BROWNFIELD REDEVELOPMENT: A DUAL CURRENCY ANALYSIS OF SOIL STABILISATION METHODS

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ABSTRACT

Evidence of climate change, such as rising sea levels and higher average temperatures, has made society become increasingly carbon conscious in recent years. Therefore, carbon estimating is becoming prominent and this research explores methods of quantifying embodied carbon of different soil stabilisation methods. This research aims at evaluating the different methods of soil stabilisation for the remediation of previously developed, brownfield sites, using a dual currency approach of investigating both cost and carbon. Therefore, the effect of using different cementitious binders such as Pulverised Fuel Ash (PFA) and Ground Granulated Blastfurnace Slag (GGBS), in lieu of Ordinary Portland Cement (OPC) was investigated.

Primary data, in the form of Bills of Quantities, was collected from a civil engineering contractor who has extensive experience in the land remediation sector in the UK. This enabled cost and carbon rates to be applied to the work items, to estimate in terms of cost and carbon inputs. This data was analysed using descriptive statistics to investigate if there is a correlation between cost and carbon inputs.

The study revealed that to stabilise soil, soil matrix changes from one binder to another, whereas a higher content of GGBS and PFA to lime in the alternative methods than there is for OPC. In lieu of OPC and PFA, GGBS was identified as the most cost effective and lowest carbon emitting cementitious binder. However, though PFA also signified a carbon saving, PFA was comparatively costly. Further, a perfectly positive correlation lies between the mean elemental unit rates for costs and carbon.

Keywords: *Cementitious Binders; Correlation; Embodied Carbon; Soil Stabilisation.*

1. INTRODUCTION

Due to increasing environmental concerns surrounding the development of greenfield sites, the UK government has stated that at least 60% of new housing developments must be on previously developed 'brownfield' land, much of which contains soil contaminants stemming from their previous uses. Traditionally, the approach was to excavate the contaminated soil and dispose at landfill (The Concrete Centre, 2005). Excavation and disposal to landfill is an important means of managing contaminated land. It can offer a 'complete solution' on the proviso that all contaminants with unacceptable risks are removed from site. However, there are numerous disadvantages, including but not limited to the following; hazards and nuisance related with the transport to landfill, noise, gases and dust arising from the excavation and the rising costs associated with the disposal at landfill (landfill taxes and the likes). There are many contamination and operations related hazards associated with 'dig and dump' with operatives working in close proximity with contaminated materials and where unstable conditions are present (CIRIA, 1995). A combination of these factors drives the search for safer, more sustainable methods of remediation.

Issues arising from the EU Landfill Directive in 1999, namely the prohibition of the co-disposal of inert and hazardous waste and subsequently the reduction of available landfill sites, led to increasing costs associated

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with the preferred "dig and dump" method of remediation. As a result, solidification/stabilisation has become a more cost-effective and sustainable approach to remediating brownfield sites.

After the advent of remediation processes in the 1970's, due to high public demand, energy-intensive engineering technologies were adopted for "quick clean-ups" of contaminated land. More recent evidence of a correlation between energy consumption and climate change has led to society, and therefore remediation professionals, to seek ways of minimizing the reliance on technologies that have a detrimental impact to the environment (Ellis and Hadley, 2009). Traditionally the management of contaminated land has been concerned with mitigating the risk posed to human health and to the environment; however, incorporating the sustainability factor into decision making and project planning is becoming more customary. Within the UK economy, the contaminated land industry is worth in the region of £1 billion so sustainability is an important issue for debate. A sustainable remediation project should aim to achieve a net benefit overall across the three main pillars of sustainability; social, economic and environmental factors. Unfortunately, measuring sustainability proves rather difficult as it is a subjective concept that is not easily quantifiable. There exists a need to compare sustainable remediation technologies and monitor remediation performance as opposed to direct measurement (Bardos, 2014). The 2009 Sustainable Remediation Forum (SURF) White Paper explains that there is a requirement for identifying a "unit of remediation" in order to be able to carry out these site versus site comparisons but at the time of that publication going to press nothing had yet been agreed upon. SURF concurs that resolving the issue of how best to define a unit of remediation would enable the industry to make better decisions regarding sustainability (SURF, 2009).

