Reducing the environmental impact of construction through use of geosynthetics

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Metadata Record: [https://dspace.lboro.ac.uk/2134/21327](https://dspace.lboro.ac.uk/2134/21327)

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Reducing the Environmental Impact of Construction Through Use of Geosynthetics

Jamil Mohammad Raja
REDUCING THE ENVIRONMENTAL IMPACT OF CONSTRUCTION THROUGH USE OF GEOSYNTHETICS

By
Jamil Raja

A dissertation thesis submitted in partial fulfilment of the requirements for the award of the degree Doctor of Engineering (EngD), at Loughborough University

May 2015

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International Geosynthetics Society
UK Chapter
www.igs-uk.org

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Leicestershire, LE11 3TU
ACKNOWLEDGEMENTS

The four year Engineering Doctorate has been a unique and life changing experience. It has brought about a lot of personal development and I hope the skills and knowledge gained will aid me in my future endeavours.

The research project would not have been possible without the support and insight of many people but I would particularly like to thank my supervisors:

- Professor Neil Dixon - Academic Supervisor at Loughborough University
- Dr Gary Fowmes - Academic Supervisor at Loughborough University
- Dr Matthew Frost - Academic Supervisor at Loughborough University
- Peter Assinder - Industrial Supervisor at IGS UK

They have provided guidance and wisdom throughout the research period not only as supervisors but also as mentors and friends. I would also like to thank Mr Ian Fraser and Professor Jacqui Glass for their involvement in the early stages of the research project. A special thank you to the CICE and most importantly Dr Steven Yeomans and Sara Cowin, without whom, the EngD would not have been possible.

Finally, I would like to thank my parents and family for their support during this four year period. In particular I would like to pay a special thanks and tribute to my late grandfather Raja Mohammad Bashir who sadly lost his brave battle with cancer in November 2014.
ABSTRACT
The changing climate and damaging effects of CO\textsubscript{2} on the environment has led to awareness throughout the construction industry of the need to deliver more sustainable solutions. The use of geosynthetics as a sustainable construction solution was demonstrated by the Waste and Resources Action Programme (WRAP) in a report entitled ‘Sustainable Geosystems in Civil Engineering Applications’ (WRAP, 2010). The WRAP report presented a series of case studies in which geosynthetic solutions provided both cost and CO\textsubscript{2} savings in comparison to non-geosynthetic solutions. However, in what is a huge field the report concentrated on specific areas relative to the calculation methods or on the potential construction applications. This EngD research built on this work by WRAP and aimed to establish a rigorous framework for the comparison of CO\textsubscript{2} emissions between geosynthetic and non-geosynthetic solutions.

This EngD research reviewed CO\textsubscript{2} calculation methodologies and techniques to produce a rigorous framework that could be adopted in comparative CO\textsubscript{2} studies between geosynthetic and non-geosynthetic solutions. It was demonstrated on three case studies looking at geosynthetics in the function of containment, drainage, and reinforcement, highlighting the possible CO\textsubscript{2} benefits of employing geosynthetics. The development of the case studies and framework highlighted the need for accurate embodied carbon data. There was an absence of geosynthetic specific embodied carbon values in the commonly employed databases. The EngD research sought to address this and through some experimental work in collaboration with geosynthetic manufacturers calculated embodied carbon values for four types of geosynthetics.

KEY WORDS
Geosynthetics, Sustainability, CO\textsubscript{2} Footprinting, Embodied Carbon
PREFACE

This thesis represents research undertaken between 2010 and 2014, to fulfil the requirements of an Engineering Doctorate (EngD) at the Centre for Innovative and Collaborative Construction Engineering (CICE), Loughborough University. The research was supported by the CICE and funded by the Engineering and Physical Sciences Research Council (EPSRC) and the International Geosynthetics Society (IGS) UK Chapter.

The EngD is a well-recognised post-graduate qualification satisfying a different research need to that of a traditional PhD. It is a collaborative research programme in which the researcher is placed within a sponsoring organisation and is guided by an industrial supervisor. Quarterly research meetings involving the academic and industrial supervisors help to ensure that the EngD research is industrially focused yet maintains a high level of academic rigour.

The EngD is examined on the basis of a thesis supported by academic publications in the form of peer reviewed conference and journal papers. This thesis is supported by two journal and three conference papers which have been numbered 1 to 5 for ease of reference and are included as Appendices A to E of the thesis. These papers support specific work items within the overall programme and are provided as a reference for further reading and detail on the EngD research presented.
### USED ACRONYMS / ABBREVIATIONS

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
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<tr>
<td>ADB</td>
<td>Asian Development Bank</td>
</tr>
<tr>
<td>BREEAM</td>
<td>Building Research Establishment Environmental Assessment Method</td>
</tr>
<tr>
<td>CICE</td>
<td>Centre for Innovative and Collaborative Construction Engineering</td>
</tr>
<tr>
<td>EA</td>
<td>Environment Agency</td>
</tr>
<tr>
<td>EAGM</td>
<td>European Association of Geosynthetic Manufacturers</td>
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<tr>
<td>EC</td>
<td>Embodied Carbon</td>
</tr>
<tr>
<td>EE</td>
<td>Embodied Energy</td>
</tr>
<tr>
<td>EU</td>
<td>European Union</td>
</tr>
<tr>
<td>GCD</td>
<td>Geocomposite Drain</td>
</tr>
<tr>
<td>GHG</td>
<td>Greenhouse Gas</td>
</tr>
<tr>
<td>GWP</td>
<td>Global Warming Potential</td>
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<tr>
<td>EngD</td>
<td>Engineering Doctorate</td>
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<tr>
<td>ICE</td>
<td>Inventory of Carbon &amp; Energy</td>
</tr>
<tr>
<td>IGS</td>
<td>International Geosynthetics Society</td>
</tr>
<tr>
<td>IGT</td>
<td>Innovation and Growth Team</td>
</tr>
<tr>
<td>LCA</td>
<td>Life Cycle Analysis</td>
</tr>
<tr>
<td>PET</td>
<td>Polyester</td>
</tr>
<tr>
<td>PE</td>
<td>Polyethylene</td>
</tr>
<tr>
<td>PP</td>
<td>Polypropylene</td>
</tr>
<tr>
<td>UNFCCC</td>
<td>United Nations Framework Convention on Climate Change</td>
</tr>
<tr>
<td>UK</td>
<td>United Kingdom</td>
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<tr>
<td>WRAP</td>
<td>Waste and Resources Action Programme</td>
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The following papers, included in the appendices, have been produced in partial fulfilment of the award requirements of the Engineering Doctorate during the course of the research.

PAPER 1 (SEE APPENDIX A)


PAPER 2 (SEE APPENDIX B)


PAPER 3 (SEE APPENDIX C)


PAPER 4 (SEE APPENDIX D)

PAPER 5 (SEE APPENDIX E)

PAPERS NOT IN THE APPENDICES

One other conference paper was produced during the research period but has not been included in the appendices with this thesis submission; the reference is therefore presented below:

1 INTRODUCTION

1.1 THE CONTEXT OF THE RESEARCH

Climate change is an issue that has been at the forefront of global discussions for many years, however, it has now become one of the biggest challenges the world faces. There has been significant scientific evidence that links increasing greenhouse gas (GHG) emissions with the changing climate (EPA, 2014). The increase in GHG emissions such as CO$_2$ (Figure 1.1) has seen global temperatures rise, with the period 2000-09 being the warmest decade on record (Royal Society, 2010). With temperatures rising, the polar ice caps melting and an increased frequency of extreme weather events (IPCC, 2014a), there has been global recognition for the need to curb CO$_2$ emissions.

![Figure 1.1 Change in CO$_2$ emissions from 1998 to 2011 (Data Source: WRI, 2014)](image)

The need to act on rising CO$_2$ emissions dates back to 1988, when the Intergovernmental Panel on Climate Change (IPCC) was formed to provide the world with a clear scientific view on climate change and its potential impacts (IPCC, 2014b). The recognition to act on CO$_2$ emissions was further strengthened in 1992 with the formation of the United Nations Framework Convention on Climate Change (UNFCCC). The UNFCCC is an international
treaty that countries (parties) joined, to supportively tackle the issues of climate change (United Nations, 1992). The parties to the convention recognised that measures to reduce emissions were insufficient and hence this led to the setting of legally binding emissions targets in the form of the Kyoto Protocol (United Nations, 1998). Due to a complex approval procedure the protocol eventually came into effect in 2005 and set emissions commitments on 37 industrialised nations to include those from the EU as well as the UK and Australia amongst others. This has led these nations to bring in their own legislations and emission reduction targets. Examples include the Emissions Trading System (ETS) set by the European Union (2013) and ‘The Climate Change Act 2008’ legislation set by the UK government (TSO, 2008).

The Climate Change Act 2008 introduced by the UK government highlighted their recognition of the problems associated with climate change. It was one of the world’s first long term frameworks to tackle the problems associated with climate change by introducing ambitious legally binding targets. The importance of it becoming legislation is that it establishes continual accountability to the UK Parliament and to the devolved legislatures. The main legally binding target set by the act was to reduce UK GHG emissions by at least 80% below base year levels by 2050 (TSO, 2008). The secondary target was to cut emissions by at least 34% below base year levels by 2020. The base year for both targets was accepted as 1990. In order for the UK to start making progress to achieving these targets the act introduced a system of carbon budgets (see Table 1.1). The budget system caps the carbon emissions over a five year period, helping the government to track progress towards the 2050 target more effectively (DECC, 2011).
Table 1.1 The first four carbon budgets (DECC, 2011)

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<tr>
<td>3,018</td>
<td>2,782</td>
<td>2,544</td>
<td>1,950</td>
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| Percentage reduction below base year levels | 23% | 29% | 35% | 50% |

In light of the UK’s ambitious objectives specific industries and sectors have been targeted to reduce CO₂ emissions and meet the sustainable low carbon agenda. One such sector that has been influenced by the sustainable agenda to reduce its CO₂ is that of construction. The construction sector is reported to influence up to 47% of the UK’s total CO₂ emissions (BIS, 2010), hence has forced the UK government to develop a strategy for sustainable construction (BERR, 2008). One of the main targets of the strategy and of most relevance to this research was to reduce CO₂ emissions by at least 60% by 2050 (Smith, 2008). Therefore sustainability, which is defined in Section 3.2, and more specifically sustainable construction targets, could be achieved through reducing CO₂ emissions from construction processes.

The government has also formed groups such as the Innovation and Growth Team (IGT) to explore methods in which the construction sector can meet the agreed sustainable low-carbon agenda (IGT, 2010). This is further complimented by the introduction of ‘Construction 2025’ (BIS, 2013), which sets out a vision and a plan for long-term strategic action by both government and industry. The plan aims to halve GHG emissions from the construction sector by 2025 and is driving implementation of strategies by the construction industry to meet the CO₂ reduction targets.

The plans and strategies set in place by the UK government have raised awareness amongst clients, consultants and contractors of the need for low carbon construction solutions. It has
Reducing the Environmental Impact of Construction Through Use of Geosynthetics

couraged CO₂ related research across the construction sector. The research ranges from CO₂ footprinting of the cement industry (Cagiao et al., 2011) to that of specific solutions and materials such as the CO₂ emissions from the use of aggregates (Thomas et al., 2009). The research and strategies have helped to identify and promote the use of sustainable ‘green’ construction solutions, which have seen growth worldwide (McGraw-Hill Construction, 2013). One example of a construction solution that has been identified as providing sustainable benefits is the use of geosynthetics in a variety of functions. These include reinforcement, containment, and drainage, amongst others.

The CO₂ and cost saving benefits of solutions that employed geosynthetics were highlighted in a study by the Waste and Resources Action Programme (WRAP, 2010). WRAP carried out a number of case studies that compared differing solutions and showed how the use of geosynthetics amongst other benefits can also reduce the amount of imported fill. This provided CO₂ savings from the embodied carbon emissions of the fresh fill as well as that from the transportation of these materials on and off site. Although the WRAP study showed significant cost and CO₂ savings of employing geosynthetics it was limited in scope to the function of reinforcement. It also did not extend the Life Cycle Analysis (LCA) boundaries to cover construction emissions as this was assumed negligible in most instances. Similar studies have also been carried out by the European Association of Geosynthetic Manufacturers (EAGM) (Stucki et al., 2011) and Heerten (2012). These studies, unlike the WRAP study, extended LCA boundaries to cradle to grave, however, they do differ on scope. The work by Heerten (2012) complimented the results of the WRAP study as it highlighted the CO₂ savings of employing geosynthetic solutions in applications such as steep slopes and roads, however, the study was again limited to the function of reinforcement. The range of functions was addressed by the EAGM (Stucki et al., 2011) which covered filtration and drainage as well as reinforcement. Figure 1.2 illustrates an application covered in the study and the
solutions compared. The scope of the EAGM study was not limited to CO₂ emissions but to compare geosynthetic and non-geosynthetic solutions for eight environmental impact categories. These categories included CO₂e emissions referred to as global warming potential as well as factors such as acidification, eutrophication etc. Although the EAGM study also echoed the findings of the WRAP study, it lacked detail in demonstrating the methodology behind the CO₂ calculations and the input data.

Figure 1.2 Example of solutions compared by the EAGM in the foundation stabilisation case (Stucki et al., 2011)
1.2 RESEARCH AIM AND OBJECTIVES

The overarching aim of the research is:

“To establish and demonstrate a rigorous framework for comparison of CO₂ emissions between geosynthetic and non-geosynthetic solutions”

In order to effectively achieve the overarching aim, the research was broken down into four core objectives:

- To understand sustainable construction and the benefits achieved through use of geosynthetics (Objective 1)
- To evaluate CO₂ calculation methods typically used in the geosynthetics industry (Objective 2)
- To compare CO₂ emissions between geosynthetic and non-geosynthetic solutions (Objective 3)
- To source embodied carbon data for specific types of geosynthetics (Objective 4)

These objectives and how they fit into the overall research methodology are explained in Chapter 4. The research map provided in Figure 1.3 shows how the core objectives relate to the key research areas/tasks and academic outputs.
1. To understand sustainable construction and the benefits achieved through use of geosynthetics

2. To evaluate CO₂ calculation methods typically used in the geosynthetics industry

3. To compare CO₂ emissions between geosynthetic and non-geosynthetic solutions

4. To source embodied carbon data for specific types of geosynthetics

Figure 1.3 Research Map linking objectives to EngD outputs
1.3 OVERALL RESEARCH APPROACH

The EngD research carried out required an innovative approach due to the unusual nature of the sponsoring organisation, with it being a society (International Geosynthetics Society UK Chapter) rather than a single company (Section 1.5). Therefore, with more stakeholders than a traditional EngD, there was a need to identify the collective aims and requirements of all the chapter sponsors involved in governing the society. Further details of the sponsoring company are provided in Section 1.5.

Whereas, typically a literature review provides the basis for the research carried out, in the case of this EngD, initial research in the form of a survey was carried out prior to the literature review. The survey (Chapter 2) provided an opportunity to interact with the chapter sponsors and identify their needs and expected outcomes for the research. With a large subject domain, the findings of the survey helped guide the literature review (Chapter 3). Chapter 2 also provides a brief background to geosynthetics which was necessary to understand the functions and applications of geosynthetics. This understanding into the use of geosynthetics was vital in the development of the survey.

Following the literature review a more conventional research approach was followed with a research methodology (Chapter 4), research undertaken (Chapter 5) and the findings and implications (Chapter 6) all reported within this thesis.

1.4 RESEARCH JUSTIFICATION

The possibility of stricter government targets and legislations (Section 1.1), is driving the construction industry to reduce CO₂ emissions and employ sustainable construction solutions.

The work carried out by WRAP (2010) and the EAGM (Stucki et al., 2011) has highlighted the environmental benefits of employing geosynthetic solutions and more specifically the CO₂ savings possible. However, there is a dearth of published studies that compare the CO₂
emissions between geosynthetic and non-geosynthetic (traditional) solutions. Moreover, the studies that have been carried out do not provide a clear, concise methodology or calculation framework that could be applied on other geosynthetic projects. They also have other limitations as they do not explicitly consider the source and accuracy of a material’s embodied CO$_2$. There is some uncertainty in the database Embodied Carbon (EC) values typically employed by such studies. This may damage the credibility of any CO$_2$ calculations and results produced. There is a need for accurate geosynthetic specific EC data which can be applied in carbon footprinting analysis of geosynthetic solutions. This data complemented with a clear CO$_2$ footprinting framework, will help to identify the sustainable benefits of geosynthetics when at their most appropriate use.

This EngD project advances on the recent preliminary work carried out by WRAP (2010) and critically reviews research in parallel areas. It extends the applications covered by WRAP to represent functions other than just reinforcement such as, containment and drainage. The case studies will follow a rigorous framework to provide a clear and concise CO$_2$ footprinting methodology that will be transferrable to other geosynthetic projects. This methodology combined with accurate input data in the form of EC values for specific geosynthetics products, will increase the credibility of future results. Thus, the outcomes of this research should help identify early in the design process whether a geosynthetic or non-geosynthetic solution is more sustainable.

1.5 THE INDUSTRIAL SPONSOR

This work was sponsored by the UK Chapter of the International Geosynthetics Society (IGS).

The IGS is an international organisation dedicated to the scientific and engineering development and promotion of geosynthetics. Founded in Paris in 1983 by a group of
Reducing the Environmental Impact of Construction Through Use of Geosynthetics

gotechnical engineers and textiles experts, it has grown worldwide to become the leading international organisation in geosynthetics. Since the formation of its first chapter in the US it has grown now to boast 43 chapters, over 3,000 individual members as well as 161 corporate members (IGS, 2014). The aims of the IGS (2014) are:

- to collect and disseminate knowledge on all matters relevant to geotextiles, geomembranes and related products, e.g. by promoting seminars, conferences, etc.
- to promote advancement of the state of the art of geotextiles, geomembranes and related products and of their applications, e.g. by encouraging, through its members, the harmonization of test methods, equipment and criteria.
- to improve communication and understanding regarding such products, e.g. between designers, manufacturers and users and especially between the textile and civil engineering communities.

