrete manufacturers and suppliers it would be more attractive to import FA from China regardless of the negative differential environmental impacts established in this study. It is hereby worthy to recommend that the UK government, which is driven as discussed to cut down the environmental impact from building materials, enforce higher taxation on the FA imported from China or similar countries with the same electricity mix and transportation distance.

3.3.2 Sensitivity to Transportation Distances

As agreed in the literature, transportation processes represent almost 25% of the environmental impact of the IFA products (Lopez Gayyare et al., 2015). Several transportation distances by sea freight were simulated to measure the sensitivity of the different IFA products and the corresponding environmental indicators. An economic allocation scenario was selected for the IFA as it was shown to provide comparable results to OPC. Using the EI-99 single indicator, the threshold of the transportation distance travelled by sea towards which the IFA would still have less environmental impact compared to OPC was found to be around 3.57 tkm (Figure 8). This covers almost the whole of Europe and parts of North Africa as seen in the Google image in Figure 9. This value is significantly lower than the 54 tkm found in the literature (O'Brien et al., 2009) but the difference in primary data used could be the variance source and the fact that the cited study used a no allocation scenario. The underlying assumption remains that the coal combustion process at the country exporting FA has the same environmental burden as that in Germany. An important factor to consider is that the same environmental laws and regulations to be adopted by the UK are expected to happen all over Europe (Vinabules et al.,2017). This means that, several other European countries will be inclined to shift away from generating electricity from coal which again compromises the potential of the availability of FA in these countries.