The works of Victoria et al. (2015) along with Victoria et al. (2016) had carried out an investigation into Embodied Carbon (EC) in commercial office buildings, and the findings have been used to produce a carbon profile. However, there is a dearth of knowledge relating to the earthworks operations carried out on construction projects, in terms of EC. This research seeks to bridge that knowledge gap.

The aim of this research is to evaluate different methods of soil stabilisation for the remediation of previously developed, brownfield sites, using a dual currency approach of investigating both cost and carbon. The research seeks to identify a less carbon intensive, more environmentally friendly method of ground remediation than using cement and lime. In order to achieve the aim, the objectives of the research are as follows:

- To critically appraise different soil stabilisation techniques using different cementitious binders
- To analyse the cost and carbon implications of the various stabilisation procedures
- To establish a carbon profile for the remediation of brownfield sites

2. LITERATURE REVIEW

2.1. SOIL STABILISATION

Soil Stabilisation (SS) also known as soil solidification is a civil engineering technique used to improve the condition of soils, either in the remediation of contaminated land or by improving the load bearing capacity of the soil. This type of ground improvement engineering utilises a reaction between binders in the solidification reagent, such as cement/lime and the contaminants present in the soil to provide stabilisation, reducing the mobility of the pollutants. Stabilisation is attained by adding reagents to contaminated soil, hence producing elements that are more chemically stable. Solidification is the process whereby the addition of these reagents imparts more physically stable properties, containing the contaminants in a solid and providing protecting from the ingress of air, water and other external agents (Environment Agency, 2004).

SS is a versatile technique working well with almost any type of contaminant. Its most effective use is in the treatment of metals but is also adept at treating inorganic and organic contaminants. This particular method of remediation is always designed with the project specific in mind, and varies from project to project. Scientific testing is used to verify the binder to be used and its composition, whereas treatability studies are employed to ascertain if the various needs of each project stakeholder are going to be met. The key stages in the design of a suitable remediation strategy are as follows. Firstly, samples are obtained from site of best and worst case scenarios, the engineering properties and the extent of contamination are then determined. This enables a suitable pre-treatment to be selected (if necessary) and appropriate binders and additives to be chosen. In the laboratory a sample remediation is conducted enabling the mix to be optimised in the most cost effective manner. Finally, field trials are carried out and a suitable remediation design is agreed upon prior to implementation (Angel, 2004).

Depending on various factors such as ground conditions, nature of contaminants, future use of site and access restraints, two SS methods are available; in-situ and ex-situ.

In-situ SS is the process where the contaminated soil is treated as it remains in the ground, in other words, it is not excavated. The specific technique of in-situ SS to be used is reliant upon the depth of ground to be remediated. If the required depth is deemed to be shallow (<0.5m) then the binder is spread across the surface of the area to be treated and mixed into the contaminated soil using a rotavator, it is then compacted and the reaction with the moisture content of the soil takes place. If the depth is intermediate (0.5-5m), then the binder is mixed into the soil using specially adapted plant. Any depth over 5m is classed as 'deep' and the binder is added to the contaminated soil using hollow stem augers, which when they withdraw mix the binder with the soil, the design allows for the augers to overlap ensuring the required coverage is attained.

Ex-situ SS takes place at the contaminated site and is the procedure where the polluted soil is excavated and stored in temporary stockpiles before being treated. There are various types of ex situ treatment. The excavated material can be mixed with the SS binder and laid in layers where it is required, this treated soil mix is then rotovated and compacted before the reaction between the binders and the soil moisture content takes place. Alternatively, the excavated material can be mixed in a drum with the appropriate reagent, where the required chemical reaction occurs, before being laid in layers and compacted. Another option is batch mixing, where the contaminated soil and the reagents are mixed in special purpose plant and left for a pre-determined time period, before the soil is laid and the reaction between the reagents and the soil moisture takes place. Ex-situ SS is particularly suitable for projects where there are buried obstructions or where the remediated soil is usable as engineered fill (The Concrete Centre, 2005).