The UK Chapter was formed in 1987 and has helped to promote the appropriate use and application of geosynthetics in the UK. It has also provided a platform to disseminate knowledge through various evening meetings, events and symposiums. The Chapter now has 29 sponsors and its growth has also encouraged it to promote research in the field of geosynthetics and their sustainable use. In order to interact with the Chapter sponsors and understand their needs for the research, a Chapter sponsors survey (Section 2.3) was carried out prior to the literature review and main body of research. The survey also presented an opportunity to gain an understanding on some key issues surrounding the use of geosynthetics.

This research was part funded by the IGS UK Chapter and undertaken as part of the EPSRC funded Engineering Doctorate (EngD) scheme at Loughborough University. At the time of
writing the author is actively involved in the committee of the IGS both nationally as part of the UK Chapter and at international level as part of the Young IGS group.

1.6 THESIS STRUCTURE

This thesis is split into six main chapters:

Chapter 1- Introduction: presents a background to the EngD research and context within which it was conducted. It also identifies the aims and objectives of the research.

Chapter 2- Background and Survey of Chapter Sponsors: provides an introduction on the use of geosynthetics and details of the Chapter sponsors survey conducted.

Chapter 3- Review of the Literature: provides a literature review of previous academic and industrial work in the subject area as well as other areas of significance in relation to the EngD research.

Chapter 4- Research Methodology: explains the overall research methodology adopted as well as how individual research objectives and tasks were tackled.

Chapter 5- Research Undertaken: presents the results and main findings drawn from the research, with reference to the corresponding publications (Appendix B to E)

Chapter 6- Findings and Implications: concludes and provides a brief summary of the EngD project. A discussion on the key findings and how they affect the sponsor and the wider industry is also provided.

Reference is made to five papers (Appendix A to E) throughout the thesis. These papers are summarised in Table 1.2. The papers are a key output of the EngD research and are an important element of the thesis, and dissemination of its findings. Although the papers are summarised and referred to in the thesis it is advisable however, to refer to the individual
papers for added insight. It will also help the reader to develop a link between the detailed work and the overall themes of the project.

Table 1.2 EngD Papers

<table>
<thead>
<tr>
<th>Title</th>
<th>Journal/Conference</th>
<th>Status</th>
<th>Thesis Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Limitations to Designing with Marginal Fills (Paper 1)</td>
<td>EuroGeo5 (2012) Valencia</td>
<td>Published</td>
<td>Appendix A</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>The sustainable use of geosynthetics: Landfill drainage case study (Paper 2)</td>
<td>10ICG (2014) Berlin</td>
<td>Published</td>
<td>Appendix B</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Comparison of CO₂ emissions for two landfill capping layers (Paper 3)</td>
<td>Proc. Of ICE Engineering Sustainability</td>
<td>Published</td>
<td>Appendix C</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Comparison of CO₂ emissions for a reinforced soil and concrete retaining structure: A case study (Paper 4)</td>
<td>Geosynthetics 2015 Portland</td>
<td>Published</td>
<td>Appendix D</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sustainable construction solutions using geosynthetics: Obtaining reliable embodied carbon values (Paper 5)</td>
<td>Geosynthetics International</td>
<td>Published</td>
<td>Appendix E</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
2 BACKGROUND AND SURVEY OF CHAPTER SPONSORS

2.1 INTRODUCTION

Initially the chapter provides an introduction to geosynthetics, which was essential in understanding the use and applications of various types of geosynthetics and vital in the development of an effective survey. The chapter then discusses the methodology, details and outputs of the IGS UK Chapter sponsor’s survey that was undertaken.

The findings of the survey provided focus to the research work and the basis for an effective literature review. The large subject domain with many potential research topics and interests meant that a survey ensured a literature review (Chapter 3) that most appropriately met the needs of the research.

2.2 INTRODUCING GEOSYNTHETICS

2.2.1 BASIC CHARACTERISTICS OF GEOSYNTHETICS

Geosynthetics are commonly available in a number of different markets for varying civil and geotechnical engineering applications. They are flexible in use and can often be adaptable to varying field situations. Due to their all-round versatility they can easily be combined with other building materials to help meet design requirements. This versatility has contributed to the increased use and sale of geosynthetics in recent years, with the market estimated to be worth $15.4 billion by 2019 (MarketsandMarkets, 2014).

The basic characteristics of geosynthetics that have attributed to their increased used and range of applications include (Shukla & Yin, 2006):

- Non-corrosiveness
- Highly resistant to biological and chemical degradation
- Long-term durability under soil cover
• High flexibility

• Minimum volume

• Lightness

• Ease of storing and transportation

• Simplicity of installation

• Speeding the construction process

• Making economical and environmentally friendly solution

• Providing good aesthetic look to structures.

The raw materials used in the production of geosynthetics are responsible for a number of the favourable characteristics mentioned above. In almost all cases the raw materials from which geosynthetics are produced are polymeric. This study only considered those geosynthetics with polymeric raw materials. Polymers are materials that have a high molecular weight; those used in the manufacture of geosynthetics are often thermoplastics. The raw materials help to explain the term ‘geosynthetics’, with geo referring to earth and synthetics referring to the polymeric material (thermoplastic)

Along with the basic characteristics listed, the importance of geosynthetics can also be observed in their ability to reduce the amount of natural material and resources being used. They can often partially or completely replace natural resources such as gravel, sand etc. or allow marginal fills (Section 3.7) to be used. This means that not only can geosynthetics be used for design and economic purposes, but also on an environmental basis.
2.2.2 Types of Geosynthetics
The geosynthetic family is a large one, with a number of different products (Figure 2.1) that provide a range of functions which include (Koerner, 1998); Separation, Reinforcement / Stabilisation, Filtration, Drainage, and Containment.

2.2.2.1 Geotextiles
Often considered as one of the largest groups in the geosynthetic family it provides the biggest range of primary and secondary functions. As the name suggests they are similar to traditional textiles, however, instead of natural materials they consist of synthetic fibres. Geotextiles are planar, permeable and are found in the form of a flexible sheet (Shukla & Yin 2006). One of the most important features of a geotextile is that they are porous to liquid flow across their manufactured planes and also within their thickness, however, the degree is dependent on the type of geotextile used (Koerner, 1998).

Geotextiles can be classified into four different groups based on their manufacturing procedure; woven, nonwoven, knitted and stitched. These different groups of geotextile have varying attributes and hence may be suited to particular functions. Overall there are over 100 specific application areas for geotextiles, however, it will always perform one of the five functions mentioned in Section 2.2.2 (Koerner, 1998). Geotextiles are also one of two possible types of geosynthetics that are able to serve all the five main functions mentioned previously.

2.2.2.2 Geogrids
Geogrids are another major part of the geosynthetics family. They don’t have the textile fabric that is associated with geotextiles instead they are plastics that are formed into an open, grid like layout which means they have large apertures (Koerner, 1998). Similar to geotextiles, geogrids also have a number of ways they can be manufactured to create specific attributes and properties. Depending on the method the main ribs of the geogrid have been linked there
are three main types; extruded, bonded and woven (Shukla & Yin 2006). Geogrids have a number of application areas but only provide one function and that is of reinforcement. They are directly competing with geotextiles as both provide the function of reinforcement however geotextiles also have the ability to provide secondary functions (Koerner, 1998).

![Different types of geosynthetics](Wikipedia, 2015)

### 2.2.2.3 Geomembranes
Geomembranes are thin (Table 2.1) synthetic sheets that are relatively impermeable and are used to control fluid migration in the form of a barrier or liner, therefore the primary function of a geomembrane is containment as a liquid or vapour barrier. They have a large range of possible applications, used not only in environmental and containment applications but also in transport, geotechnical and hydraulic applications. Geomembranes are an important member of the geosynthetics family and compete with both geogrids and geotextiles in terms of global sales and revenues generated. In 2009 they accounted for an estimated 22% of geosynthetic sales in the U.S./Canada (see Figure 2.2).
Table 2.1 General range of some specific properties of geosynthetics (based on data compiled by Lawson and Kempton, (1995))

<table>
<thead>
<tr>
<th>Types</th>
<th>Thickness (mm)</th>
<th>Mass per unit area (g/m²)</th>
<th>Apparent opening size (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Non-woven-Geotextiles</td>
<td>0.25 – 7.5</td>
<td>100 - 2000</td>
<td>0.02 – 0.6</td>
</tr>
<tr>
<td>Woven -Geotextiles</td>
<td>0.25 – 3</td>
<td>100 – 1500</td>
<td>0.05 – 2</td>
</tr>
<tr>
<td>Geomembranes</td>
<td>0.25 – 3</td>
<td>250 – 3000</td>
<td>≈ 0</td>
</tr>
<tr>
<td>Geogrids</td>
<td>5 – 15</td>
<td>200 – 1500</td>
<td>10 – 100</td>
</tr>
<tr>
<td>Geonets</td>
<td>3 – 10</td>
<td>100 - 1000</td>
<td>5 – 15</td>
</tr>
</tbody>
</table>

2.2.2.4 Geosynthetic Clay Liners (GCLs)

GCLs are one of the newest additions to the group of geosynthetics. They are rolls of thin layers of bentonite clay sandwiched between two geotextiles or bonded to a geomembrane. They form a composite component and are generally used beneath geomembranes or individually in environmental containment applications. Similar to geomembranes they serve a primary function of containment and are used in a range of applications.
2.2.2.5 Geocomposites
Geocomposites as the name suggest are a combination of two materials, at least one of which is always a geosynthetic. The most commonly found combinations include geocomposite drains comprising a geonet or similar, and filtration geotextiles. All of the mentioned geosynthetics can also be combined with other materials such as plastic sheets or steel cables (Koerner, 1998). This means that like geotextiles, geocomposites provide the whole range of functions possible, and have a number of different application areas.

2.2.2.6 Other Geosynthetics
Apart from the geosynthetics already mentioned there are also a number of other products which include:

- Geonets- open grid-like materials used to carry relatively large fluid or gas flows
- Geopipes- perforated or solid-wall polymeric pipes used for drainage of liquids or gas
- Geocell- constructed from strips of polymeric sheet joined together to form interconnected cells that are infilled with soil and sometimes concrete
- Geofoam- blocks or slabs created by expansion of polystyrene foam used for thermal insulation or as a lightweight fill.

2.2.3 Applications
The choice of functions provided by geosynthetics allows them to serve in a variety of applications. Table 2.2 highlights some possible applications and what functions the geosynthetics can provide. Often reinforcement applications such as roads and slopes are those where you would commonly see geosynthetics being employed. However, the increased awareness has led to geosynthetics being employed in more novel applications such as erosion control or mining. The use of geosynthetics has demonstrated not only to provide cost and sustainability benefits (WRAP, 2010), but also design and aesthetic benefits. Figure 2.3
highlight examples where a vegetated geosynthetic solution is used in a landfill stabilisation application, but also provides aesthetic benefits and fits in with the existing surroundings.

The use of geosynthetics often faces competition from commonly perceived ‘traditional’ solutions that employ concrete or higher quality imported fill. The term ‘traditional’ is frequently used in the literature to describe non-geosynthetic solutions. However, in recent times the IGS (Section 1.5) have discouraged the use of this term, as it can inadvertently imply that geosynthetic solutions are novel and untried. Where possible this thesis employs the term ‘non-geosynthetic’ however, Papers 1 to 5 (Appendix A to E) produced prior to the thesis employ the terms ‘traditional’ and ‘non-geosynthetic’ interchangeably.

Figure 2.3 Vegetated face steep slopes in landslide stabilisation: a1, a2 Boscaccia, Italy & b1, b2 Valpol, Italy (Cazuffi et al., 2014)
Reducing the Environmental Impact of Construction Through Use of Geosynthetics

<table>
<thead>
<tr>
<th>Sl. no.</th>
<th>Application areas</th>
<th>Main purpose of geosynthetics</th>
<th>Major functions</th>
<th>Major geosynthetic products</th>
<th>Most Important properties</th>
<th>Special consideration</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Retaining walls and steep-sided embankments</td>
<td>Reinforce and protect backfill/soil</td>
<td>Reinforcement</td>
<td>Geotextiles, Geogrids</td>
<td>Strength, Soil—geosynthetic friction</td>
<td>Creep</td>
</tr>
<tr>
<td>2</td>
<td>Embankments on soft ground</td>
<td>Improve stability, provide drainage</td>
<td>Separation, Drainage</td>
<td>Geotextiles, Geogrids</td>
<td>Strength, Soil—geosynthetic friction</td>
<td>Creep/stress relaxation</td>
</tr>
<tr>
<td>3</td>
<td>Shallow foundations</td>
<td>Increase load-bearing capacity and reduce settlement</td>
<td>Reinforcement</td>
<td>Geotextiles, Geogrids, Geocomposites</td>
<td>Strength, Soil—geosynthetic friction, Pore size</td>
<td>Elongation</td>
</tr>
<tr>
<td>4</td>
<td>Uncaveled roads</td>
<td>Increase bearing capacity and reduce degree of rutting</td>
<td>Reinforcement, Separation</td>
<td>Geotextiles, Geogrids, Geocomposites</td>
<td>Strength, Soil—geosynthetic friction, Pore size</td>
<td>Repeated loading, Elongation</td>
</tr>
<tr>
<td>5</td>
<td>Paved roads</td>
<td>Inhibit crack propagation, improve cyclic fatigue behaviour</td>
<td>Separation, Drainage</td>
<td>Geotextiles, Geogrids, Geocomposites</td>
<td>Pore size, Permeability</td>
<td>Repeated loading, Elongation</td>
</tr>
<tr>
<td>6</td>
<td>Railway tracks</td>
<td>Prevent ballast contamination; distribute load on subgrade</td>
<td>Separation, Drainage</td>
<td>Geotextiles, Geogrids, Geocomposites</td>
<td>Pore size, Permeability</td>
<td>Repeated loading, Elongation, Resistance to impact and wear abrasions</td>
</tr>
<tr>
<td>7</td>
<td>Slopes</td>
<td>Protect soil slope against erosion; reinforce soil, provide drainage</td>
<td>Reinforcement, Drainage</td>
<td>Geotextiles, Geogrids, Geocomposites</td>
<td>Pore size, Permeability, Strength, Soil—geosynthetic friction, Abrasion resistance</td>
<td>Rapid changes in water level, Clogging, Construction stresses</td>
</tr>
<tr>
<td>8</td>
<td>Landfills</td>
<td>Extract leachate out of the waste and retain the same</td>
<td>Fluid barrier, Drainage, Filtration</td>
<td>Geomembranes, Geotextiles, Geogrids</td>
<td>Pore size, Permeability, Strength</td>
<td>Leachate characteristics, Construction stresses, Elongation</td>
</tr>
<tr>
<td>9</td>
<td>Dams</td>
<td>Reduce seepage through the dam embankment; prevent internal erosion/piping; provide drainage; protect slope against erosion</td>
<td>Reinforcement, Filtration, Drainage</td>
<td>Geomembranes, Geotextiles, Geogrids, Geocomposites</td>
<td>Abrasion resistance, Pore size, Permeability</td>
<td>Clogging, Construction stresses</td>
</tr>
<tr>
<td>10</td>
<td>Containment ponds, reservoirs and canals</td>
<td>Reduce seepage of water/liquid into ground</td>
<td>Fluid barrier, Drainage, Filtration</td>
<td>Geomembranes, Geocomposites, Geonets, Geocomposites</td>
<td>Permeability, Abrasion resistance, Pore size</td>
<td>Construction stresses</td>
</tr>
<tr>
<td>11</td>
<td>Pipeline and drainage facilities</td>
<td>Protect the drainage medium; provide drainage</td>
<td>Drainage, Filtration</td>
<td>Geomembranes, Geocomposites, Geotextiles, Geocomposites</td>
<td>Permeability, Transmissivity, Permeability</td>
<td>Clogging</td>
</tr>
</tbody>
</table>

Table 2-2 Major application areas of geosynthetics (Shukla, 2002)
2.3 SURVEY OF CHAPTER SPONSORS

2.3.1 INTRODUCTION

The initial phase of the EngD research required some preliminary work that would help in guiding the research and the literature being reviewed. The aims of this preliminary work were to:

a) Interact with the Chapter Sponsors and identify areas of importance from the key project stakeholders
b) Gain information on geosynthetic products, solutions and market
c) Understand the constraints and barriers to the use of geosynthetics
d) Ascertain the awareness of sustainability and CO₂ emissions in the industry
e) Identify the literature to be reviewed.

The most effective process of achieving these aims was deemed to be through a survey of the Chapter Sponsors. The survey in the form of a questionnaire was developed and managed using an online platform (kwiksveys, 2014), which also stored the responses and provided useful analytical tools. This section discusses the development of the survey as well as presenting some of the key findings. Further details and outcomes of the survey were presented in a paper by Raja et al. (2011) titled “Constraints and barriers to the application of geosynthetics”.

2.3.2 SURVEY METHOD

Survey research is a key area of measurement in applied social research and includes any measurement procedure that involves asking questions of respondents (Trochim, 2000). There are two main types of surveys that can be carried out; a questionnaire or an interview. These can range from mail group and household drop off questionnaires to personal or telephone interviews. Selection of the correct survey method is critical in achieving the aims of the
research being carried out. Issues such as population, sampling, questions, administration, content and bias can all determine what type of survey is most appropriate (Trochim, 2000).

In the case of this research and the mixed nature of questions being asked (Section 2.3.3), an online questionnaire was deemed as the most effective way of quantifying the answers and results. It also allowed the respondents (IGS UK Chapter Sponsors) to complete the questionnaire within their own timeframe and consistency was maintained between all the respondents. The questionnaire provided an opportunity to introduce the EngD research and allowed for a number of follow up visits.

2.3.3 DESIGN OF THE SURVEY
The effectiveness of any survey is based on a number of factors. These factors can include design considerations such as the goal, topics and content of the survey to more specific format related factors such as question layout and page design (Fanning, 2005). Therefore in order to ensure the survey would fulfil its aims, research was carried out into appropriate survey/questionnaire methodologies. Guidance was sought from various sources such as Fink (2005) and Dillman (2000), which helped to highlight the importance of what each type and form of question would achieve and the outputs it would provide. The broad nature of the survey and the range of information required meant a mixture of both qualitative and quantitative questions were deemed most applicable.