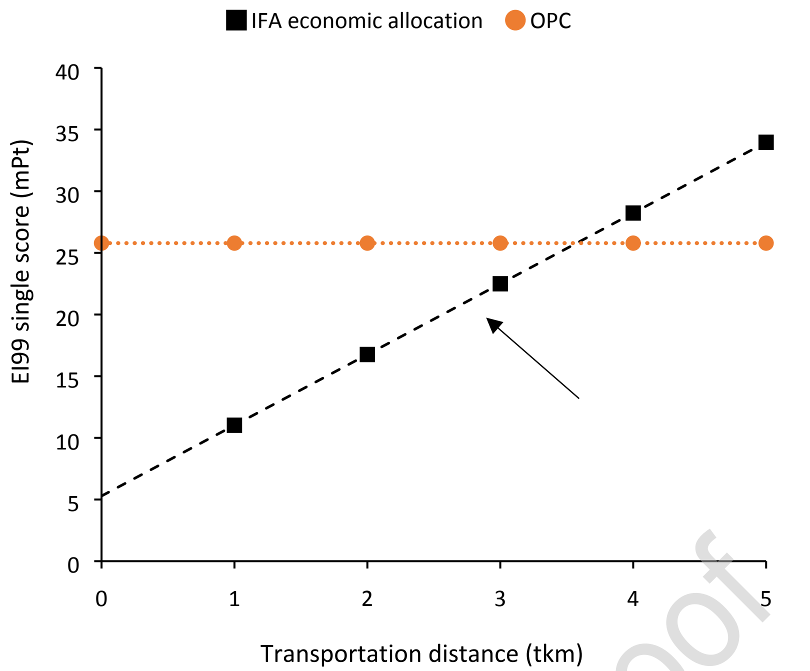

Figure 8: Sensitivity of importing FA to the UK to the transportation distances

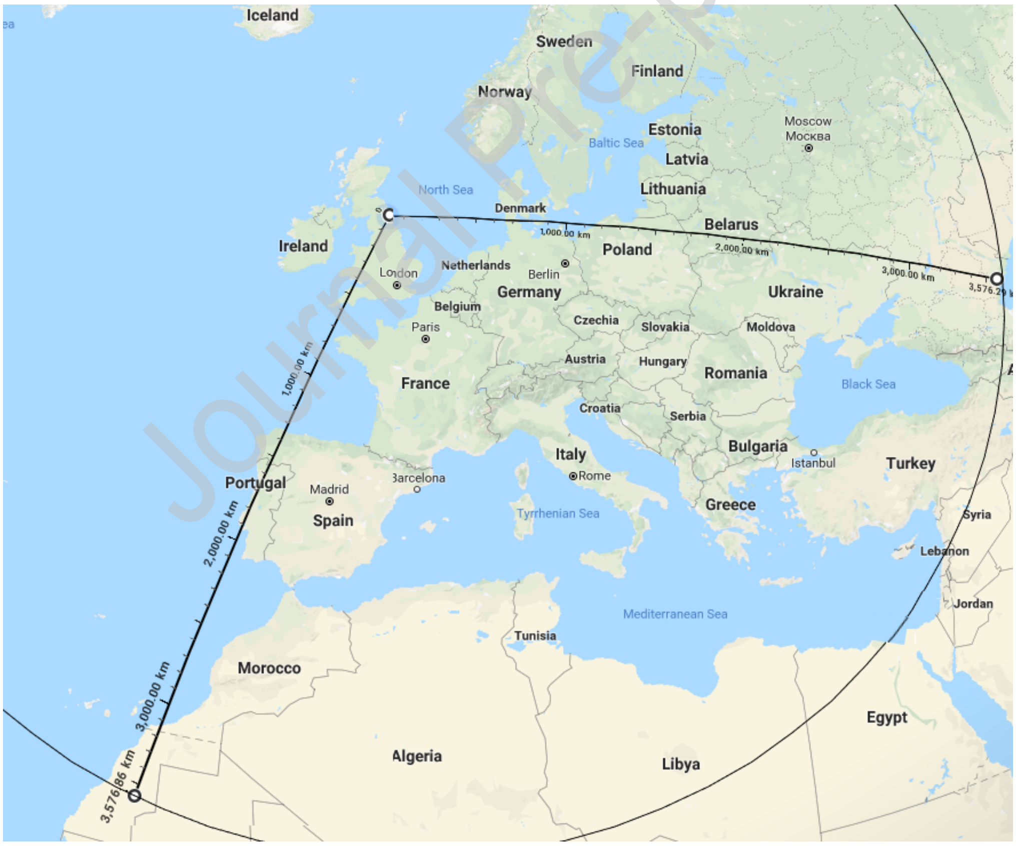

Figure 9: A Google maps image showing the radius of 3.57 tkm that can be covered by IFA to the UK

3.3.3 Sensitivity to Recovery Process

Since recovering landfilled FA was found to be the best alternative in terms of environmental impacts, its sensitivity to the amount of energy and emissions involved in the recover process was investigated. The “Dry-processing” technique of recovery as explained by McCarthy et al. (2018) and modelled in this study consisted of two steps: heating for five hours to get rid of the excess water which was estimated to consume around 200 kWh/tonne and mechanical grinding which was estimated to consume around 300 kWh/tonne. The latter was changed to a range between 400-1200 kWh/tonne to accommodate for more industrial solutions. It shows that increasing it four times and up to 1160 kWh per tonne would still yield an improvement in the impact of RFA compared to OPC as shown in Figure 10. Although the “Dry-processing” recovery process is still only successful at the laboratory scale, it seems that the results are very promising since it carries no allocation scenario due to the fact that it was already scrapped. Nevertheless, minimal environmental impact are expected to be added to RFA due to transportation. According to Carroll (2015), landfilled FA where the recovery plants are to be located are very close geographically to the same locations of coal-fired electrical power plants that are expected to be shut down in the UK after 2020.