2.2. CEMENTITIOUS BINDERS

The mixture of additives and elements used in the stabilisation procedure is known as the binder. A binder can either be a single component or a combination of various reagents, or multi-component binder. Each remediation site differs from the next in terms of the type of contaminant to be dealt with, the make-up of the soil and the remedial objectives. As such the binder selection is influenced by scientific tests conducted in laboratories along with previous experience, and is specific to the contaminant being treated (Angel, 2004).

The main binders used in this research are Ordinary Portland Cement (OPC), Pulverised Fuel Ash (PFA) and Ground Granulated Blastfurnace Slag (GGBS).

Ordinary Portland Cement

Due to its use in the manufacturing of concrete, cement is one of the most commonly used building materials worldwide. The benefits of using cement are that it is durable, versatile and provides great economic value. It is readily available and is manufactured using local products, transport related energy and pollution costs are kept to a minimum (Juenger et al., 2011). However, there are many drawbacks to the use of OPC. The cement manufacturing process requires the input of many raw materials. As such, cement plants have traditionally emitted large amounts of solid waste and waste particulates, hence having a detrimental effect on the environment (Sabnis and Carter, 2011). Hammond and Jones (2011) in the Inventory of Carbon and Energy (ICE) have approximated the EC content of Portland cement at 0.93kg/CO_2 per kilogram, signifying that it has an extremely carbon intensive production process. This leads the quest for environmentally friendly alternatives like, as mentioned above, PFA and GGBS.

Pulverised Fuel Ash

Pulverised Fuel Ash, or fly ash, is produced by burning coal in power stations. The molten ash drips to the bottom of the furnace creating 'furnace bottom ash', or when carried via convection with the gas stream, fly ash. This unprocessed material can be used in the production of cement and concrete or further refined by the use of classifiers into a finer ash. As this material is a by-product of coal burning power stations the EC content is lower and is a greener alternative to Ordinary Portland Cement. It has an EC content of 0.008kg/CO_2 (Hammond and Jones, 2011).

Ground Granulated Blastfurnace Slag (GGBS)

Ground granulated blastfurnace slag is the by-product of the steel manufacturing process. In this process, the iron ore is converted into iron and the excess materials float on top of the molten iron as slag. This slag is then subjected to large volumes of water to convert it into coarse granules, which are then ground to produce GGBS. Due to being a by-product created in the manufacture of steel it is considered to be a more environmentally friendly cementitious binder (Concrete Society, 2011). GGBS is listed in the ICE as having an EC content of 0.083kg/CO2 (Hammond and Jones, 2011).

2.3. CARBON ESTIMATING AND PROFILING

Embodied carbon/energy

Embodied energy is defined by Hammond and Jones (2008) as the total primary energy consumed by a building material over its life cycle. 90% of this carbon released is apportioned to 'operational energy' with the remainder labelled embodied energy, or the total energy expended to create the building fabric, from raw materials to disposal (Goggins et al., 2010). This description is emphasised by the Hammond and Jones (2008) which pronounces that embodied energy should include the carbon emitted in the building material manufacturing process, the energy and emissions associated with transporting the goods to site, assembly, refurbishment, replacement and demolition or disposal at the end of the life cycle. As regulations are introduced to reduce the operational carbon emissions in order to achieve the 2050 targets, the spotlight will fall more on the embodied energy of a building (WRAP, 2011). This is also brought to light in the Low Carbon Construction Final Report (Morell, 2010).