The survey questions were grouped into different sections based on areas of key interest. These sections included personal information, sales, sustainability, considerations/inputs and design. The grouping of questions in sections allows the goals and aims of the survey to be achieved more effectively and is also recommended by Dillman (2000). A draft survey was presented to select industry members that were representative of the target population, in order to refine and test the questions as recommended by Schutt (2011). A technique referred
to as “cognitive interview” (Dillman, 2007) was employed and the individuals were asked to “think aloud” as they answered the questions. These questions were then followed up by a discussion on how the respondent understood the questions, which provided feedback and helped to refine the questions.

Overall the survey comprised of seventeen questions that varied from closed to open ended in nature. It was produced on online software (kwiksurveys, 2014) that was deemed the most effective method of both delivering the survey and managing the responses. A primary test of the survey highlighted that the participants would only require a maximum of fifteen minutes to complete the survey. Therefore ten to fifteen minutes was provided as an advised time to the participants. Using the online tool the survey accompanied with a covering letter was emailed to a total of 29 IGS UK Chapter Sponsors.

2.3.4 FINDINGS
The survey received a 34% response with ten IGS UK Chapter Sponsors completing the survey. The responding companies included consultants, contractors and manufacturers, thus representing a variety of stakeholders from both the geosynthetic and the broader civil engineering industry. This is represented in Figure 2.4 which highlights the range of sectors covered by the participants of the survey. The questions were grouped into topics (Section 2.3.2) and these topics as well as the key findings are summarised in Table 2.3. For a more detailed review of the results and the survey please refer to the paper published by Raja et al. (2011)
Figure 2.4 Sectors represented in the survey (Raja et al., 2011)
Table 2.3 Key findings from the survey

<table>
<thead>
<tr>
<th>Topic</th>
<th>Key findings</th>
</tr>
</thead>
</table>
| Design and services | • Participants providing various services, products and solutions  
                        • Majority of participants provided design services, both as technical assistance and fully indemnified  
                        • Results representative of geosynthetics industry and not bias towards any specific sector, solution or product  
                        • Key design documents identified such as BS 8006 (2010) & BS EN 14475 (2006) |
| Competition and sales| • 70% of participating companies have seen an increase in geosynthetics sales over last 5 years (2006 -2011)  
                        • Companies perceive a fairly even mixture of competition from within and outside the industry  
                        • Some companies still perceive those providing ‘traditional’ solutions as their main competition |
| Promotion and advertising | • Promotional literature and presentations deemed the most effective from of advertising  
                                • Majority of new clients were also new to the geosynthetic industry  
                                • Big group of clients still unaware of the benefits and uses of geosynthetics |
| Sustainability      | • Sustainability is not the governing parameter in design however, is frequently considered  
                        • Sustainability benefits used in marketing of solutions  
                        • Cost is still the primary factor |
| Barriers to the use of geosynthetics | • Perceived costs and lack of education biggest barriers  
                                        • Lack of clarity in guidance documents with regards to acceptable fill materials  
                                        • Poor quality geosynthetic imitations entering the market |
| Selection of solutions | • Savings in cost influences clients in selecting a geosynthetic solution, other factors include time reduction, aesthetics and interaction with the landscape  
                              • Lack of experience and geosynthetics being perceived as ‘new technology influences clients to stick to ‘tried and tested’ solutions |

2.3.5 CONCLUSIONS FROM IGS SPONSOR SURVEY

The answers received from the survey helped to provide an understanding of the geosynthetics industry and the factors influencing the use and application of geosynthetic products. The survey provided an insight into a number of important topics and highlighted
some of the reasons why geosynthetics are not being used in preference to ‘traditional’ methods.

There were a number of key findings that resulted from the survey and in particular it highlighted the barriers faced by the use of geosynthetics. The biggest barrier was the lack of education amongst the clients that ultimately resulted in consultants recommending ‘tried and tested’ solutions. The survey highlighted the need to raise awareness about geosynthetic solutions and products amongst the broader civil engineering industry. Other factors influencing the use of geosynthetics included cost apprehensions, substandard materials, and ambiguity in design guidelines regarding acceptable fill material.

One important topic covered was sustainability, with an emphasis on the importance and applicability of sustainability in the geosynthetic industry. The results from the survey highlighted that clients gave cost precedence over sustainability in selection of solutions. However, sustainability was still being considered in most designs and being marketed as a notable benefit of employing a geosynthetic solution.

The main aim of the survey was to shape the EngD research and provide a basis for the literature review. The survey highlighted that there was reservations with regards to acceptable fill materials. Therefore whilst considering the sustainable benefits of geosynthetics, there was also a need to understand this particular barrier affecting the use of geosynthetics in reinforcement applications. As a result of the survey key focus areas for the literature review were identified:

- Drivers for sustainable construction
- Embodied Carbon and CO₂ footprinting
- Sustainable benefits of geosynthetics and the use of marginal fills
3 REVIEW OF THE LITERATURE

3.1 INTRODUCTION

This chapter provides a literature review that considers sustainable construction and the CO₂ footprinting techniques employed in both the construction and geosynthetic industry. The review helps to identify the drivers for sustainable construction which are promoting low CO₂ solutions. Whilst considering the sustainable benefits of geosynthetics the literature review also aims to investigate the CO₂ footprinting techniques and EC data employed.

One particular application the review specifically focuses on is the use of marginal fills when combined with geosynthetics in reinforcement applications. Marginal fills are lower quality, often site-won, poor draining cohesive fills with a high content of fines and often possess weak mechanical characteristics. With proven sustainable and economic benefits, the use of marginal fills is still restricted due to uncertainties regarding their appropriate use and design. This review investigates this further, focusing specifically on backfill/fill applications such as embankments/slopes and behind retaining walls. Paper 1 included as Appendix A summarises the findings of this aspect of the literature review and provides recommendations on the use of marginal fills and geosynthetic reinforcement in such applications.

3.2 DEFINING SUSTAINABILITY

The term ‘sustainability/sustainable’ is frequently employed throughout this thesis and the author acknowledges that this term can often have a number of meanings. In this thesis the term is being referred to in the context of sustainable development, which was defined in ‘The Brundtland Report’ (Brundtland, 1987) as: “development that meets the needs of the present without compromising the ability of future generations to meet their own needs”. Subsequently the application of sustainable development to the construction industry is termed ‘sustainable construction’
Sustainable development can be interpreted in many ways but fundamentally it is development that looks to balance different requirements against awareness of the environmental, social and economic issues faced by society (Sustainable Development Commission, 2014). The ‘Three Spheres of Sustainability’ (Figure 3.1) highlight how social and economic factors are just as important as environmental factors in defining sustainability. However, in the context of this EngD research the term sustainability considers only the environmental aspects. Therefore sustainable construction is being measured on the reduction of harmful environmental impacts with a focus on the category of climate change and reduction of CO₂ emissions.

Figure 3.1 The ‘Three Spheres of Sustainability’ (Vanderbilt University, 2014)
3.3 DRIVERS FOR SUSTAINABLE CONSTRUCTION

3.3.1 INTRODUCTION
The issues surrounding sustainability are at the forefront of modern day engineering. There has been considerable research into approaches that can produce more sustainable designs and construction processes with a growing demand for such solutions. An important measure of sustainable development and construction is a reduction in CO$_2$ emissions (Section 3.2). The main factor driving the push to reduce CO$_2$ emissions is the recognition globally that increased CO$_2$ emissions are accountable for the changing climate. This is explained in Section 1.1 and Figure 1.1 illustrates the global increase in CO$_2$ emissions from 1998 to 2011. As explained in the context of the research (Section 1.1) the recognition to act has led to the Kyoto Protocol treaty (United Nations, 1998) as well as legislations such as the Climate Change Act 2008 (TSO, 2008) and the ETS (European Union, 2013). These carbon reduction targets have influenced various industries and sectors to evaluate their performance and adapt to meet the sustainable low carbon agenda.

In the UK the low carbon agenda has resulted in the formation of groups such as the IGT and the production of various strategies and long term sustainable targets by the government. These targets and strategies alongside environmental assessment methods such as CEEQUAL (2011) and BREEAM (BRE, 2012) have pushed the construction industry to become more sustainable. In order to fully comprehend how such targets and assessment techniques are driving sustainable construction in the UK, some of these key drivers were reviewed.

3.3.2 LOW CARBON CONSTRUCTION – INNOVATION AND GROWTH TEAM
In light of the UK’s ambitious targets a number of plans and guidelines have been developed, some industry specific. The Low Carbon Construction report (IGT, 2010) developed by the IGT, drawn from the UK construction industry, addresses how the construction industry can meet the needs of the low carbon agenda. The report was created with support from the
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Department of Energy and Climate Change (DECC), Department for Communities and Local Government (CLG) and Department for Environment, Food and Rural Affairs (DEFRA).

The guidance provided by the IGT addresses the long term CO\(_2\) targets set by The Low Carbon Transition Plan (DECC, 2009) which is followed up by The Carbon Plan (DECC, 2011). Although the plans do not focus specifically on the construction industry they do place an emphasis on reducing CO\(_2\) emissions from buildings. Therefore, the focus of the IGT report is on how the construction industry can help provide buildings and infrastructure that are zero carbon over the whole life cycle. Figure 3.2 highlights the different life cycle phases that are considered, the size of each arrow is representative of the percentage influence of each phase. For example the ‘In Use’ phase influences 83% of the UK’s construction CO\(_2\) emissions, whereas at the opposite end of the scale the ‘Refurbish/Demolish’ phase influences 0.4% (BIS, 2010).

![Figure 3.2 Broad phases of a buildings life cycle (IGT, 2010)](image)

The influence of the ‘In Use’ phase on total construction emissions is the reason why CO\(_2\) reduction targets (DECC, 2011) focus on sustainable construction that produces energy efficient zero carbon buildings. However, the IGT report recognises the importance of the phases prior to the ‘In Use’ phase, where CO\(_2\) emissions could be reduced by selecting a sustainable construction process or solution. For example the use of a geosynthetic solution (Section 3.6.2) which allows the re-use of site material would reduce CO\(_2\) emissions in both the ‘Materials’ and ‘Distribution’ (Figure 3.2) phases. The IGT report acknowledges the CO\(_2\) reduction targets set for construction processes in the ‘Strategy for Sustainable Construction’
(BERR, 2008). The strategy included an initial target of a 15% reduction in carbon emissions from construction processes and associated transport compared to 2008 levels by 2012.

In summary, the report produced by the IGT is acting as a driver for the construction industry to become more sustainable. Importantly it tackles and provides guidance on reducing emissions from the whole life cycle of buildings/infrastructure, which promotes and highlights the benefits of using sustainable construction methods and processes. However, the IGT recognises that most of the recommendations made in the report are directed to government and due to the scale of the challenge, only they can set the framework for action.

3.3.3 Construction 2025

Construction 2025 (BIS, 2013) is an industrial strategy launched by the UK government in July 2013. Working together the construction industry and the UK government have set some joint ambitions they aspire to achieve by 2025:

1. A 33% reduction in both the initial cost of construction and the whole life cost of assets

2. A 50% reduction in the overall time from inception to completion for new build and refurbished assets

3. A 50% reduction in greenhouse gas emissions in the built environment

4. A 50% reduction in the trade gap between total exports and total imports for construction products and materials

In order to meet the ambitious targets listed above Construction 2025 looks at addressing three strategic priorities:

1. Smart construction and digital design

2. Low carbon and sustainable construction
3. Improved trade performance

The GHG emissions target and identification of low carbon and sustainable construction as a strategic priority, highlight the importance of sustainable construction in the Construction 2025 vision and framework. The strategy set, recognises the potential business opportunities and growth in the construction industry from low carbon construction. The global green and sustainable construction has been estimated to grow at 22.8% annually from 2013 to 2017 (IbisWorld, 2012). The main factors identified as influencing this growth are low carbon regulatory requirements and greater social demand for greener products.

In order to effectively meet the targets set for 2025 the Construction Leadership Council was tasked with developing an action plan. The action plan focused on all three strategic priorities, however, only that of the low carbon and sustainable construction, is of relevance to the EngD research (Table 3.1). The actions identified in the Construction 2025 strategy focus on sustainability post-construction, such as employing construction techniques to produce ‘zero-carbon’ infrastructure. In some ways very similar to the IGT (2010) report reviewed (Section 3.3.2). However, the action points stated can also help to influence sustainable construction solutions and identify and publicise those that are reducing carbon emissions. One specific action point that would promote construction solutions is the voluntary commitment to resource efficiency (Table 3.1). This would help to promote the sustainable benefits of solutions that re-use site-won or waste materials.
Table 3.1 Construction 2025 Low carbon and sustainable construction action plan (BIS, 2013)

<table>
<thead>
<tr>
<th>Strategic Priority</th>
<th>Action</th>
<th>Target Date</th>
<th>Owned By</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low Carbon and sustainable construction</td>
<td>Develop a series of market based plans which set out the programme for investment in energy low carbon construction</td>
<td>First plan complete by Autumn 2013</td>
<td>Green Construction Board</td>
</tr>
<tr>
<td></td>
<td>Develop a series of technology based plans which set out the programme for investment in energy low carbon construction</td>
<td>First Plan complete by Winter 2013</td>
<td>Green Construction Board</td>
</tr>
<tr>
<td></td>
<td>Commit to a resource efficiency voluntary agreement</td>
<td>Spring 2014</td>
<td>Construction businesses with support from WRAP</td>
</tr>
<tr>
<td></td>
<td>Consider the scope to develop a climate change adaptation plan</td>
<td>Autumn 2013</td>
<td>Green Construction Board</td>
</tr>
</tbody>
</table>

The Construction 2025 report does not focus only on sustainability but also integrates other factors such as reduction of costs and time amongst other things. In the present economic climate without strict legislation on carbon emissions of construction projects, cost and time remain the dominant factors in selection of designs and construction techniques. This was also highlighted in the findings of the survey in Section 2.3 and summarised by Raja et al. (2011). However, by combining all three factors into one report sustainability is given equal importance, and demonstrating that it is possible for low carbon construction to also be more cost and time effective. It is arguable that the action points do not specifically target low carbon construction solutions. However, the purposely broad natured action points help target the wider construction industry, whether it is those involved in the construction of low energy buildings or those employing low carbon construction techniques and methods.

There is still a lack of clarity how the Construction Leadership Council will deliver the action points stated, however, the strategy is still in its early stages and this should be addressed over
time. The implementation of the plan and any further action points identified will help to drive clients, consultants and contractors to follow the low carbon, sustainable construction agenda.

3.3.4 Waste and Resources Action Programme (WRAP)

A brief introduction to WRAP and a report published by them was provided earlier (Section 1.1). However, in order to fully understand the extent of which the work being carried out by WRAP in encouraging and driving the construction industry to become more sustainable, a detailed review of their operations was carried out.

WRAP have often run a number of initiatives and funded/supported detailed work such as the report produced on Sustainable Geosystems (WRAP, 2010). The focus of their work in the construction industry is on reducing waste and promoting resource efficiency. The reduction of waste subsequently has CO₂ emissions benefits. The re-use of otherwise waste material, reduces the amount of virgin material quarried and transported, as well as less waste material being transported to landfills, which has both sustainable i.e. reduced CO₂ emissions and economic benefits (WRAP, 2010).

One particular initiative that was run for the construction industry was the ‘Halving Waste to Landfill’ commitment (WRAP, 2011). This commitment designed by WRAP is to provide a supportive framework to encourage the construction industry to reduce its waste. Signing up to the commitment allows companies to show their interest in sustainable policies and practices as well as measuring and reporting on their success. This commitment focuses on all of those involved in the supply chain from clients and developers to designers, contractors and trade and sector bodies. Although this commitment was up until 2012, it is still being actively employed and recognised. By committing to this voluntary agreement the companies are asked to:
• Set a specific target for reducing waste to landfill;

• Embed the target in corporate policy and processes;

• Set corresponding requirements in project procurement and engage with the supply chain;

• Measure performance relative to a corporate baseline; and

• Report annually on overall corporate performance.

The success of the initiative can be measured by those signing on to the voluntary agreement (Figure 3.3) and the case studies that have been produced. Interest in this commitment ranges from both the public sector with local councils to the private sector, with notable market leaders such as Balfour Beatty, BAM Construct and Carillion all already committed to this agreement. In the public sector one example would be Dumfries and Galloway council who in Sept 2011 became the fourth local authority to sign up to the commitment.
3.3.5 ENVIRONMENTAL AND SUSTAINABILITY ASSESSMENT METHODS
The use of environmental and sustainability based assessment methods and rating systems is an important factor in driving sustainable construction. The methods most commonly employed in the UK include the Building Research Establishment's Environmental Assessment Method (BREEAM) and CEEQUAL.

BREEAM was formed in 1990 and identifies itself as one the world’s foremost environmental assessment method and rating system for buildings, with 425,000 buildings with certified BREEAM assessment ratings (BRE, 2012). BREEAM encourages designers and clients and others involved in the construction industry to think about low carbon and low impact design, as well as how to minimise the operational energy requirements of the building. The
BREEAM manual (BRE, 2008) measures performance over a variety of categories such as energy to ecology. The assessment can be carried out on new construction (BRE, 2011) or on existing buildings to improve their environmental impact and also help to reduce costs. In many domestic and non-domestic sectors a BREEAM rating of excellent is required in all new-builds. Therefore this pushes the construction industry to producing more sustainable designs and construction techniques.

CEEQUAL is another sustainability assessment method, which was launched in 2003 to improve project specification, design and construction of civil engineering works (CEEQUAL, 2011). Similar in methodology to BREEAM, assessments of project or contract performance on management and a range of environmental and social factors are carried out. The assessors will use the CEEQUAL (2012) manual to measure the performance and collect evidence to score each category. These scores will then provide a CEEQUAL award for a project or contract on a scale of Pass, Good, Very Good and Excellent. The awards can range for whole projects or to recognise individual efforts such as client and design or construction only awards. The acquisition of a CEEQUAL award helps demonstrate the commitment to go that ‘extra’ mile and attain environmental excellence above that required in legal standards. The CEEQUAL scheme has been adopted by various clients, consultants and contractors on their projects. Furthermore public sector clients such as Welsh Assembly Government, Thames Water and London Underground are specifying the use of CEEQUAL on large scale projects.