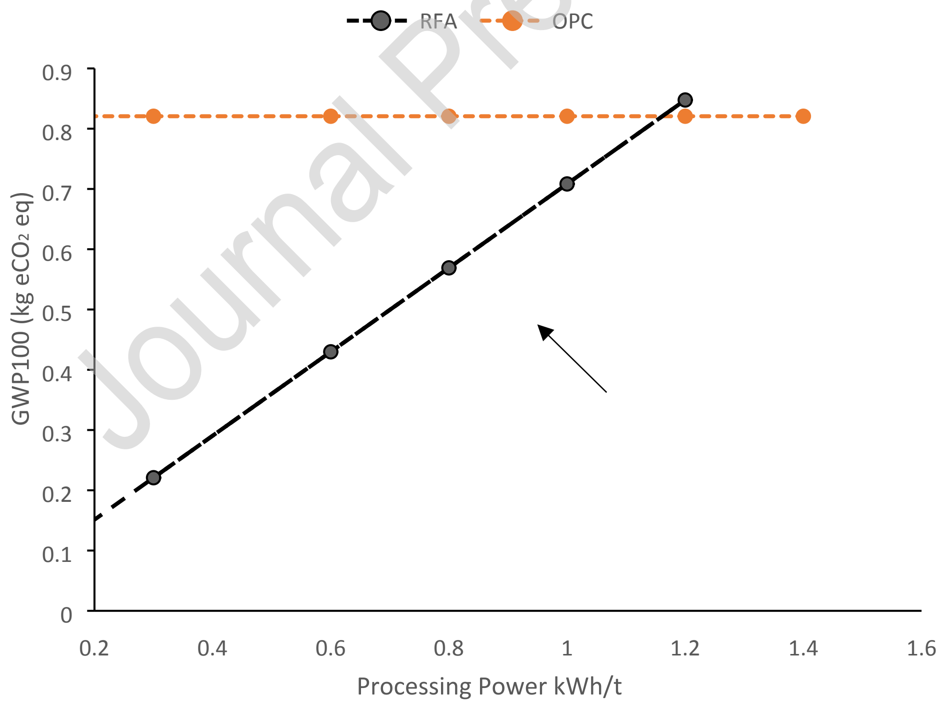

Figure 10: Sensitivity of RFA to the different energy demands of processing methods of recovery using GWP 100

4. Conclusion

The work presented in this paper is to investigate a critical problem facing the concrete industry in the UK to find alternatives to locally sources FA. Generally, the following could be concluded from the paper given the aforementioned scope and limitations:

- Imported FA from Germany has less environmental impact than that from China. The latter appeared to have around 4 and 1.5 times the relative score of the using GWP100 (Mid-point) and EI-99 (End-point) indicators, respectively.
- It is worth noting that given the Chinese electricity power generation process from Ecoinvent, imported FA from China will have higher environmental impact than OPC regardless of the allocation scenario. This is worth noting since this is the most appealing alternative economically given the surveyed market prices in this study.
- Recovering the 50 million tonnes of landfilled FA using the Dry-processing technique could be the alternative with the least environmental impact compared to importing it. It would also be enough for almost 30 years of FA demand.
- FA products, in general, seem to possess high sensitivity to allocation scenarios. An increase of 1% allocation leads to an increase of the global warming potential within the specified scope up to 0.5 kg CO_2 eq.
- Given the assumptions in this study, importing FA from anywhere with the same power generation process and the same transportation distance as Germany will have a less environmental impact than OPC as long as the allocation scenario attributes less than 15% from the original process to FA.
- The selling price of FA in China is a lot lower than that in Europe. Hence, as long as the negative environmental impacts associated with it as established in this study still prevail, the UK government should increase the taxes to discourage suppliers from importing FA from China.
- Shipping transportation processes could contribute to up to 25% of the FA environmental burden. However, assuming a 0.5% allocation, importing FA from Europe or North Africa could still have less environmental impact than locally sourced OPC given that the main production process and market prices are similar to that in Germany.
- The Dry-processing recovery technique is not very sensitive to the increase in energy demand for the recovery process. The process could even have up to 4 times the assumed energy and still would have less kg CO_2 eq than OPC.

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Declaration of interests

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

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Comparative life cycle assessment between imported and recovered fly ash for blended cement concrete in the UK

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Keywords: Blended cement, supplementary cementitious materials, Life Cycle Assessment, Recovered fly ash, Imported fly ash

Highlights

- **Life Cycle Assessment tool to analyse the environmental impact of importing and recovering fly ash from different countries;**
- **Environmental impact of importing fly ash from Germany and China, and recovering landfilled fly ash in the United Kingdom;**
- **Optimum solution for importing and recovering landfilling fly ash.**