Embodied Carbon (EC) estimating

The embodied impact of a building material on the environment is measured as EC, in main due to the increasing awareness of the correlation between energy emissions and climate change. The total EC of a product can then be calculated by assessing the energy expended in the production of the material and adding in the CO_2 emissions from that process (Hammond and Jones, 2008). EC measurement is a branch of a process called Life Cycle Assessment, which is used by construction material manufacturers for the production of robust environmental data about their products, primarily concerning emissions (Anon, 2016). Dixit et al. (2010) observed that there are three boundaries to which embodied energy can be attributed: cradle to gate, cradle to site and cradle to grave. Although the Institution of Civil Engineers definition above points towards a cradle to grave analysis for EC, the Inventory of Carbon and Energy suggests that this should be subdivided into sections, as transport "from gate to site" accounts for less than 7% of the cradle to site EC (Hammond and Jones, 2011). More recent research conducted by Victoria et al. (2016) identified further system boundaries in the form of cradle to end of construction and cradle to cradle (which accounts for recycling of materials at the end of their life cycle).

As of yet, there are no published regulations for the assessment of EC, making the implementation of carbon reduction policies somewhat difficult. Recommendation 2.1 of the Low Carbon Construction Final Report states that as soon as a robust system of carbon assessment is available then the requirement to conduct a Whole Life carbon appraisal should be implemented into the Green Book (Morell, 2010). As there is an absence of an industry standard for accurately measuring Embodied CO2 there are many different models in existence. The Building Research Establishment has established "envest2", a software tool that predicts the environmental impact of a project (Envest, 2016); The RICS has published "Redefining Zero" which estimates the EC at each stage of the RIBA Plan of Work, from cradle to grave (Sturgis and Roberts, 2010) and there also exist carbon calculators from the Carbon Trust and Cap2 IT.

Geoffrey Hammond and Craig Jones of Bath University's Sustainable Energy Research Team have produced a database of embodied energy and carbon of construction materials; this is published by BSRIA, a construction research body. This database is the Inventory of Carbon and Energy (ICE) and according to al Philip Lee of the Select Committee for Climate Change, highlights the difficulties encountered in assessing carbon. Hammond and Jones (2011) state that although there is in existence, a number of similar inventories available, the ICE is well established and recognised industry wide. Other reputable methods of measuring EC include the Civil Engineering Standard Method of Measurement 4 (CESMM4), the RICS' New Rules of Measurement 3 (NRM3) and the UK Building Blackbook. The Institution of Structural Engineers is also publishing an EC guide for its members (Hammond and Jones, 2011).

Carbon profiling

In the United Kingdom, construction legislation traditionally concentrated on the operational carbon emissions from a building when the whole life cycle carbon emissions were being quantified. The industry was all too keen to disregard or ignore the relationship between operational and embodied carbon. In the RICS research paper "Redefining Zero", Sturgis and Roberts (2010) state that the quantity of carbon used to create and maintain a building is significant, and by simply disregarding its importance, environmental and financial resources have been misallocated. In order for the UK to fulfil its commitments to the Kyoto Protocol of reducing greenhouse gases by 80% by 2050 (HM Government, 2008), the UK implemented various legislations and regulations in order to reduce the operation carbon emissions of buildings. The problem being the lack of legislation governing EC in projects, which can reach levels as high as 62% of a buildings whole life carbon emissions. The main problem identified by Sturgis and Roberts was that there was no identifiable standard method for measuring whole life carbon in buildings. Their proposal was a simple carbon metric known as Carbon Profiling be used to quantify all carbon emissions. This method considers the operational and embodied carbon of a project together, enabling a better allocation of the aforementioned resources (Sturgis and Roberts, 2010).

Under their proposed new metric of Carbon Profiling, work items are grouped into elements in order to analyse the EC content for each section of the works. The fundamental objective of this metric is to analyse both operational and embodied carbon over the same time and crucially, in the same units of measurement (Sturgis and Roberts, 2010). Part L of the Building regulations requires that a Building Emission Rate (BER) is calculated, this is the operational carbon cost of the construction project, in other words the carbon emissions associated with the building in operation. Using the same unit of measurement (kg/CO_2) carbon profiling estimates the EC efficiency of a building, by analysing each component in turn (Hartmann, 2009).