The selection of which assessment method to use is dependent mainly on experience, purpose of the assessment and client requirements. BREEAM is more recognised worldwide, however in the UK, CEEQUAL was developed as its civil engineering equivalent. They can often be used in combination and an example would be employing BREEAM for individual buildings
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and CEEQUAL for the whole infrastructure. With an increased number of private and public sector clients specifying the need for high BREEAM or CEEQUAL ratings, it is forcing all the stakeholders of the construction industry to become more sustainable. It is also important to note that these assessment methods are driving individual construction projects to meet the low carbon and sustainable agenda. This gives an opportunity to employ innovative construction techniques that would help gain higher ratings and potentially more business opportunities.

3.4 CARBON FOOTPRINTING IN THE CONSTRUCTION INDUSTRY

3.4.1 INTRODUCTION

A carbon footprint can be defined as the total CO₂ emissions produced by an organisation, activity, project, event or person. Carbon footprinting is the method employed in measuring such emissions and the level of impact they have on the environment. The scope of carbon footprinting can range from very large scale measurement at a global level or at a finer product based level. In the case of this research the focus is on carbon footprinting of construction projects and their related CO₂ emissions. More specifically the CO₂ emissions produced from the construction techniques and materials employed. Operational CO₂ emissions such as the use of electricity to run the site offices on a construction project are not considered in the scope of this research. Carbon footprinting of a construction project/method allows the EC (Section 3.5) of the materials used to be combined with CO₂ emissions from processes such as transport of materials/waste or plant use. Using the EC values in their simplest form allows those carrying out the carbon footprinting to add their required boundary conditions to the raw data.

This section of the report will identify and explain the carbon footprinting process and calculation of CO₂ emissions specific to the construction and geosynthetic industry. Life
Cycle Assessment (LCA) and the criteria set play an important role in carbon footprinting and will also be discussed. Furthermore the section will explore footprinting methods and tools most commonly employed in the construction industry such as the one produced by the Environment Agency (EA, 2012). Other tools and methods provided by those within the geosynthetic industry will also be explored for their detail and accuracy.

### 3.4.2 The Process

Carbon footprinting has no specific definition or generalised process, and is based on the criteria set and level of analysis required. Factors such as the LCA boundary conditions (Section 3.4.3) employed will govern the extent, detail and scope of the carbon footprinting. The carbon calculation and techniques employed vary, however, when focusing on the construction industry there is often a common methodology employed. This methodology uses the EC data (Section 3.5) for the materials employed combined with CO₂ emissions from other construction related activities, dependent on the LCA criteria set (Section 3.4.3). There are many different examples available of methodologies applied in calculating the carbon emissions from a construction project e.g. WRAP, (2010) and ADB, (2010).

#### 3.4.2.1 Methodology for Estimating Carbon Footprint of Road Projects, Case Study: India (ADB, 2010)

The aim of the case study was to calculate the carbon footprint of Asian Development Bank (ADB) funded road construction/improvement projects. This would create a comprehensive approach for calculating the carbon emissions from the road construction, operation and maintenance phases. The ADB considered phases such as operation and maintenance, which may not be considered in other similar footprinting calculations. However, the emissions produced in these phases are linked to the construction phase, and may rely on factors such as the quality of construction.
The detailed methodology produced by the ADB was split into three distinct phases as mentioned previously this included: Road Construction, Operation and Maintenance phases. The methodology from the road construction phase is of most relevance to this EngD research, as it could be used in comparing CO₂ emissions for comparable construction solutions (Section 4.3.3) to LCA boundaries of cradle to site or to end of construction (Section 3.4.3). In the methodology produced the construction phase is split into a number of key monitoring areas (ADB, 2010):

I. Embodied Carbon from Construction Materials

II. Fossil Fuels
   i. Direct emissions due to combustion of fossil fuels
   ii. Embodied Carbon in fossil fuels

III. Removal of Vegetation
   i. Carbon sequestration potential lost
   ii. Direct emissions due to combustion of fuel wood

IV. Construction Machinery and Vehicles
   i. Embodied carbon in machinery and vehicles

The identification of key monitoring areas helped to show the carbon hotspots in the construction of a road. These areas selected may vary in carbon footprinting calculations depending on the nature, type and method of construction being employed. However, they provide an example and guidance for other CO₂ studies of construction projects. The methodology developed by the ADB may be specific for road construction, but can be easily adapted to suit the requirements of other construction carbon footprinting studies.
3.4.3 Life Cycle Analysis (LCA) and the Criteria Applied

The use of LCA and its criteria (discussed in Section 1.1) affects the detail and scope of any carbon footprinting undertaken; therefore, it is important to understand some of the key elements involved in LCA and how they may be applied. In the case of this research, the focus is on carbon footprinting comparisons of construction methods and solutions in particular those incorporating geosynthetics. For this reason, the knowledge of LCA required and the criteria to be set may be simpler than those used in studies such as the one carried out by the ADB (ADB, 2010). Therefore, the LCA discussed in this section will be simplified and relevant to the carbon footprinting and calculations that may be used to compare the emissions from geosynthetic and non-geosynthetic construction solutions.

LCA is a technique employed to assess the environmental impacts of products, buildings or other services throughout their life-cycle (Menzies, 2007). Figure 3.4 illustrates the flow process of an LCA. In construction, designers and decision-makers will often use LCA to assess the environmental, social and economic impact of the product or solution being employed (Kiani et al., 2008). The use of LCA in the construction and geosynthetic industry is often limited to the construction phase, as is the scope of this research. This research focuses on the CO₂ emissions produced in the construction phase, rather than for the whole life cycle, hence a much simpler form of LCA with reduced boundary conditions. The different boundaries or criteria of analysis can be described as: cradle-site, cradle-gate and cradle-grave. In the case of construction materials, Figure 3.5 helps to define the system boundaries.
In the construction industry and the carbon calculations carried out by WRAP (2010) they assessed the environmental impact of CO₂ emissions with the criteria of cradle-site. This allowed them to use the EC data which was provided at a cradle-gate level and add transport related emissions to provide an overall cradle-site LCA. This is different to the whole life cycle approach taken by the ADB (Section 3.4.2.1), however, it allows for easy comparison of data. More specifically the environmental impact of employing a geosynthetic or a non-geosynthetic solution can be compared directly with regards to their EC and transport related
CO₂ emissions. There are obvious benefits of carrying out a whole LCA of cradle to grave, however, in many instances there is not enough reliable data or a specific construction method to allow an accurate analysis to be carried out. Also the scope of this research is to focus on the carbon calculation and its effectiveness for use by the geosynthetic industry. Therefore when comparing a geosynthetic solution to a non-geosynthetic solution it may be argued that the biggest difference in CO₂ emissions from the two solutions occurs from cradle to site (Section 3.6.2). The difference in CO₂ emissions produced in the installation or the maintenance phases between the two solutions may be minimal so often ignored as demonstrated by WRAP (2010).

3.4.4 Carbon Footprinting Standards: PAS (Publicly Available Specification) 2050

PAS 2050 (BSI, 2011a) provides a method to assess the life cycle GHG emissions of goods and services, that are collectively referred to as ‘products’. In combination with the PAS2050 carbon footprinting guide (BSI, 2011b), it can help organisations to calculate the carbon footprint of their products and identify areas of potential CO₂ savings within the supply chain. As stated in the PAS2050 guide (BSI, 2011b), it provides organisations with a tool to:

- carry out internal assessment of the existing life cycle GHG emissions of products to identify ‘hotspots’ and related cost/energy saving opportunities
- evaluate alternative product configurations sourcing and manufacturing methods, raw material choices and supplier selection
- devise ongoing programmes aimed at reducing GHG emissions
- report on corporate responsibility

The PAS2050 methodology involves the use of stepwise process to carbon footprinting which involves four key steps; Scoping, Data collection, Footprint calculations and Interpretation of
results (Figure 3.6). The steps help to define the scope and system boundary and identify the data requirements, limitations and assumptions required for the study. The application of the methodology is demonstrated in the landfill case study on clay and geosynthetic capping solutions in Section 5.3.6. Certain aspects of PAS 2050 are unavoidably technical in nature, however, the accompanying guide (PAS, 2011b) provides clarity on the specific technical aspects and its application in practice.

PAS 2050 was developed to fulfil the extensive community and industry need for a consistent method in assessing the life cycle GHG emissions of goods and services. It allows those users calculating carbon footprint information in accordance with PAS 2050, a common basis for understanding the life cycle GHG emissions of goods and services. This helps to provide a consistent methodology when comparing CO₂ emissions between differing construction solutions, such as the geosynthetic and non-geosynthetic solutions covered within this EngD research (Section 5.3). The application of PAS 2050 has ranged from CO₂ footprinting studies of asparagus (Schafer et al., 2014) to that of coffee supply chains (Killian et al., 2013) and specific construction solutions such as road surface treatments (Spray et al., 2014). This helps to demonstrate the versatility of the standards and how they can be applied to different goods and services.

The development and implementation of the PAS 2050 standards has been a key factor in the reduction of global carbon emissions. However, Gao et al. (2013) highlight some of the problems faced in the application of standards such as PAS 2050 and ISO 14064 (2006), in relation to uniformity of accounting methods, unscientific boundary definitions and uncertainty in the carbon emission factors. Further research and analysis in these issues is recommended by Gao et al. (2013), especially in the organisation and product fields.
3.4.5 TOOLS AND TECHNIQUES EMPLOYED—GEOSYNTHETIC AND CONSTRUCTION PROJECTS

There are a number of general carbon footprinting tools and techniques employed in the construction industry. However, tools used in calculating the CO₂ emissions released from the construction phase are of most relevance to this research. The main aim of these tools is to use the EC data of the materials with addition of transport associated CO₂ emissions, to give the total cradle to site (Section 3.4.3) emissions for the construction method employed. These tools and calculations allow for comparison between a geosynthetic solution and a non-geosynthetic solution in terms of carbon emissions. One example would be the construction of embankment in a traditional manner using high quality fills or alternatively with a geosynthetic solution. Both methods are adequate, however, may have significant differences in cost and CO₂ emissions (WRAP, 2010). Hence carbon calculation tools/techniques are employed and in demand, so that an accurate comparison of the CO₂ emissions produced between the two solutions can be carried out.
There are a number of carbon calculation tools employed, however, some are very basic and others applicable to broad range of functions and applications. At present there is no universally agreed upon carbon calculation tool or technique in the geosynthetic industry, which could be employed to compare variety of different geosynthetic applications for their CO₂ emissions. This study will briefly discuss one of the basic tools provided by a geosynthetic manufacturer, as well as a more generic carbon calculator produced by the Environment Agency (EA).

3.4.5.1 Environment Agency Carbon Calculator
This tool was initially developed by Jacobs Engineering UK Ltd and then further modernised by a team from Jacobs and a steering group including the carbon reduction company Sustain and Balfour Beatty (EA, 2012). The carbon calculator allows the user to efficiently calculate the CO₂ emissions in a construction project that arise from EC of materials, travel, transportation, site activities and waste management. This then allows the user to effectively target specific areas to reduce the CO₂ emissions produced.

The tool was initially based on EC (Section 3.5) data from the Inventory of Carbon and Energy (ICE) database (Section 3.5.2.1); this data has subsequently been updated to include the latest EC data. It provides the data input in a simplified manner by breaking into a number of small steps, using an excel spread sheet. When focusing specifically on the geosynthetic industry and how this tool may be applied by them, there are still a number of questions that arise with regards to its broadness. Hence a tool that specifically targets applications in which geosynthetics could be applied may prove to be more beneficial.

The validity of the CO₂ results produced are dependent on the accuracy of the EC data employed which is discussed in more detail in Section 3.5. As a calculation tool itself it is simple, easy to use and applicable to a broad range of construction projects. It could be
employed in calculating the CO₂ emissions for a whole project or for more specific phases, processes or materials. Depending on the LCA system boundaries (Section 3.4.3) it could be used to compare both geosynthetic and non-geosynthetic solutions for cradle to gate or cradle to site CO₂ emissions (Section 4.3.2). The tool also covers a range of applications and in the view of this author is the most effective general construction carbon calculation currently available. The tool is available free at http://www.environment-agency.gov.uk/ (EA, 2012).

3.4.5.2 Other Tools- Geosynthetic Specific
In the geosynthetic industry some manufacturers are offering very simple carbon calculators to show the possible carbon emission savings between employing their product and a non-geosynthetic solution. These can be used by designers and clients to gain a quick understanding of the sustainable benefits of employing a geosynthetic based solution. The calculators are limited in scope and presentation of results, however, the calculations themselves are externally validated, following PAS2050 (BSI, 2011a), and using raw material data and manufacturer specific energy usage data (Section 5.4) as recommended by this thesis. The review of tools available highlights the need for an industry specific carbon calculator or methodology, one that is backed and endorsed by a number of geosynthetic manufacturers and suppliers.

3.5 EMBODIED CARBON
3.5.1 INTRODUCTION
Accurately performing carbon footprinting or calculations is based on reliable input data. EC values for the materials make up a considerable amount of the input data, and their accuracy will govern the reliability of the carbon calculations being carried out and the success of the results produced. Therefore, alongside the methods, tools and applications of carbon footprinting there is a need to understand the raw data and any variations that may occur within it.
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There are number of different ways in which EC could be defined based on whether the value is calculated on cradle to gate, cradle to site or cradle to grave (Figure 3.5). This report is focusing on the EC values applied for materials on a cradle to gate basis and can be defined as the amount of carbon released from material extraction and manufacture. These EC values are then applied in various carbon footprinting techniques that may wish to include carbon released during material transport to the site, hence becoming cradle to site values or similarly for the whole life cycle of the material; cradle to grave.

The accuracy of the EC values applied ultimately effects the validity of the carbon footprinting carried out. With a range of different assumptions that can be applied there is some ambiguity in the accuracy of EC values. This section will look at the assumptions made in calculating EC values and analyse the databases such as the ICE produced by Bath University (Hammond & Jones, 2008a) to discuss any variation in the values stated. The representation of geosynthetic products in the ICE database and EcoInvent v3.0 (EcoInvent Centre, 2013) will also be discussed.

3.5.2 SOURCE AND ACCURACY OF EMBODIED CARBON DATA

In work with EC or Embodied Energy (EE) data there is often confusion surrounding which measurement should be used and when. Similar to how EC is the amount of carbon released from extraction, processing and manufacture of a material/product, EE represents an equivalent value in terms of the energy used in these processes. These figures may vary depending on what Life Cycle Assessment criteria are set (Section 3.4.3). EE and EC values are often used interchangeably in literature, depending on what form of analysis is being carried out. The difference between them both and which value you wish to use is based on its purpose. In the case of this research the focus is on carbon footprinting, hence EC values are
of more significance as they represent the amount of carbon embodied in the materials. Therefore this report will use the term EC unless it is citing other sources which refer to EE.

EE and EC values are often representative of the amount of energy consumed or carbon released up until the material reaches the factory gate (Cradle-Gate). This allows the data to be kept in its simplest form and can be easily adapted to add the emissions produced or energy consumed from associated processes such as transport to site. Keeping the data to these boundaries allows each material to be comparable with one another, providing a clearer picture on which is more sustainable. It is important to understand the process used and the key assumptions made in calculating and recording EC/EE values. These calculated values are created into an inventory, where the data is then used in various carbon footprinting techniques. Hammond & Jones (2008b) explain the process of creating the ICE database and the assumptions made.

3.5.2.1 Inventory of Carbon and Energy (ICE)

The Inventory of carbon and energy (ICE) created by the University of Bath (Hammond & Jones, 2008a) was formed to provide reliable and easily accessible values of EE and EC for construction materials. Most of the data used in compiling the inventory was in fact data that was collected from secondary resources. The original database included materials that were specified by the Chartered Institute of Building Services Engineers (CIBSE, 2006) and initial EE values taken from the handbook created by Boustead & Hancock (1979). The inventory has continued to develop and now boasts a database of over two hundred different materials and their respective EE/EC values. The wide variety of materials covered makes the inventory a popular choice for the majority of the construction industry. The original database was extended to the size it is now by researching various literatures which included published energy and LCA analysis. The development of the inventory is illustrated by a flow chart in Figure 3.7.
The Inventory produced associated two sources of EC with construction materials. One would be the EC involved in the fossil fuels input and the other source would be from the release of processes such as converting limestone to cement. This is where an important assumption is made about the use of fossil fuel as the energy source. Alongside this assumption there is also a problem with how precise EC values are when applied to a general category of material such as (aluminium and steel). Both of these points will be discussed in further detail in Section 3.5.2.2. The practice of selecting a best value is open to much debate, however, in order to create consistency within their data and to collate data of the highest accuracy, the
team at Bath University set out a selection criterion. The five criteria employed in the
selection of EE/EC data to be included in the ICE database were (Hammond & Jones, 2008a):

a) Compliance with approved methodologies/standards

b) System boundaries

c) Origin (country) of data

d) Age of data

e) Embodied carbon.

There are some questions that do arise over the reliability of the ICE database and these issues
will be discussed in Section 3.5.2.2. However, the success of the ICE database in the UK is
unparalleled. The data is used by a number of carbon footprinting tools and techniques and is
the unrivalled source of EC data in the UK construction industry. This may be down to the
vast range of materials covered with almost 200 different materials listed in the database. It is
also recognisable that there has been a lot of research and resources gone into developing this
database. The ICE database was the first in the UK to provide such an inventory and has
become the preferred source of data.