In this research the carbon profile will be compiled as follows; site clearance, excavation, disposal, breaking out obstructions, filling (including stabilisation with different cementitious binders) and compaction and surface finishes. A calculation will be carried out to find the elemental total cost and elemental carbon score for each. Once these totals are known, they will be divided by the site area in order to produce an Elemental Unit Rate (EUR) for both cost and carbon, measured in pounds (£) and kg/CO_2 per m^2. This enables to identify the more cost and carbon intensive elements present in the study.

3. METHODOLOGY

3.1. UNITS OF DATA MEASURE

The research considers a single case study by selecting a civil engineering contractor and within the case study, approximately thirty sites in which SS techniques have been employed, were selected as the principal data set for the research. Hence, the results are subjective to the single case study. A cradle to end of construction system boundary was implemented in the data collection. The raw data were developed with the application of cost and carbon rates to each item of work in order to estimate a project total in pounds and also a carbon score (kg/CO_2) for each. Secondary data in the form of the UK Building Blackbook (2011), CESMM4 Carbon and Price book and the Inventory of Carbon and Energy, were used for the dual currency rates. The Inventory of Carbon and Energy was used to provide carbon rates for soil stabilised with OPC, PFA and GGBS.

Unpublished Rates

The UK Building Blackbook (2011) does not contain all the information required to complete the study to a satisfactory level. For the contractor's stabilisation techniques employed throughout the study, the financial rates were obtained from the Civil Engineering contractor directly. The ICE publishes the EC content of stabilised soils in kilograms only. For the purposes of this research it is required that the rates be converted into m^3. This was done by taking the published rate in kilograms, converting into tonnes by multiplying by 1000 and then converting from tonnes into cubic metres (Hammond and Jones, 2011). This last step of the conversion is done by dividing the tonnage by a bulking factor of 2.1 tonnes/m^3. This is a figure widely used in the earthworks industry as a bulking factor for soil and Arup who have used a figure of 2.09 tonnes/m^3 on some of their sites (Arup, 2015) corroborates this. The tabulated results for carbon rates to be used in the data collection can be seen in Table 1.

Table 1: Conversion from kg to m³ for Stabilised Soils

Material	$kgCO_2/kg$	$kgCO_2/tonne$	$kgCO_2/m^3$	Comments
Portland Cement (100%)	0.93	930	442.86	
General soil (rammed)	0.023	23	10.95	
5% cement stabilised soil	0.06	60	**28.57**	
GGBS stabilised soil	0.045	45	**21.43**	8% GGBS / 2% lime
PFA stabilised soil	0.039	39	**18.57**	8% PFA / 2% lime

In order to work out rates for soil stabilised with PFA and GGBS a simple calculation is required. The material specification for cement and lime is 3.5% cement and 1.5% lime, with the percentages in relation to the quantity of soil stabilised. It is assumed that a tonne of stabilised material would contain 35kg of cement; this is divided by the bulking factor (2.1tonnes/m³) to specify a cement content of 16.67kg in every m³ of stabilised soil. From the tonne rate for cement taken from CESMM4 Carbon and Price book (2013) a rate per kilogram of cement has been calculated. When this is applied to the quantity of cement above and the total subtracted from the cement and lime rate the ‘base rate’ for labour, plant and lime can be obtained. This same process will then be used to calculate the cost of substituting cement for the alternative binders, PFA and GGBS. These calculations are tabulated in Tables 2 and 3.

Table 2: Calculation of Stabilisation 'Base Rate'

Soil stabilisation material	Rate (£/m³)	Binder	kg/t	kg/m³	Rate per kg	Base rate less 3.5% cement
Cement/lime	£18.00	3.5% cement	35	16.67	£0.16	£15.33

Table 3: Calculation of binder rates

Soil stabilisation material	Binder	kg/t	kg/m³	Rate per kg	Rate (£/m³)	Base Rate
PFA stabilised soil	8% PFA	80	38.10	£0.22	£23.58	*£216.63/t
GGBS stabilised soil	8% GGBS	80	38.10	£0.06	£17.77	*£64/t

Correlation Co-efficient

The researcher will attempt to prove the existence of a correlation between cost per m² and carbon score per m². In order to carry out this investigation a correlation coefficient will be calculated. This co-efficient takes the form of a number between -1 and +1, with +1 being a perfectly positive relationship and -1 being perfectly negative (Witte and Witte, 2010).