3.5.2.2 Variations and Assumptions in the Data

The ICE database was compiled by filtering the data that met their selection criterion. Once
this was carried out an arithmetic mean of the selected data was taken to derive values of EE
and EC from different sources to give a respective value for a specific material. A study
carried out by Menzies et al. (2007) and their diagrammatic representation in Figure 3.8 helps
to demonstrate the range of variation in EE values from different sources collated by the ICE
database. It is important to understand the reasoning behind these variations, and more
specifically the assumptions made that can lead to such differences in EE and EC data.
One of the biggest reasons for variation in EE/EC values for a specific material is down to assumptions made about the energy source. Often the calculation of EC values can be based on fossil fuel input; this assumption can lead to a large variation in the data as fossil fuels may not be the energy source used. Different energy sources such as oil, gas or solid fuels have varying carbon coefficients. Therefore not accurately identifying the energy source or assuming a source can lead to incorrect representation of the EC value for a specific material. One example is provided by Menzies et al. (2007), where the generation of electricity from hydroelectric power or other renewable sources has different impacts when compared to conventional techniques. A practical application of this example can be found in Canada and Norway, where aluminium is produced only by hydroelectric power. Another example is in Nottinghamshire where the brick production uses methane from landfills rather than the more conventional energy source (coal-fired). The variation in energy sources will have an impact on both the EC and EE (due to cycle efficiencies) values (Menzies et al., 2007). These values
may be considerably lower/higher than those stated in databases such as the ICE, hence creating a degree of variability. A study carried out by Buchanan & Honey (1994) confirmed this. They found that the carbon emissions produced in material production could differ by a factor of three depending on the energy source assumptions made. One important factor highlighted from this study is the effect of geographic location and conditions on the EC value of the material produced. There are many variances that exist between different geographic locations such as; environmental conditions, access, legislation, transport, resources etc. All of these variances could lead to different EC values even if the material produced is of the same specification.

The degree of variability in the data can also be accredited to material classification. EE/EC values will vary greatly within material classifications. For example mild steel and stainless steel, similarly glulam and sawn timber will have different EE. So when databases provide an EE/EC value for materials such as steel, aluminium and timber, these have been generalised and may vary greatly depending on the form or type of material being used. Figure 3.8 helps to highlight this point by showing materials such as aluminium and plastics that possess many different specification classes, forms and types have the biggest range of variation. Therefore a generalised value from a database may be useful in many footprinting tools and techniques, but it is possible that it won’t be providing an accurate representation of the actual EC value of the material.

The assumption of energy sources employed and grouping of different material classifications can be attributed as the main reasons for the variation of EE/EC values. However, the review carried out by Menzies et al. (2007) highlighted a number of other factors that may also affect EE/EC values. Menzies et al. (2007) carried out a life cycle energy analysis case study on steel. The case study not only demonstrated the degree of variation (Figure 3.8) but also some
of the major reasons for the variations in EE studies of steel. Excluding those points already covered in this section, they also provided a number of other factors (Menzies et al., 2007):

- Transport of raw materials
- Differences between end products
- Recycled material content and process differences
- Boundary definition

There may be reasons to question the data and the variation that exists as well as methods in which to increase the accuracy and reduce this variation. However, it is important to realise the purpose that the EE/EC databases provide and their scope. For a database to provide the EE/EC value of every production method, energy source and class of material would be unfeasible. The databases have been created to provide general figures, with as much accuracy as possible. This accuracy is based on their boundary conditions and selection criterion. There may however, be scope for improvement and development on such databases. For example listing EE/EC values for construction materials produced with sources such as hydroelectric power. This grouping of values based on energy source would help to decrease the variation between the data. There may also be scope for manufacturers to carry out their own LCA and Energy Analysis to provided EE and subsequently EC values for specific products, such as geosynthetics. These values provided by the manufacturers would help to create more detailed databases, and ultimately reduce variations in the data.

3.5.3 Embodied Carbon Data for Geosynthetics

In the UK the ICE database discussed in Section 3.5.2 is the primary source of EE/EC data for construction materials. However, there are alternative databases available such as the European life cycle analysis database called ‘EcoInvent v3.0’ (EcoInvent Centre, 2013).
Unlike the ICE database, which specifically focuses on the EE/EC of materials, the EcoInvent provides data for a wide range of life cycle indicators ranging from global warming to eutrophication. So although EcoInvent can be used to source EC data, it is particularly applicable for use in Life Cycle Assessments similar to those carried out by the EAGM (Stucki et al., 2011) discussed in Section 3.6.3.

When considering EC data for geosynthetics studies, often the ICE database or EcoInvent will be used as the primary source. With no specific values for geosynthetics products readily available in the databases, EC values based on the plastics used in the manufacture of the geosynthetics are employed. It is important to understand how these values compare between the databases and how accurately they represent the actual EC of geosynthetic products (Section 5.4).

3.6 SUSTAINABILITY WITH GEOSYNTHETICS

3.6.1 INTRODUCTION
The low carbon and sustainable agenda has presented growth and business opportunities for construction solutions that report CO₂ savings. The use of geosynthetics as discussed in Section 1.1 has demonstrated such CO₂ savings. This review will look at examples of how geosynthetics have provided CO₂ savings when compared to ‘non-geosynthetic’ solutions. This will highlight applications where geosynthetics are at their most appropriate sustainable use. In particular how the use of marginal fills in combination with geosynthetics has some of the most obvious CO₂ and cost benefits.

3.6.2 WRAP CASE STUDIES
A brief introduction to the work carried out by WRAP was provided in Section 1.1 and Section 3.3.4. WRAP is a not-for-profit company established in 2000 and funded by the UK Government. They work to help businesses and individuals gain the benefits of reducing
waste, develop sustainable products and use resources in an efficient manner. In the report titled ‘Sustainable Geosystems in Civil Engineering Applications’ (WRAP, 2010) aimed at demonstrating the beneficial use of geosynthetics to reduce the environmental impact of construction projects. Production of the report was supported by UK geosynthetics companies who contributed to a series of case studies.

The case studies compared the cost and CO₂ emissions for geosystem and non-geosynthetic solutions in a range of applications. WRAP (2010) employs the term geosystem which it defines as the composite working system in the ground. This therefore does not necessarily mean a geosynthetic solution. However, in most instances the composite employed in a geosystem solution and in the case studies presented by WRAP is a geosynthetic. The case studies do not present a total carbon or cost for the project but are comparative studies. Therefore CO₂ emissions and costs associated with materials and activities used in both solutions were omitted, for example, set-up of the site, transport of machinery and operation of site cabins and welfare. The studies were carried out to LCA boundary conditions of cradle to site and although construction emissions are considered they are assumed to be negligible or ‘carbon neutral’. The cost and CO₂ comparisons of each of the five main case studies are summarised in Table 3.2

The results from the case studies show that the geosystem solution is more sustainable and cost effective than the non-geosynthetic solution in all five cases. The amount of savings in cost and CO₂ emissions vary depending on the size and nature of the project. However, the findings of the case studies highlight that there is a correlation between cost and CO₂ and savings with a reduction in CO₂ emissions can also providing desirable cost benefits. These case studies were also supported by several less detailed case studies which also showed the geosystem solution to be more sustainable.
The main difference between the CO\textsubscript{2} emissions of the geosystem and non-geosynthetic solutions arose from the EC of the materials. The geosystem solutions were able to reduce the amount of imported material required, often re-using the site-won material. This reduced the CO\textsubscript{2} emissions from both the embodied and transport of imported material. The WRAP (2010) study employs the ICE database (see Section 3.5.2) as its source for EC data. However, without specific values for geosynthetic products in the ICE database (see Section 3.5.3) substituted values such as those for polypropylene (PP) and polyethylene (PE) are employed. The use of substituted values could potentially be over or under estimating the actual EC of the geosynthetics. Therefore in order to provide further credibility to CO\textsubscript{2} analysis and calculations involving geosynthetics there is a need for more specific EC data.

The WRAP (2010) report targets those that are unaware of the solutions provided by geosynthetics or ‘geosystem’ as defined by WRAP. It highlights the sustainable benefits of geosynthetics but also provides a clear methodology and step by step guidance on how the CO\textsubscript{2} emissions were calculated. This is very useful in allowing potential readers to follow this methodology on their own project and identify potential cost and CO\textsubscript{2} savings. The case studies produced are however, limited in scope to the function of reinforcement. The inclusion of other case studies for a range of functions and possible extension of the LCA boundaries to include construction emissions would help to maximise the impact of the study.
Table 3.2 CO₂ and cost results from the WRAP (2010) case studies

<table>
<thead>
<tr>
<th>Case Study</th>
<th>Geosystem Solution</th>
<th>Non-geosynthetic Solution</th>
<th>Savings with Geosystem</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>CO₂ (t)</td>
<td>Cost (£)</td>
<td>CO₂ (t)</td>
</tr>
<tr>
<td>Axis Business Park</td>
<td>19.21</td>
<td>15,000</td>
<td>143.17</td>
</tr>
<tr>
<td>Commonhead Junction</td>
<td>314.02</td>
<td>374,000</td>
<td>454.12</td>
</tr>
<tr>
<td>Crib Wall, Ash Vale</td>
<td>9.55</td>
<td>11,000</td>
<td>32.26</td>
</tr>
<tr>
<td>Hunters Lane</td>
<td>72.78</td>
<td>75,500</td>
<td>393.42</td>
</tr>
<tr>
<td>Modular Block Wall, Mansfield</td>
<td>42.64</td>
<td>29,500</td>
<td>96.95</td>
</tr>
</tbody>
</table>

3.6.3 EAGM STUDY

The EAGM study titled ‘Comparative Life Cycle Assessment of Geosynthetics versus Conventional Construction Materials’ (Stucki et al., 2011) was briefly introduced in Section 1.1. The study provides comprehensive qualitative and quantitative information of the environmental performance of commonly applied construction materials (i.e. concrete) versus geosynthetics. It compares geosynthetic solutions against non-geosynthetic solutions on eight environmental impact indicators; Cumulative Energy Demand, Climate Change (Global Warming Potential), Photochemical Ozone Formation, Particulate Formation, Acidification, Eutrophication, Land Competition and Water Use. The aim of the study was to assist EAGM members to improve environmental performance and communicate results and findings to customers, clients and stakeholders.

The study reports on four construction systems/cases; filter layer, foundation stabilisation (Figure 1.2), landfill construction and slope retention. Whereas WRAP (2010) employed actual projects in its case studies, the EAGM study is based on hypothetical designs. The constructions are designed so that both the geosynthetic and non-geosynthetic solutions are technically equivalent. The studies do not compare the solutions over a complete project but rather in terms of a functional unit which varies from case to case. For example in the filter...
layer case Stucki et al. (2011) define the functional unit as ‘The construction and disposal of a filter with an area of 1 square meter, with a hydraulic conductivity (k-value) of 0.1 mm/s or more and a life time of 30 years’. Furthermore the study employs LCA boundary conditions of cradle to grave. This is another notable difference to the WRAP (2010) study and therefore accounts for environmental impact from LCA stages such as the construction and disposal (Figure 3.9).

The results from each of the four cases highlighted that the geosynthetic solution was more environmentally beneficial than the non-geosynthetic solution. As mentioned previously, the study was carried out for a range of environmental impact indicators, however, that of Climate Change (Global Warming Potential) was of most relevance to the EngD research. This indicator represents the amount of CO₂ emissions released by each solution and its potential impact. In this category across all four cases the geosynthetic solution had a lower Global Warming Potential (GWP), highlighting the CO₂ benefits of employing a geosynthetic solution. The CO₂ emissions and GWP were calculated using EC data from the EcoInvent v2.2 (EcoInvent Centre, 2010).

The absence of geosynthetic EC data from the databases was discussed in Section 3.5.3. The EAGM sought to overcome this by calculating the EC of the geosynthetic products employed in the study by way of questionnaire. Questionnaires were sent to those involved in the manufacture of geosynthetics used in the specific cases to source production data. This data such as the content of raw material, oil, electricity consumption etc., was then used to calculate the EC of 1kg of geosynthetic material. However, there is a lack of clarity and transparency in the calculation process and no specific EC value for geosynthetic products is presented.
The study by the EAGM helps highlight the environmental benefits of geosynthetics. In comparison to WRAP (2010) it covers more functions and to a bigger LCA system boundary of cradle to grave. Although more detailed and covering a range of environmental impact indicators the EAGM study lacks clarity in the calculation of CO₂ emissions. In this regards the WRAP report provides a more clearly defined methodology and presentation of results. It is important however to consider the scope and target audience of the reports. The EAGM study targets the geosynthetic industry, to help them promote the environmental benefits of their products or solutions. Whereas WRAP (2010) target the wider engineering industry, introducing those unfamiliar with geosynthetics to their use as well as possible cost and CO₂ savings.

Figure 3.9 LCA process chart illustrating the most important steps and processes (Stucki et al., 2011)

3.6.4 SUSTAINABILITY OF GEOSYNTHETIC SOLUTIONS WITH MARGINAL FILLS
Geosynthetics when used in reinforcement applications can often reduce the amount of fill material required. They can also allow the re-use of site-won, lower grade marginal material, which would not have been employed in a non-geosynthetic solution. The use of site-won marginal material combined with a reduction in both imported fill and exported waste material, provides significant cost and CO₂ savings. It is in such applications, where geosynthetics employ site-won marginal fills that they have their most apparent sustainable
savings when compared to a non-geosynthetic solution. It is not necessary for all site-won material to be classified as marginal, however, if this material is not being employed in a non-geosynthetic solution it would be fair to assume it is due to its weaker mechanical characteristics hence termed marginal.

The sustainability and cost savings of employing site-won material have been reported in the case studies produced by WRAP (2010). In one particular case study, WRAP (2010) compared the cost and CO₂ emissions between a geosynthetic and non-geosynthetic solution for the construction of an embankment. The embankment was part of a dual two-lane flyover construction to the southeast of Swindon. In the original scheme proposal granular fill was suggested in the construction of the approach embankments, in order to provide sufficiently steep slopes without the footprint exceeding the allowable space. This non-geosynthetic solution would have required the import of 81,444 tonnes of granular fill and the removal of 60,564 tonnes of Gault Clay. The geosynthetic solution was able to re-use more than 50% of the site-won Gault Clay with only 25,176 tonnes exported off site. The reuse of the site-won marginal fill (Gault Clay) had considerable cost and CO₂ savings which are highlighted in Figure 3.10. In this particular instance the geosynthetic solution generated CO₂ savings of around 140tCO₂.

The re-use of site-won marginal fills provides CO₂ savings in three main phases; EC of fresh material, transport of imported fill and export of waste material. When applied with geosynthetics the WRAP (2010) case studies demonstrated the CO₂ savings possible. Although geosynthetics have shown cost and sustainability savings in a range of applications, it is in applications involving site-won marginal fills that geosynthetics are arguably at their most sustainable and appropriate use. However, before a geosynthetic solution can be
considered in such applications there is a need to understand and address the concerns regarding the application of marginal fills with geosynthetics.

![Flow chart comparing a non-geosynthetic and geosynthetic solution in terms of CO₂ emissions- Commonhead Junction Case Study (WRAP, 2010)](image)

**Figure 3.10** Flow chart comparing a non-geosynthetic and geosynthetic solution in terms of CO₂ emissions- Commonhead Junction Case Study (WRAP, 2010)

### 3.7 APPLICATION OF MARGINAL FILLS

#### 3.7.1 INTRODUCTION

The use and application of marginal fills has demonstrated economic and environmental benefits, hence their usage in backfill/fill applications such as slopes or retaining walls is being seriously considered by designers. However, the use of such lower quality cohesive fill creates a lot of concern for engineers and designers and has prevented utilising marginal fills where most appropriate. There is however, evidence of applications where marginal backfills have been applied successfully. Also with research and technological advances in the type of
geosynthetics being used and available, the lower mechanical properties maybe counter-acted with more technical geosynthetic products.

3.7.2 The Theory-Technical Constraints
Rowe and Jones (2000) looked at the innovative properties of geosynthetics. Amongst a wide variety of different geosynthetic related topics, particular attention was paid to geosynthetics with improved reinforcement and drainage characteristics. This study focused on the issue of cohesive fills and the problems that arise with their use, such as low strength, high moisture content, creep and low bond strength between the reinforcement and the soil.

Marginal/cohesive fills have high fines content and early research in undrained conditions showed that the relative volume of the fine grained portion of the fill controlled the shear strength of the reinforced soil (Schlosser and Long, 1974). Therefore within the soils classed as marginal/cohesive there are a range of different properties. For instance those marginal fills with lower fines content may have increased drained, long term, shear strength properties than those with a higher fines content. This showed that certain marginal fills may actually be suitable for specific applications. However, the use of such marginal fills in places such as North America is restricted by guidelines provided by The American Association of State Highway and Transportation Officials and The Federal Highway Administration. These guidelines require granular fills with low fines content (i.e., less than 15% finer than 0.075mm) to be used for publics works projects (Christopher and Stulgis, 2005). In the private sector in North America, the National Concrete Masonry Association (NCMA) allows backfills with up to 35% fines (Christopher and Stulgis, 2005).

Research by Murray and Boden (1979), Ingold (1979) and Lee (1976) led to the conclusions that the insertion of impermeable reinforcements in clay fill leads to excess pore water pressures at the soil-reinforcement interface. This causes a reduction in the soil-reinforcement
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bond and reduces the overall strength of the structure in the short term (Rowe and Jones, 2000). Therefore employing a method to reduce or eliminate the excess pore water pressures would result in more stable structures. This led to the concept of including a permeable reinforcement element which would also act as a drainage layer.

Mitchell and Zornberg (1995) also recognised the problems surrounding pore water pressure generation and the inclusion of permeable reinforcing elements. Mitchell and Zornberg (1995) discuss an experiment carried out by the Transport and Road Research Laboratory (TRRL), U.K. This experiment was created to investigate the feasibility of cohesive fills, by constructing a full-scale experimental reinforced wall. The construction and instrumentation used is described by Boden et al. (1978). The pore water pressures were measured during construction of the embankment and the tests showed the generation of high excess pore water pressure. Figure 3.11 shows the test structure as well as the pore water pressure that was generated.

![TRRL experimental reinforced wall](image)

Figure 3.11 Experimental reinforced wall (a) and (b) the pore water pressure distribution (Mitchell and Zornberg, 1995)
Paper 1 (Appendix A) explains how the use of a permeable reinforcing element providing lateral drainage, would allow the build-up of pore water pressures to be controlled. This approach of promoting lateral drainage in combination with soil reinforcement is also agreed upon by Christopher et al. (1998). In the study by Christopher et al. (1998), they state three adverse conditions of pore water pressure generation and/or loss of strength due to wetting, that can be of concern when reinforcing marginal/poor draining backfills. The three conditions are (illustration provided in Figure 3.12):

\( a) \) Generation of pore water pressures within the reinforced fill

\( b) \) Wetting front advancing into the reinforced fill

\( c) \) Seepage configuration established within the reinforced fill

Figure 3.12 Different conditions of concern in reinforced soil slopes using poorly draining backfills (Christopher et al., 1998)

Christopher et al. (1998) suggest that the use of permeable reinforcements could be employed to handle the three conditions mentioned. The method in which the permeable inclusions would tackle each particular condition is described:
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Condition a) - The pore water pressures that are generated during the construction and post-construction phases can be dissipated if the reinforcements provide lateral drainage.

Condition b) - The development of surface tension cracks is a common problem in particular in unreinforced embankments compacted with cohesive soils. Research has shown that the wetting front and surface tension cracks extend only down to the area above the first geosynthetic layer. Hence a reinforcement layer that possessed drainage capabilities could drain away the water that would have accumulated in the crack.

Condition c) – The inclusion of permeable reinforcements can stop the development of flow configurations with destabilising seepage forces within the backfill.

The use of permeable reinforcement does not just address stability problems but can also have significant construction benefits, by helping in the compaction of the fill (Indraratna et al., 1991). With the benefits of permeable reinforcement understood it is also important to understand what permeable reinforcements are available and recommended. One particular type of permeable reinforcement is a nonwoven geotextile. Although a suitable nonwoven geotextile has good drainage characteristics, tests on the development of soil-reinforcement bond (Smith et al. 1979) show that nonwoven geotextiles do not have great strength or in-plane stiffness. The solution could be to combine existing materials to form a composite, for example a nonwoven geotextile with a geogrid.

3.7.3 Composite Material

The creation of a composite material that tackles both the drainage and reinforcement functions is considered a possible solution to designing with marginal fills. Heshmati (1993) studied the effects of combining a drainage material with a geogrid in clay soil. His work confirmed that the drainage and reinforcement functions were both as important as each other in producing a stable structure. However, Heshmati (1993) also found that the method in
which the drainage material was combined with a geogrid was vital, and that by simply placing a drainage material such as a nonwoven geotextile in combination with a geogrid would actually result in a loss of strength. Therefore, it was necessary for the drainage and reinforcement functions to be made integral and into one material. A new geosynthetic which matched the findings of Heshmati (1993) was produced (Figure 3.13).

Tests were carried out on this new geosynthetic material with confirmation of its performance made by Boardman (2000). Boardman carried out both pore water pressure tests and pull out tests to confirm that the material would sufficiently serve both functions. Another key thing noted in the testing was that no clogging of the drain was experienced, even when using fine-grained London Clay. There are however, arguments to suggest that the use of a composite material would be unnecessary in most situations. The conclusions made by Dobie (2010) suggest that in many cases high excess pore water pressure is not generated, rather the reinforced structure is in a state of suction, or negative pore water pressure. Therefore an impermeable reinforcement such as woven geogrid would suffice. For further details please refer to Paper 1 (Appendix A).

![Figure 3.13 Geosynthetic material with integrated reinforcement and drain (Rowe and Jones, 2000)](image)

### 3.7.4 Case Studies

Mitchell and Zornberg (1995) describe a number of case studies carried out where permeable reinforcements are combined with marginal fills. One example is of an experimental
embankment that was constructed in Rouen which delivered information on the combined mechanical and hydraulic functions of permeable geotextiles (Perrier et al., 1986). The test structure was 5.6m high and constructed with a marginal (silt) backfill comprising a water content 5% wet of optimum. The embankment was split into four different sections, three of which were reinforced with various types of woven geotextiles and one section was reinforced with a composite nonwoven attached to a geogrid. The pore water pressures were measured over a set period of time and displayed in Figure 3.14. The results showed that pore water pressures along the composite geotextile were far lower than those experienced along the woven geotextiles. The lack of drainage provided by the woven geotextiles ultimately affected the stability of the structure with anchorage failure witnessed in a close-by test section. This experimental work helped to highlight the success of a composite material in providing both drainage and reinforcement functions. Studies by Barrows et al. (1994), Tatsuoka and Yamuchi (1986) and Tatsuoka et.al, (1990) have also successful trialled the use of permeable reinforcement in combination with marginal fills.
3.7.5 **SERVICEABILITY AND ULTIMATE LIMIT STATE DESIGN**

One of the biggest problems associated with the use of marginal fills is their anticipated increase in horizontal and vertical deformations, both during and after the construction phase. Christopher and Stulgis (2005) highlight several issues that may arise from increased deformation and need to be tackled in the design:

- Maintaining wall alignment during and after construction
- The possible deformation of supported structures
- Down drag on the back of facing units and connections
- Increased risk of tension cracks
It is very difficult to predict the level and amount of deformation even for structures with good quality backfill (Scotland et al., 2012), so with marginal ‘high fines’ backfill the situation is not clearer. Mitchell and Zornberg (1995) explain that horizontal displacement depends on a number of different factors which include compaction efforts, reinforcement and facing properties. However, as mentioned previously the deformation of a reinforced structure is related to the drainage characteristics of the marginal backfill being employed. With the use of a permeable geosynthetic this drainage issue could be addressed resulting in much smaller, acceptable deformations.

It is essential to consider, the application of the structure when designing for deformation. This brings in the issue of ultimate and serviceability limit states. Certain applications such as a highway embankment that is not supporting any structure may have a higher serviceability limit state, hence higher than normal deformations may not be a concern. In cases such as these an impermeable reinforcement such as a geogrid could be employed as long as the pore water pressures were monitored during construction. This means that deformation may occur due to water ingress from rain, however, they may only be large enough to reach the serviceability limit state. When designing reinforced structures to the ultimate limit state, the use of marginal fills for certain applications is prohibited by some standards, thus preventing the most appropriate use of marginal fills. Dealing with each application on individual basis will allow more designs to be carried out with serviceability limit state in mind, in particular those applications where high deformations may not be critical or lead to failure.

3.7.6 **Design Documentation – British Standards**

On an international level there is a range of different guidelines and standards employed in the design of reinforced soil structures. In order to fully understand the use of marginal fills and the concerns that exist with their usage, it is important to assess the relevant guidance in
currently available standards. In the UK it is the BS 8006 (2010) code of practice for strengthened / reinforced soils and other fills that is referred to for guidance.

BS 8006 (2010) goes in to a lot of detail into the design methods for reinforced structures as well as the testing procedures and stability checks, providing detailed guidance notes for an experienced user or designer. It is more than adequate for a designer/engineer using standard fills and working on a common application. However, when considering marginal fills, Paper 1 (Appendix A) explains how there is a lack of clarity and uncertainty with regards to their use. This is coupled with certain clauses which could be perceived to be prohibiting the use of marginal fills. There is a need for clearer, more specific guidance on the use of marginal fills with geosynthetic reinforcement. Paper 1 (Appendix A) presents some recommendations on how the ambiguity in BS 8006 (2010) can be addressed, allowing designers to utilise marginal fills most appropriately.

3.8 CONCLUSION

The UK government is working collaboratively with the construction industry to drive sustainable construction. They have produced frameworks (IGT, 2010) and targets implanted through visions such as Construction 2025 (BIS, 2013). However, targets such as those to reduce CO₂ emissions from construction, currently lack clarity on how they will be achieved. Aside from government targets, the increased insistence of clients for ratings of ‘excellent’ on environmental assessments of construction projects such as CEEQUAL and BREEAM is also acting as a driver for sustainable construction solutions.

The need to identify the CO₂ savings possible from construction projects and techniques has led to the development of construction specific methodologies and tools such as the Environment Agency carbon calculator (EA, 2012). This also includes the development of standards such as PAS 2050 (BSI, 2011a) which allow a common basis for understanding the
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life cycle GHG emissions of goods and services. The accuracy of the CO$_2$ results produced is dependent on the use of reliable EC data. Databases such as the ICE (Hammond and Jones, 2008a) and EcoInvent (EcoInvent Centre, 2010) are commonly employed as a source of EC data in UK and Europe. However, neither database has specific EC values for geosynthetics. Therefore substituted values for plastics such as PP and PE are often used to represent geosynthetics in CO$_2$ studies. The use of these values may be over or underestimating the total CO$_2$ emissions produced.

The sustainable benefits of geosynthetics over non-geosynthetic solutions are highlighted in the studies by WRAP (2010) and EAGM (Stucki et al., 2011). However, there is still a lack of guidance on CO$_2$ footprinting of geosynthetic solutions in comparison to non-geosynthetic solutions. There is a need for an industry specific CO$_2$ footprinting methodology that is demonstrated on a range of applications to provide a comparison against non-geosynthetic solutions.

The use of site-won or marginal fills is an example of one of the most sustainable uses of geosynthetics. However, the poor drainage characteristics of a marginal fill provided the biggest hindrance to its usage. One way of overcoming this problem is by including a permeable reinforcement which proved successful in a number of case studies, both in test and permanent environments. There is also a needed for clearer design guidelines as review of BS 8006 (2010) highlighted a lack of clarity on the use of marginal fills.

Overall the literature review has helped to identify how the construction industry recognises the need to move towards sustainable construction, in order to take advantage of the growth in the ‘green’ construction market. Solutions such as geosynthetics have demonstrated CO$_2$ savings, however, there is still a dearth of publications that compare these CO$_2$ benefits with non-geosynthetic solutions commonly perceived as ‘traditional’. A clear CO$_2$ calculation
framework with first-hand EC data would help to identify where geosynthetic solutions would be at their most appropriate sustainable use. The literature review has identified the need for:

- Clearer government or industry backed CO₂ targets aimed at the construction phase of a project
- Clearly defined framework or methodology for comparing CO₂ emissions between geosynthetic and non-geosynthetic solutions
- Case studies demonstrating CO₂ methodology for different functions of geosynthetics to include construction related CO₂ emissions
- EC data for different types of geosynthetics
- Research into the types of reinforcement that could be used in combination with marginal fills
- Clearer design guidance on the applicability of marginal fills.
4 RESEARCH METHODOLOGY

4.1 INTRODUCTION

This chapter provides details of the research methodology employed and briefly discusses some of the specific research methods used to achieve the objectives. It details how the four main objectives (Section 1.2) are aligned to the different methods and tasks employed in the research. The research map (Figure 1.3) outlines how each objective is achieved and the research outputs. Further details of the methodologies employed in specific tasks are provided in the Papers included from Appendix A to E.

4.2 OVERVIEW

There are three common research techniques that are employed; quantitative, qualitative and mixed method (Williams, 2007). The technique employed is based on the research needs and in anticipation of the type of data required to meet the needs of the research, whether this is numerical (quantitative), textural (qualitative) or a mixture of both data sets (mixed method). Based on an initial assessment one of the three research techniques is selected:

- Quantitative research involves a numerical or statistical approach to research design (Williams, 2007). It is ‘objective’ in nature and creates meaning through impartiality uncovered in the collected data. It begins with a problem statement and involves the formation of a hypothesis, a literature review, and a quantitative data analysis (Williams, 2007).

- Qualitative research is a holistic approach that involves discovery (Williams, 2007). It is ‘subjective’ in nature, with an emphasis on experiences and description (Naoum, 1998). Also described as an effective model that occurs in a natural setting which allows the researcher to develop a level of detail from high involvement in the actual experiences (Creswell, 2003).
• Mixed method research involves a mixture of both quantitative and qualitative techniques. It allows researchers to collect and analyse numerical and narrative data from both techniques and incorporate it into one study (Tashakkori and Teddlie, 2003).

This EngD study employed a mixed method. In the main the research follows a quantitative technique, with the data analysis carried out in Objectives 2, 3 and 4. However, there are elements of the research that require qualitative techniques. The literature review as part of Objective 1 requires a qualitative approach in identifying and understanding the drivers to sustainable construction as well as the use of geosynthetics. Moreover, the survey of Chapter Sponsors (Chapter 2) as part of Objective 1, presented qualitative findings that helped provide a basis for the literature review. The formation of case studies (Objective 3) reported in EngD Papers 2, 3 and 4 (Appendix B, C and D) also have a component of qualitative research.

4.3 METHODOLOGY CONSIDERATIONS AND RESEARCH TASKS

The research process requires collection, examination and interpretation of data in order to understand a phenomenon (Leedy & Ormrod, 2001). It is systematic in approach where an objective is defined, data managed and the findings disseminated all occur through established frameworks (Williams, 2007). The frameworks and guidelines help to shape the research and allow the progress and effectiveness of the research to be measured. As part of this research, the framework involved four main objectives (Section 1.2) which were broken down into a series of research tasks. Table 4.1 provides a breakdown of the research tasks and methods as well as outputs in the form of published papers.
## Table 4.1 Research programme

<table>
<thead>
<tr>
<th>Objective Number</th>
<th>Methodology</th>
<th>Research Task/ Areas</th>
<th>Paper Output</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Survey</td>
<td>Drivers and barriers to the application of geosynthetics</td>
<td>Raja et al. (2011)</td>
</tr>
<tr>
<td></td>
<td>Literature Review</td>
<td>Geosynthetics and their applications</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Literature Review</td>
<td>Drivers for Sustainable Construction</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Literature Review</td>
<td>LCA, CO₂ footprinting and environmental impact indicators employed in the construction and geosynthetics industry</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Literature Review</td>
<td>Sustainable benefits of geosynthetics</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Literature Review</td>
<td>Importance of accurate embodied carbon data</td>
<td>EngD Paper 5 (Appendix E)</td>
</tr>
<tr>
<td></td>
<td>Literature Review</td>
<td>Limitations to designing with marginal fills.</td>
<td>EngD Paper 1 (Appendix A)</td>
</tr>
<tr>
<td>2</td>
<td>Numerical Analysis</td>
<td>Testing and comparison of CO₂ footprinting tools, methods and embodied carbon data</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Numerical Analysis</td>
<td>CO₂ comparison study in drainage application</td>
<td>EngD Paper 2 (Appendix B)</td>
</tr>
<tr>
<td></td>
<td>Numerical Analysis</td>
<td>CO₂ comparison study in containment application</td>
<td>EngD Paper 3 (Appendix C)</td>
</tr>
<tr>
<td></td>
<td>Numerical Analysis</td>
<td>CO₂ comparison study in reinforcement application</td>
<td>EngD Paper 4 (Appendix D)</td>
</tr>
<tr>
<td></td>
<td>Numerical Analysis</td>
<td>Total CO₂ footprint for containment case study</td>
<td>-</td>
</tr>
<tr>
<td>4</td>
<td>Survey</td>
<td>Sourcing of embodied carbon data</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Experimental Research</td>
<td>Field measurements of embodied carbon data</td>
<td>EngD Paper 5 (Appendix E)</td>
</tr>
<tr>
<td></td>
<td>Numerical Analysis</td>
<td>Producing an embodied carbon value geosynthetics</td>
<td>EngD Paper 5 (Appendix E)</td>
</tr>
</tbody>
</table>
The individual research tasks were achieved by selection of appropriate research methods such as surveys, literature review as well as numerical analysis and experimental work. The research method employed was dependant on the nature and type of research being carried out i.e. quantitative, qualitative or mixed (Section 4.2). An example would be the quantitative research required in Objective 3 (Section 4.3.3), where the development of CO$_2$ case studies required a mathematical approach. Therefore, numerical analysis was the most appropriate research method. It is important to note however, the context in which the term numerical analysis is being applied. In the scope of this research it is being used to describe any numerical methods, calculations and data analysis.

The research map (Figure 1.3) illustrates how the objectives and tasks interact with each other and demonstrates the information flow, developments and outputs. Phase 1 covers the initial survey (Chapter 2) and the literature review aspects of the research, which combined fulfil the requirements of objective 1. Phase 2 covers the research undertaken (Objectives 2, 3 and 4).

4.3.1 SUSTAINABLE CONSTRUCTION AND THE BENEFITS ACHIEVED THROUGH USE OF GEOSYNTHETICS

The first objective was to develop an understanding into sustainable construction with the use of geosynthetics. The methodology devised to meet this objective was in the form of a survey (Chapter 2) and a literature review (Chapter 3). Details of the survey methodology are provided in Section 2.2 and by Raja et al. (2011). The findings of the survey provided a basis for the literature review, which is an important aspect of any research project regardless of the type (Creswell, 2009). It gave an important opportunity to review and reflect on previous work and research that had been carried out within the subject domain of this EngD. The literature reviewed ranged from government sponsored reports and initiatives to academic papers. It highlighted the current state of play and identified the gap in the research which this
EngD is striving to fill. The key focus areas of the review in order to meet the requirements of the objective were as follows:

- Drivers to sustainable construction in the UK
- CO₂ footprinting tools, data and methodologies employed
- The CO₂ and environmental benefits of employing geosynthetic solutions
- Barriers to the use of marginal fills with geosynthetics

### 4.3.2 Evaluation of CO₂ Calculation Tools and Methodologies in the Geosynthetic Industry

Objective 2 of the study looked at the reliability of CO₂ calculations in the geosynthetic industry. There is no agreed upon calculation tool or methodology provided for geosynthetic solutions, opening up the possibility for variability in results produced. This part of the study employed a numerical analysis research method to compare two possible methodologies that could be employed on geosynthetic solutions to calculate their CO₂ emissions. One of these methodologies is that demonstrated by WRAP (2010) on their cases studies (Section 3.6.2). This is compared to the EA (2012) construction carbon calculator (Section 3.4.5.1) which is applicable to most construction projects and techniques. There is an obvious difference in form with the WRAP carrying out the calculations by hand and the EA as a software based tool, however, essentially they are both targeting to provide the same end result. Each method has its benefits but the overall aim was to investigate whether there are any variances in the results between them.

The methodology for this numerical analysis involved the use of the EA carbon calculator and data from a sample case study (Table 4.2): Modular Block Wall, Mansfield Community Hospital (WRAP, 2010). The analysis used the EA carbon calculator to calculate the CO₂ emissions that would be produced from the geosynthetic and non-geosynthetic solutions and
compare those with the results already identified by WRAP. This was carried out by breaking the analysis into two tests; each test had varying input data (Table 4.3). The WRAP report uses EC values from an older version of the ICE database (Hammond and Jones, 2008a), whereas the EA calculator uses the latest set of data version 2.0 (Hammond and Jones, 2011).