4. APPLICATION OF PRIMARY DATA

To enable the researcher to meet the aim and objectives of this study, primary and secondary data was collected and processed to produce results. The collected data relates to cost in pounds and carbon measured in kg/CO_2. The purpose of this section is to analyse the collected data by utilising descriptive statistics and statistical testing, as outlined in Section 3.

4.1. CARBON PROFILING

The primary data was collected by the application of cost and carbon rates to items of work in each Bill of Quantities. This enabled the researcher to calculate totals for each project in relation to cost (£) and carbon score (kg/CO_2) for each soil stabilisation technique.

Filling with Cement/Lime

The unadjusted mean elemental unit cost is £15.72/m² with a standard deviation of £11.82. The process of statistically analysing each element identified extreme values which were disregarded before the calculation of descriptive statistics took place. Hence, the adjusted mean EUR was calculated to be £12.94 with a standard deviation of £4.99. This informs the researcher that the data points lie close to the mean and could be accepted as being representative of the whole population.

The unadjusted mean elemental carbon rate is 17.128 kg/CO_2 and the standard deviation is 14.326 kg/CO_2. The adjusted mean value EUR is shown to be 13.754 kg/CO_2 with a standard deviation of 7.063 kg/CO_2. The rather large deviation from the mean suggests that this mean EUR for carbon is representative of the sample only.

Pulverised Fuel Ash Filling

The unadjusted mean elemental unit cost is £15.84/m^2 with a standard deviation of £11.89. Removing anomalies in the dataset adjusts the mean value to £13.05 with a standard deviation of £5.03. As the data points lie close to the mean, this rate can be deemed to representative of the population.

The unadjusted mean elemental unit carbon rate is shown as 14.550 kg/CO_2 with a standard deviation of 12.697 kg/CO_2. The adjusted mean value is 11.558 kg/CO_2 with a standard deviation of 5.968 kg/CO_2. This dispersion away from the mean proposes that these figures are only representative of the sample projects.

Ground Granulated Blastfurnace Slag Filling

The unadjusted mean value elemental unit rate is £15.02/m^2 and the standard deviation was shown to be £11.99. These figures are adjusted to £12.24 and £5.33 respectively. This signifies that as the data lies close to the mean value then it can be accepted as representative of the population.

The unadjusted mean elemental unit rate for carbon was calculated as 14.706 kg/CO_2 and the standard deviation shown to be 13.450 kg/CO_2. The adjusted mean EUR for carbon is 11.560 kg/CO_2 with a standard deviation of 6.615 kg/CO_2. These figures will be deemed representative of the sample only due to large dispersion from the mean average.

The large standard deviations in this filling element can be attributed mainly to the range of quantities of filling across the sites used in the sample. The unit carbon rates for some of the sub elements are quite high meaning that whenever these activities take place in large quantities on some sites the elemental carbon score is affected, hence affecting the mean and standard deviation of the data.

4.2. *COMPARISON OF ALTERNATIVE BINDERS*

In order to achieve the aim of the research a comparison must be investigated between the 'original' soil stabilisation method of cement and lime and the alternative binders proposed by the researcher. The information for comparison is included in Table 4.

Table 4: Comparison of Different Cementitious Binders

Element	Binder	EUR (£)		EUR Carbon (kg/CO_2)	
		Mean	Standard Deviation	Mean	Standard Deviation
Filling	Cement/lime	£12.94	£4.99	13.754	7.063
	PFA	£13.05	£5.03	11.558	5.968
	GGBS	£12.24	£5.33	11.560	6.615

Replacing Cement with Pulverised Fuel Ash (PFA)

When substituting cement for PFA in the soil stabilisation method, as can be seen in table 3, the mean average EUR cost increases from £12.94 to £13.05. However, this change in cementitious binder brings forth a reduction in embodied carbon of 2.196 kg/CO_2 per square metre of treated land.