The overall aim of the analysis was to identify any variances and review the two methods to help develop a methodology for use in Objective 3 of the research (Section 5.3). It also helped to highlight any differences due to modernisation of the input EC data.

**Table 4.2 Case Study data employed by WRAP (2010)**

<table>
<thead>
<tr>
<th>Product</th>
<th>Mass (tonnes)</th>
<th>Embodied Carbon (tCO$_2$e/t)</th>
<th>Total Embodied Carbon (tCO$_2$e)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Concrete for retaining wall</td>
<td>306.07</td>
<td>Concrete RC35</td>
<td>73.76</td>
</tr>
<tr>
<td>Rebar</td>
<td>8.19</td>
<td>Steel rods (Virgin)</td>
<td>21.95</td>
</tr>
<tr>
<td>Footer concrete</td>
<td>19.12</td>
<td>Concrete RC20</td>
<td>2.49</td>
</tr>
<tr>
<td>Tensar 40RE</td>
<td>0.50</td>
<td>HDPE</td>
<td>0.80</td>
</tr>
<tr>
<td>Tensar TW1 blocks</td>
<td>81.18</td>
<td>Concrete RC40</td>
<td>13.72</td>
</tr>
<tr>
<td>Granular fill</td>
<td>507.46</td>
<td>Aggregate</td>
<td>2.54</td>
</tr>
<tr>
<td>Facing Bricks</td>
<td>45.79</td>
<td>Concrete</td>
<td>23.81</td>
</tr>
</tbody>
</table>

**Table 4.3 Summary of methodology employed in Tests 1 and 2**

<table>
<thead>
<tr>
<th>Test No</th>
<th>1</th>
<th>2</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tool/Methodology Employed</td>
<td>EA calculator</td>
<td>EA calculator</td>
<td>Data input into EA calculator in both tests.</td>
</tr>
<tr>
<td>Project Information</td>
<td>WRAP</td>
<td>WRAP</td>
<td>See Table 4.2</td>
</tr>
<tr>
<td>Embodied carbon data</td>
<td>EA integrated data (v2.0 ICE database)</td>
<td>WRAP (v1.6 ICE Database)</td>
<td>Test 2 employed data from WRAP into the EA calculator</td>
</tr>
<tr>
<td>Transport emissions calculation</td>
<td>EA calculator</td>
<td>EA calculator</td>
<td>Similarity in transport emissions calculated by EA and WRAP, hence for both the tests the EA calculator was employed</td>
</tr>
<tr>
<td>Solutions covered</td>
<td>Geosynthetic and Non-geosynthetic</td>
<td>Geosynthetic and Non-geosynthetic</td>
<td>Tests carried out on both solutions, producing 4 sets of results.</td>
</tr>
</tbody>
</table>
4.3.3 **Comparison of CO$_2$ Emissions between Geosynthetic and Non-Geosynthetic Solutions**

Objective 3 of the study looked at producing case studies that compare the CO$_2$ emissions between geosynthetics and non-geosynthetic solutions. These case studies extended and built on the work carried out by WRAP (2010). The WRAP (2010) studies focused on the function of reinforcement (Section 3.6.2) and whilst clear and easy to follow, they were not exhaustive on their coverage of calculation methods or potential construction applications. The case studies produced as part of this EngD research and objective 3 address these issues, with a total of three case studies produced covering the functions of containment, drainage and reinforcement. Further work was carried out on the containment case study to calculate a total CO$_2$ footprint in accordance with PAS 2050 (BSI, 2011a) and reported in Section 5.3.6.

The research map (Figure 1.3) highlights how the individual objectives interacted to shape the methodology employed in objective 3 and more specifically, in producing the case studies. Papers 2, 3 and 4 (Appendix B-D) report these case studies and demonstrate the rigorous methodology employed. All three case studies follow the same calculation methodology based on the CO$_2$ comparison framework developed (Section 5.3.2). However, they do vary in scope with case studies 1 and 2 (Papers 2 and 3) employing LCA boundaries of cradle to end of construction and case study 3 (Paper 4) working to LCA boundaries of cradle to site. The change in LCA scope is explained in Section 5.3.1 and Paper 4 (Appendix D). Other minor variations between the case studies include any extended analysis carried out such as the inclusion of a sensitivity analysis in the containment case study reported in EngD Paper 3 (Appendix C). The overall aim of the case studies was to demonstrate in detail:

- The use of a rigorous framework to compare CO$_2$ emissions between geosynthetic and non-geosynthetic solutions
- A clear, precise and accurate CO$_2$ calculation methodology
• The use and importance of embodied carbon data

• Comparison of construction CO\textsubscript{2} emissions

• Applications where geosynthetics may be at their ‘most appropriate’ sustainable use

4.3.4 **EMBODIED CARBON DATA FOR GEOSYNTHETICS**

Objective 4 and the final research objective, was to produce EC data for geosynthetics. The absence of EC data for geosynthetics in commonly employed databases was identified as a big gap in the knowledge and research. Therefore, in order to fill this gap a mixture of research methods were employed. These included a survey, experimental work and numerical analysis, which all contributed to producing EC data for four different types of geosynthetic.

Initial contact was made with UK Chapter Sponsors by way of a survey, in addition to the survey discussed in Section 2. The survey accompanied by a covering letter and project details (Appendix F) sought to understand what EE/EC data manufacturers had available and if they would contribute it to this study. However, due to competition between the manufacturers fears regarding confidentiality of the data were relayed to the author. This resulted in no completed survey being returned. However, the survey helped to initiate communication with four different manufacturers who were willing to contribute to the study. Measurements of EE/EC were derived for products from these four manufacturers. The details of the calculations and analyses used are documented in detail in Paper 5 (Appendix E). The geosynthetics studied are summarised in Table 4.4.
Table 4.4 Geosynthetics covered in the EC study

<table>
<thead>
<tr>
<th>Manufacturer</th>
<th>Category</th>
<th>Type</th>
<th>Material</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Geotextile</td>
<td>Non-woven (Needle Punched)</td>
<td>Polypropylene</td>
</tr>
<tr>
<td>B</td>
<td>Geotextile</td>
<td>Non-Woven (Needle Punched/Thermally Bonded)</td>
<td>Polypropylene</td>
</tr>
<tr>
<td>C</td>
<td>Geogrid</td>
<td>Extruded</td>
<td>Polypropylene</td>
</tr>
<tr>
<td>D</td>
<td>Geogrid</td>
<td>Woven</td>
<td>Polyester</td>
</tr>
</tbody>
</table>

4.4 SUMMARY

This chapter has presented the research methodology and considerations employed in the EngD. Overall the research was quantitative in a nature but also employed some qualitative techniques in individual research tasks and areas. A brief overview of the research methods employed in each objective was provided. However, Papers 2 to 5 (Appendix B to E) provide a more detailed methodology with regards to specific research methods, such as the CO₂ case studies carried out as part of objective 3. The research methodology presented in this chapter supports the research undertaken which is presented in the next chapter.
5 RESEARCH UNDERTAKEN

5.1 INTRODUCTION

This chapter presents the research undertaken as part of the EngD programme. It summarises the fulfilled research objectives and tasks detailing the key aspects of the research undertaken. The three research objectives covered in this chapter include:

- To evaluate CO₂ calculation methods typically used in the geosynthetics industry (Objective 2)
- To compare CO₂ emissions between geosynthetic and non-geosynthetic solutions (Objective 3)
- To source embodied carbon data for specific types of geosynthetics (Objective 4)

The publication of research papers in appropriate conferences and journals is a key requirement of the EngD. These papers are included as appendices and provide further detail on the research tasks and results achieved. The research led to the publication of four conference papers and two journals, with EngD Papers 2 to 5 (Appendix B to E) most relevant to the research summarised within this chapter.

5.2 EVALUATION OF CO₂ CALCULATION TOOLS AND METHODOLOGIES IN THE GEOSYNTHETIC INDUSTRY

5.2.1 INTRODUCTION

Objective 2 of the research looked at comparing two CO₂ calculation methods that were most relevant to geosynthetic projects. The WRAP (2010) methodology and results were compared to the EA (2012) construction carbon calculator. The aim of this objective was to identify any variances and review the results between the two methods, to help develop a methodology that could then be employed in the case studies being produced in Objective 3 (Section 5.3).
The research methodology employed to fulfil this objective is described in Section 4.3.2. This section presents the results and key conclusions.

5.2.2 RESULTS

5.2.2.1 Test 1

Test 1 used all the project information from the WRAP (2010) case study, however, the EC data used for the materials was that which was already incorporated in the EA calculator. Table 5.1 shows the data employed compared to that employed by WRAP from Table 4.2.

<table>
<thead>
<tr>
<th>Product</th>
<th>Solution</th>
<th>Materials</th>
<th>Embodied Carbon – EA Calculator (tCO₂e/t)</th>
<th>Embodied Carbon - WRAP (tCO₂e/t)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Concrete for retaining wall</td>
<td>Non-geosynthetic</td>
<td>Concrete RC35</td>
<td>0.233</td>
<td>0.241</td>
</tr>
<tr>
<td>Rebar</td>
<td>Non-geosynthetic</td>
<td>Steel rods (Virgin)</td>
<td>2.77</td>
<td>2.68</td>
</tr>
<tr>
<td>Footer concrete</td>
<td>Geosynthetic</td>
<td>Concrete RC20</td>
<td>0.132</td>
<td>0.130</td>
</tr>
<tr>
<td>Tensar 40RE</td>
<td>Geosynthetic</td>
<td>HDPE</td>
<td>1.93</td>
<td>1.6</td>
</tr>
<tr>
<td>Tensar TW1 blocks</td>
<td>Geosynthetic</td>
<td>Concrete RC40</td>
<td>0.188</td>
<td>0.169</td>
</tr>
<tr>
<td>Granular fill</td>
<td>Non-geosynthetic</td>
<td>Aggregate</td>
<td>0.005</td>
<td>0.005</td>
</tr>
<tr>
<td>Facing Bricks</td>
<td>Geosynthetic</td>
<td>Concrete</td>
<td>0.54</td>
<td>0.52</td>
</tr>
</tbody>
</table>

One important point to note is that the data uploaded into the EA calculator originates from the latest Version 2.0 of the ICE database produced by the University of Bath (Hammond and Jones, 2011). The WRAP study was based on EC data from the older Version 1.6 of the ICE database (Hammond and Jones, 2008a). The calculator covers a wide range of materials and specification classes, however, in some instances values may need to be obtained directly from the ICE database.

The values shown in Table 5.1 were combined with the project information such as material quantities (Table 4.2) and transport distances (WRAP, 2010), to provide the total CO₂
emissions for the project. The results produced for both the geosynthetic and non-geosynthetic solutions are presented in Table 5.2

Table 5.2 Test 1 Results, total CO₂e emissions and percentage influence for both geosynthetic and non-geosynthetic solutions

<table>
<thead>
<tr>
<th>Source of CO₂</th>
<th>Non-geosynthetic Solution</th>
<th>Geosynthetic Solution</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>tCO₂e</td>
<td>%</td>
</tr>
<tr>
<td>Quarried Material</td>
<td>2.5</td>
<td>3%</td>
</tr>
<tr>
<td>Concrete, Mortars &amp; Cement</td>
<td>71.3</td>
<td>73%</td>
</tr>
<tr>
<td>Metals</td>
<td>22.7</td>
<td>23%</td>
</tr>
<tr>
<td>Plastics</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Waste Removal</td>
<td>0.6</td>
<td>1%</td>
</tr>
<tr>
<td>Material transport</td>
<td>0.7</td>
<td>1%</td>
</tr>
<tr>
<td>Total CO₂ (tCO₂)</td>
<td>97.8</td>
<td></td>
</tr>
</tbody>
</table>

5.2.2.2 Test 2
Test 2 was carried out in a similar manner to Test 1, however, in this case all the EC data input into the calculator was that which was originally used by WRAP (Table 5.1). Similar to Test 1, the analysis and carbon calculation was carried out for both non-geosynthetic and geosynthetic solutions. Therefore not only would the techniques and values be comparable, but also the different solutions. The results that were obtained are presented in Table 5.3 with a summary of the results from both tests in Table 5.4
Table 5.3 Test 2 Results, total CO\textsubscript{2}e emissions and percentage influence for both geosynthetic and non-geosynthetic solutions

<table>
<thead>
<tr>
<th>Source of CO\textsubscript{2}</th>
<th>Non-geosynthetic Solution</th>
<th>Geosynthetic Solution</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>tCO\textsubscript{2}e</td>
<td>%</td>
</tr>
<tr>
<td>Quarried Material</td>
<td>2.5</td>
<td>3</td>
</tr>
<tr>
<td>Concrete, Mortars &amp; Cement</td>
<td>73.7</td>
<td>74</td>
</tr>
<tr>
<td>Metals</td>
<td>21.9</td>
<td>22</td>
</tr>
<tr>
<td>Plastics</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Waste Removal</td>
<td>0.6</td>
<td>1</td>
</tr>
<tr>
<td>Material transport</td>
<td>0.7</td>
<td>1</td>
</tr>
<tr>
<td><strong>Total CO\textsubscript{2} (tCO\textsubscript{2}e)</strong></td>
<td><strong>99.5</strong></td>
<td></td>
</tr>
</tbody>
</table>

Table 5.4 Summary of results from Tests 1 and 2

<table>
<thead>
<tr>
<th>Solution</th>
<th>Test 1 (tCO\textsubscript{2}e)</th>
<th>Test 2 (tCO\textsubscript{2}e)</th>
<th>WRAP (tCO\textsubscript{2}e)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Non-geosynthetic</td>
<td>97.8</td>
<td>99.5</td>
<td>96.95</td>
</tr>
<tr>
<td>Geosynthetic</td>
<td>46.1</td>
<td>43.4</td>
<td>42.64</td>
</tr>
</tbody>
</table>

5.2.3 FINDINGS AND CONCLUSIONS

Overall the tests carried out proved to be very successful in highlighting the sources of errors in CO\textsubscript{2} calculation methods. They provided a useful experience in handling such tools as well as how to use them accordingly. The main aim of the testing and analysis carried out was to provide insight into the calculation methods, and help to provide a basis for the case studies carried out (Section 5.3) and identify a clear accurate methodology (Figure 5.1). This aim was clearly fulfilled, with a number of key conclusions made.

The results of the tests showed that even though there was newer data employed and a different calculation tool, the geosynthetic solution was still far more sustainable than the non-geosynthetic solution. This helps to validate the work carried out by WRAP (2010) and
boost the sustainable credentials of geosynthetics. Test 1 results had very small differences when compare to the WRAP results. This helped to highlight two main points:

- The EA calculator and the WRAP calculations have very little difference between them.
- Small differences were due to the variation in input data, hence the results can be explained.

Test 2 provided some interesting results which on stand-alone basis when compared to the WRAP results would have been acceptable, with only small differences in the total CO$_2$ emissions. However, with the results from Test 1 showing that the EA calculator and WRAP calculations are in agreement, the results from Test 2 should have had a smaller difference with the WRAP results than those of Test 1. Investigation of the WRAP calculations highlighted some basic numerical errors. Factorising in these errors and by employing the correct data, the results of Test 2 would have produced a reduced difference and comparable results to those by WRAP.

The analysis and calculations carried out highlighted the importance of EC data in the carbon footprinting process. The methods and tools themselves had very little difference and the actual source of variance existed in the EC data itself. Therefore to improve footprinting calculations there is a need for more reliable data, which could be sourced directly from manufacturers. It is important that not only does the data need to be more reliable but the selection procedure needs to be detailed and consistent. Often the values used by WRAP were representative and general of the material class, hence a lack of detail. Therefore when compared to calculations that sourced their data in greater detail, there will be obvious differences and variances in the results. Hence there is a need for accurate, reliable EC data which is sourced in a consistent and detailed manner.
5.3 COMPARISON OF CO₂ EMISSIONS BETWEEN GEOSYNTHETIC AND NON-GEOSYNTHETIC SOLUTIONS

5.3.1 INTRODUCTION
Objective 3 of the research looked at demonstrating the CO₂ benefits of geosynthetic solutions. This was achieved by way of case studies, which highlighted applications where geosynthetics may provide CO₂ savings as compared to non-geosynthetic solutions. They presented a clear detailed methodology that could also be followed on similar applications. In total three cases studies were carried out covering the functions of drainage, containment and reinforcement. Life cycle boundaries of cradle to end of construction were set. Except however, in Case Study 3 where construction emissions were assumed negligible further details of which are provided in Section 5.3.5 and Paper 4 (Appendix D). In the addition to the three comparative case studies, a total CO₂ footprint in accordance with PAS 2050 (BSI, 2011a) was also calculated for Case Study 2 (Section 5.3.6)

This section covers some of main results and discussion points, however, further details are provided in Papers 2, 3 and 4 (Appendix B, C and D). There has been a slight change of terminology as discussed in Section 2.2.3, with the Papers referring to ‘non-geosynthetic’ solutions as ‘traditional’ solutions.

5.3.2 CO₂ COMPARISON FRAMEWORK
In order to ensure the accuracy and impact of the case studies a CO₂ calculation framework was required. The framework would keep the methodology employed in calculating the CO₂ emissions consistent between the two solutions being compared. This would increase the validity and credibility of the results, ensuring like for like activities are being compared with respect to their CO₂ emissions being generated. The framework would also help to keep all three case studies comparable in methodology and scope with one another. The framework developed (Figure 5.1) was based on the findings of Objective 1 and the tests carried out in
Objective 2. It was established for the purpose of this research, however, considerations were made to keep it open to use on other CO₂ comparative studies.

**Figure 5.1 CO₂ calculation framework**
5.3.3 **CASE STUDY 1 - THE SUSTAINABLE USE OF GEOSYNTHETICS: LANDFILL DRAINAGE CASE STUDY**

5.3.3.1 **Introduction**
This case study is presented in Paper 2 (Appendix B). The study looked at the use of geosynthetics in a drainage application on a landfill project in South Wales. More specifically, it focused on the under cell drainage system, which is used to relieve groundwater pressure beneath the base of the landfill. Figure 1 from Paper 2 illustrates the landfill lining system layers, as well as the geocomposite under drainage layer design used in the project.