These results seem to suggest that the use of PFA as an alternative binder would result in a slight increase in project costs but would offer a significant carbon reduction, so would be a worthwhile consideration for the decision makers.

Replacing Cement with GGBS

The mean average elemental unit rate for the GGBS method is £12.24/m^2, a decrease in cost from the original rate of £12.94. The difference in mean elemental unit rate due to this binder replacement is therefore £0.70/m^2. The mean elemental unit rate reduces by 2.194 kg/CO_2. These figures demonstrate that replacing cement with

GGBS in the stabilisation technique offers significant reductions in terms of both cost and carbon. It would therefore be beneficial for the prudent contractor to consider this material substitution.

4.3. CORRELATION

By analysing all of the above cost and carbon rates, it appears that the expensive work elements are also the most carbon intensive. It could be proposed that there is a correlation between cost and carbon, more specifically it could be deduced that as cost increases so does carbon, indicating a positive correlation between the two variables. This can be seen in the following cluster chart (see Figure 1).

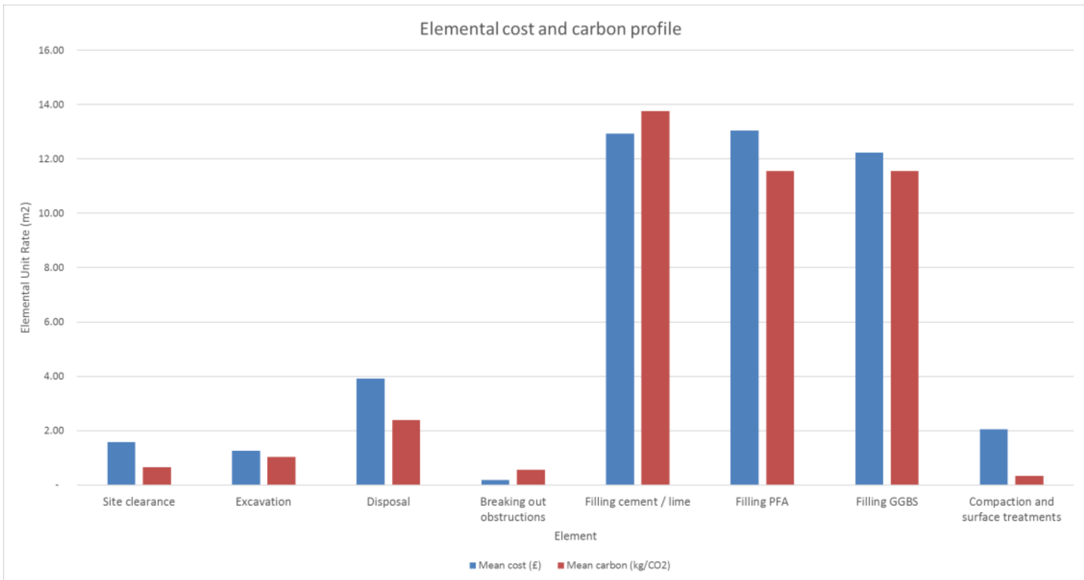

Figure 1: Elemental Comparison of Cost and Carbon

This hypothesis was tested using the correlation function on Microsoft Excel to compare the mean elemental unit rates of cost and carbon and calculate the correlation co-efficient, as outlined in Chapter 3. The results are as given in Table 5.

Table 5: Correlation between Cost and Carbon

Element	Binder	EUR (£) Mean	EUR Carbon (kg/CO_2) Mean
Site clearance		£1.58	0.654
Excavation		£1.25	1.032
Disposal		£3.92	2.388
Breaking out obstructions		£0.18	0.553
Filling	Cement/lime	£12.94	13.754
	PFA	£13.05	11.558
	GGBS	£12.24	11.560
Compaction and surface treatments		£2.05	0.328
Correlation co-efficient		**0.99**	

It can clearly be seen that, by comparing the elemental unit rates for costs with those for carbon, as the mean cost increases from element to element, so does the mean rate for carbon.

The correlation co-efficient was calculated as 0.99. A perfectly positive correlation between two sets of variables has a coefficient of +1. This leads the researcher to infer that there is a strong positive correlation between the mean elemental unit rates for cost and carbon. Element cost increases as the quantity of work in that element increases. On civil engineering sites this translates as more excavation work, more filling, more plant movements and in general more carbon intensive activities taking place. This correlation is better described in the illustration overleaf.

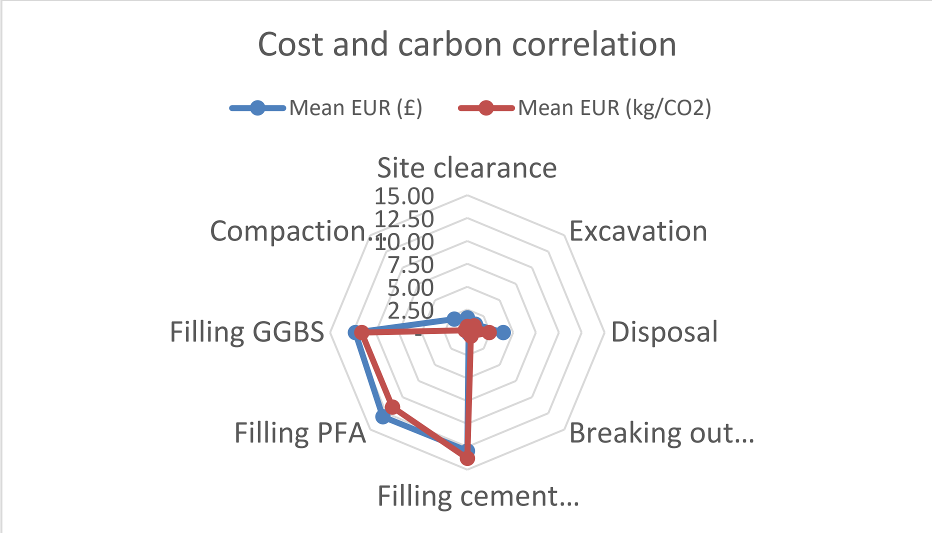

Figure 2: Elemental Correlation between Cost and Carbon

5. Conclusions

The principal aim of this research was to evaluate different methods of soil stabilisation for the remediation of previously developed, brownfield sites, using a dual currency approach of investigating both cost and carbon. In order to achieve the first objective; to critically appraise different soil stabilisation techniques using different cementitious binders, initially, in the data collection, the researcher gained knowledge on the chemical composition of the various binders and soil stabilisation mixes to be employed in the study. From analysing the secondary data, namely the ICE, it was evident that in order to stabilise soil, the soil matrix changes from one binder to another. There is for example, a higher content of GGBS and PFA to lime in the alternative methods than there is for OPC.

Subsequently, the second objective was to analyse the cost and carbon implications of the various stabilisation procedures was achieved. The published data highlighted that there were different EC values for the various cementitious binders. The expectation before conducting the study was that removing the more carbon intensive Portland Cement and replacing with more environmentally sustainable options would mean the contractor would incur an increase in material costs but would benefit from the carbon savings. The data analysis produced different results. It was discovered through the detailed analysis of results in relation to the elemental data that in replacing cement with PFA the costs did, as expected increased, albeit slightly, and the expectations in regard to carbon savings were realised. However, it was found that when GGBS was the alternative binder used in stabilisation costs actually dropped and the carbon reduction was even greater than with PFA.

The Hutchins UK Building Black Book (2010) provided costs and carbon rates for work items included in the primary data. These rates were applied to the work items and elemental totals for each project were obtained. The process of statistically analysing each element, as discussed in section 4, identified extreme values which were disregarded before the calculation of descriptive statistics took place. The mean averages and standard deviations were calculated and the carbon profile depicting cost and carbon rates on an elemental basis was produced to represent the sites in the case study. A perfectly positive correlation lies between the mean elemental unit rates for costs and carbon.

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