The case study compared the CO₂ emissions for three possible design solutions (Figure 5.2) for LCA boundary conditions of cradle to end of construction. The as-built design employing a geocomposite (GCD) layer was compared with two alternative solutions all of which employed some form of geosynthetics. However, the two alternative solutions also relied heavily on the use of imported granular fill. The client and designer involved with this project were directly consulted to source design details such as the materials used and how they were sourced.

![Figure 5.2 The original drainage layer employed (a) and two possible alternatives (b) and (c)](image)

5.3.3.2 **Results**
The final results were compiled by combining the CO₂ emissions from each of the three LCA stages covered in the study; EC, transport emissions and construction emissions. This presented a cradle to end of construction CO₂ comparison between the three solutions. The results showed that the GCD is more sustainable than continuous gravel solution (Table 5.5). The 30 tCO₂ difference
between the two solutions is a considerable amount as it means the GCD solution only produces about a quarter of the CO\textsubscript{2} emissions that the continuous gravel solution would have produced. The GCD solution does have a slight advantage by having negligible construction emissions; however, the major difference is in the EC of the materials and in the transport of the large quantities of gravel.

In this particular project the Environment Agency (EA) had insisted on a continuous solution, therefore, only the continuous gravel solution (b) would have been considered as a possible alternative to the as-built geocomposite solution (a). However, if this requirement was not in place the gravel trench solution also proves to be more sustainable than the continuous gravel layer. In fact it could be as sustainable as the GCD solution, which makes it a credible alternative if there are no specific design requirements to discount it as a viable option.

The comparison does show that for all three solutions the construction emissions have little effect on the overall results. The majority of emissions are generated in the EC and transport stages of the LCA. A small increase or decrease in transport distances of bulk materials such as gravel can have significant impact on CO\textsubscript{2} emissions.

**Table 5.5 Summary of overall results**

<table>
<thead>
<tr>
<th>Solution</th>
<th>Transport</th>
<th>Embodied</th>
<th>Construction</th>
<th>Total (tCO\textsubscript{2})</th>
</tr>
</thead>
<tbody>
<tr>
<td>Geocomposite (GCD)</td>
<td>0.65</td>
<td>10.27</td>
<td>-</td>
<td>10.91</td>
</tr>
<tr>
<td>Continuous Gravel</td>
<td>11.92</td>
<td>25.65</td>
<td>3.04</td>
<td>40.61</td>
</tr>
<tr>
<td>Gravel Trench</td>
<td>3.38</td>
<td>6.15</td>
<td>1.07</td>
<td>10.60</td>
</tr>
</tbody>
</table>

Note: Polypropylene (Oriented Film) EC value of 3.43 tCO\textsubscript{2}/t employed for PP geotextile and GCD. HDPE EC value of 1.93 tCO\textsubscript{2}/t employed for HDPE core in GCD. See Paper 2, Table 2 (Appendix B).

**5.3.3.3 Conclusions**

The original GCD design employed in the project was found to be more sustainable than the continuous gravel alternative. The major difference between the two solutions was the CO\textsubscript{2} emissions produced at both the embodied and transport stages. The results also indicate that the gravel trench solution would be very similar to the GCD in terms of CO\textsubscript{2} emissions, and
more sustainable than the continuous gravel. Therefore, in projects without the requirement of continuous layer it would also be a sustainable solution.

The cradle to end of construction LCA approach detailed as part of this study and in Paper 2 (Appendix B) can be used to compare the CO₂ emissions of geotechnical design options, with and without geosynthetic elements. In this particular study all three solutions compared, employed some form of geosynthetics albeit of various properties and quantities. The inclusion of construction emissions highlights that although not large compared to embodied and transport emissions, it should still be taken into consideration in any CO₂ comparative study. The use of accurate EC data is important in verifying any results produced and there is a need for the geosynthetic industry to produce more product specific data.

5.3.4 Case Study 2- Comparison of CO₂ Emissions for Two Landfill Capping Layers

5.3.4.1 Introduction
This case study is presented in Paper 3 (Appendix C). The case study was based on a landfill site situated in the south-east of England. The study focused on capping of one landfill cell, which covered an area of 9572m², and compared the CO₂ emissions produced by the actual geosynthetic based design employed and an alternative clay design (Figure 5.3). Design details were sourced directly from the clients, designers and contractors involved in the project. The site was selected as both clay and geosynthetic solutions had been used to cap different landfill phases over the life of the site, thus, the clay solution was a credible alternative.
The LCA boundary conditions employed for the study were of cradle to end of construction, coherent to case study 1 (Section 5.3.3) and also as stated in the research methodology (Chapter 4). Therefore the comparison of CO₂ emissions calculated included the EC, transport of the materials and construction related emissions.

The results obtained from the CO₂ comparison provided a basis for an analysis on the EC value for clay. A first-hand EC value for clay was calculated and then employed in a sensitivity analysis to understand what impact it would have on the CO₂ comparison results. Details of this analysis are provided in Paper 3 (Appendix C) and summarised in Section 5.3.4.3

5.3.4.2 Results
The results showed that the geosynthetic solution produced significantly lower CO₂ emissions than if an alternative clay solution had been employed. In both solutions the EC contributes the most towards the overall CO₂ emissions, although construction and transport phases also
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make a significant contribution and highlight the need for the inclusion of the construction phase in LCA studies. Table 5.6 provides a summary of the results from each phase and the combined total CO₂ emissions.

**Table 5.6 Summary of results**

<table>
<thead>
<tr>
<th>Solution</th>
<th>Transport</th>
<th>Embodied</th>
<th>Construction</th>
<th>Total (tCO₂)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clay</td>
<td>5.24</td>
<td>95.72</td>
<td>10.40</td>
<td>111.37</td>
</tr>
<tr>
<td>Geosynthetic</td>
<td>1.09</td>
<td>29.20</td>
<td>1.92</td>
<td>32.20</td>
</tr>
</tbody>
</table>

Note: EC values for LLDPE of 2.08 tCO₂e/t and Polypropylene (orientated film) of 3.43 tCO₂e/t employed for geomembrane and geotextile respectively. See Paper, Table 2(Appendix C)

The contribution of both the construction and transport related emissions is higher in the clay solution than in the geomembrane solution. This result was expected as construction of the clay cap required significant compaction effort, and also a large mass of material transport would be required. The results help to demonstrate where the largest emissions are generated and show that the geosynthetic solution is more sustainable even if the clay for the cap was available on site (i.e. with no transport emissions). In this particular case study the clay was sourced from a location close to the site (3.5 km) although in many sites this could be a larger distance, hence the clay transport related emissions are low for this case study. The calculation of construction related emissions is important as it allows their contribution to the overall solution emissions to be understood, which in the clay solution was over 10 tCO₂.

The geosynthetic solution was the one employed in the actual design, and it was selected due to its cost and time benefits. However, this study shows that it was also the more sustainable solution and with the help of these findings, the client could promote the environmental benefits. The results could also help them in achieving better scores on ratings such as the CEEQUAL (2010) and also any Environmental Product Declarations (BSI, 2012).
5.3.4.3 Accuracy of EC value for Clay

The results from the comparative CO₂ study highlighted the biggest source of emissions in the traditional solution arose from the EC of the clay. The details of which are reported in Paper 3 (Appendix C) which also highlight the need for this analysis. The main aim was to calculate an EC value for the clay and compare it to the value employed in the case study from the ICE database (Hammond and Jones, 2011).

In order to calculate a comparable value it had to have the same LCA boundaries of those cradle to gate. To meet this criterion, the calculations included three key LCA stages; excavation, loading of road going vehicle and transport to site exit (Figure 5.4). The emissions generated for these processes were calculated using data provided by an earthworks contractor and are summarised in Table 9 of Paper 3 (Appendix C).

The calculated value of EC for the clay of 0.0003tCO₂e/t was considerably lower than the ICE database quarried aggregate value of 0.005 tCO₂e/t employed in the study as the most suitable alternative, in the absence of a specific EC value for clay. The difference in the values may be due to the ICE database value including processing, such as crushing and screening that are not relevant for clay. Therefore, although using database values such as for quarried aggregates may be convenient, the EC value calculated showed it may not be the most reliable approach thus highlighting the importance of attention to detail in LCA comparisons.

The use of the calculated EC of clay in the CO₂ analysis would reduce the CO₂ emissions of the clay solution by 90 tCO₂. Therefore this could potentially make the clay solution more sustainable than the geosynthetic solution. This analysis has shown that the ranking of design options in terms of CO₂ emissions can be dependent on the source and accuracy of material EC data. In this study, the geosynthetic solution is more sustainable if ICE database EC values are used for the clay but using calculated EC values for the clay reverses the ranking.
In certain cases when the clay is available on site or only has to be transported a short distance (such as in this case study), it may be both more economical and sustainable to employ the clay solution. A detailed summary on the sensitivity analysis and the results obtained is provided in Paper 3 (Appendix C).

![Figure 5.4 Process map for clay](image)

### 5.3.4.4 Conclusions
The original geosynthetic design for this case study site was found to be more sustainable than an alternative clay solution. This conclusion was based on EC data commonly employed in the UK. However, the value of EC of the clay compared to the construction and transport emissions was questionable.

In order to investigate the accuracy of the clay input values, further analysis of the EC of clay fill was carried out. The analysis involved calculating an EC value of clay directly from...
Research Undertaken

contractor data. The calculated value was considerably lower than the original value employed in the case study and also much lower than other quarried material values stated in the ICE database (Hammond and Jones, 2011). The use of this revised value in the case study had a major effect on the results, making the clay solution a more sustainable alternative.

In this particular case study the transport distance of the clay fill was very short, hence minimising the transport CO₂ emissions. However, many sites import clay from greater distances, and in these cases using geosynthetics to form the barrier layer will be a more sustainable solution.

The cradle to end of construction LCA approach detailed in this paper can be used to compare the sustainability (as defined in Section 3.2) of geotechnical design options, with and without geosynthetic elements. The need for accurate input data such as the EC values is highlighted by the case study.

### 5.3.5 Case Study 3- Comparison of CO₂ Emissions for a Reinforced Soil and Concrete Retaining Structure

#### 5.3.5.1 Introduction

This case study is presented in Paper 4 (Appendix D). The study was based on a road alignment project in the south of Wales, where part of the project involved the construction of a geosynthetic reinforced soil structure. This as-built solution was compared in terms of CO₂ emissions with a non-geosynthetic concrete retaining wall solution (Figure 5.5).

The project details sourced from the designer for this case study did not include the non-geosynthetic design. Therefore a concrete retaining structure that was comparable to the geosynthetic solution was designed (Appendix G) as part of this study in accordance to Eurocode 2 (BSI, 2008a) and guidance sought from Mosley et al. (2007). The LCA boundary conditions to which the study was carried out also had to be altered to that of cradle to site due to a lack of construction details. Therefore unlike Case Study 1 (Section 5.3.3) and 2 (Section
5.3.4), construction emissions were not included. Inclusion of construction emissions would have been based on a number of assumptions which may have compromised the integrity of the study. Also the construction sequence highlighted that the majority of construction activities would be common to both solutions and any CO₂ emission produced would be small and negligible. This is also supported by the results from Case Study 1 and 2.

Paper 4 (Appendix D) presents a detailed methodology following the framework suggested in BS EN ISO 14040 (BSI, 2006) and reviews the key considerations and results produced from the CO₂ study. It also discusses the possibility of post-construction CO₂ savings from the geosynthetic solution due to its vegetated face. Therefore for a more comprehensive understanding of the case study Paper 4 (Appendix D) should be consulted. This section will focus on summarising the results obtained and some of the key conclusions drawn from the case study.

![Diagram](image)

**Figure 5.5** The as-built geosynthetic design solution employed (a) and (b) a possible non-geosynthetic alternative

### 5.3.5.2 Results

The results of the individual LCA phases were combined to give an overall CO₂ comparison between the two solutions. The comparison showed that the geosynthetic solution was more sustainable than the alternative reinforced concrete wall solution. The geosynthetic solution
produced 16.2 tCO₂ compared to the 42.2 tCO₂ produced by the concrete solution (Figure 5.6). The biggest difference between the two solutions arises in the EC of the materials, with the concrete solution producing almost 30 tCO₂ more than the geosynthetic solution.

The transport of the materials in the concrete solution produced only 0.2 tCO₂ and had minimal impact on the overall results. In the geosynthetic solution the transport of materials produced 3.8 tCO₂ which is much higher than that produced in the concrete solution. It accounted for nearly a quarter of the overall CO₂ emissions for the geosynthetic solution and was predominantly due to the transport of granular fill which accounted for almost 2.7 tCO₂.

The results obtained show that although the geosynthetic solution may have been selected on preference of cost and aesthetics, but it was also the more sustainable solution. The study presented a worst-case scenario for the geosynthetics and assumed the concrete wall solution would re-use the onsite fill. In some instances, fill would also have been imported for the concrete wall solution dependant on the geometry, length of wall, site conditions and soil parameters. Further details of this and other key assumptions are provided in Paper 4 (Appendix D).
5.3.5.3 Conclusions

The case study presented a CO\textsubscript{2} comparison between a geosynthetic reinforced retaining slope and a reinforced concrete wall solution. The results of the carbon footprint analysis showed that the geosynthetic solution produced 60\% lower CO\textsubscript{2} emissions in comparison to the concrete solution. The biggest source of difference was in the EC of the materials with transport related emissions appearing small in comparison. However, in the geosynthetic solution it still accounted for a quarter of the overall CO\textsubscript{2} emissions. Therefore, even for a project of this size the import of fill can have a significant impact on the overall CO\textsubscript{2} emissions and emphasises the sustainable benefits of re-using material, and reducing transport of material on and off site.

The case study was carried out to LCA boundary conditions of cradle to site therefore not including emissions from the construction phase. However, inspection of the construction methods revealed that the majority of techniques and processes would have produced very small if any CO\textsubscript{2} emissions, as well as some of them being common to both solutions.
Therefore the extension of the study to cradle of end of construction would have had very little impact on the overall results.

The vegetated geosynthetic solution not only provided an aesthetic advantage but could continue to reduce CO₂ emissions in the ‘life’ phase of the structure. Carbon fixation in vegetation through photosynthesis absorbs CO₂ from the atmosphere. Therefore, the use of a vegetated structure would continue to provide CO₂ savings in comparison to the concrete solution.

5.3.6 TOTAL CO₂ FOOTPRINT OF GEOSYNTHETIC SOLUTION- CASE STUDY 2

5.3.6.1 Introduction

The case studies (Section 5.3.3-5.3.5) provided comparative CO₂ footprints excluding processes/emissions common to both geosynthetic and non-geosynthetic solutions. To demonstrate the difference in total and comparative CO₂ emissions, a total CO₂ footprint was calculated for both the geosynthetic and clay solutions compared in case study 2. The LCA scope of cradle to end-of construction was employed to maintain consistency with the case study (Section 5.3.4), whilst it was also ensured that the calculations conformed to PAS2050 standards. Details of the case study and design solutions are provided in Section 5.3.4 and Paper 3 (Appendix C) respectively.

5.3.6.2 Method

The overall CO2 footprinting methodology employed was that provided by BSI (2011b) to compliment and conform to the PAS2050 standards and comprised of four key stages; scoping, data collection, footprinting calculations and interpretation (Section 3.4.4).

The scoping and data collection had been carried out as part of the original case study reported in Section 5.3.4 and Paper 3 (Appendix C) respectively. The overall scope remained the same with the calculations being carried out to a system boundary of “cradle to end of construction” (Paper 3, Appendix C). However, with this study reporting total CO₂ emissions,
materials and processes that were excluded from the original case study due to being common to both solutions, were also included. A process map (Figure 5.7) was developed to indicate the processes that need to be included in the carbon footprint and those that could be excluded in accordance to PAS 2050 (BSI, 2011a). The key exclusions and their justification are provided in Table 5.7. The overall process map is complimented with the individual process maps for the clay (Figure 5.4) and geotextile (Figure 5.10) for which first-hand EC values were calculated. Although first-hand EC values for the sand and geomembrane were not calculated a flow chart of processes that should be considered within a cradle to gate analysis has been provided in Figure 5.8
Figure 5.7: Process map and system boundary
Table 5.7 Key exclusions from the carbon footprinting assessment

<table>
<thead>
<tr>
<th>Assumption</th>
<th>Justification</th>
<th>PAS2050 Clause</th>
</tr>
</thead>
<tbody>
<tr>
<td>Utilities will account for less than 1% of the total carbon footprint,</td>
<td>• Permanent site office/accommodation in place for the larger project and management of the landfill site.</td>
<td>Clause 6.3 allows flows anticipated to contribute less than 1 percent of the total footprint can be excluded from the system boundary of the carbon footprint, provided that at least 95 per cent of the total anticipated emissions are included.</td>
</tr>
<tr>
<td>hence excluded from the total carbon footprint.</td>
<td>• Use of Grid electricity which produces lower CO₂ emissions than on-site electricity generation</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Water is a low intensity material (BSI, 2011b)</td>
<td></td>
</tr>
<tr>
<td>Mobilisation of plant will account for less than 1% of the total carbon</td>
<td>• Small number of, and locally sourced plant employed, hence low transport emissions.</td>
<td>Clause 6.3 allows flows anticipated to contribute less than 1 percent of the total footprint can be excluded from the system boundary of the carbon footprint, provided that at least 95 per cent of the total anticipated emissions are included.</td>
</tr>
<tr>
<td>footprint, hence excluded from the total carbon footprint.</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Note:
- General exclusions as part of the PAS2050 guidelines are outlined by BSI (2011b) and relate to Clauses 6.4.4 and 6.5 (BSI, 2011a) respectively.
- Although Utilities and Mobilisation were excluded from the overall carbon footprint, their CO₂ emissions were calculated to validate the assumption made above.

Figure 5.8 Simplified flow chart of processes for sand and geomembrane within a cradle to gate analysis
Prior to any CO₂ footprinting calculations, the initial scoping of the study also involved defining the functional unit. The original case study employed the total area of capping i.e. whole project, as the functional unit. However, by defining a functional unit that is more granular and not specific to a particular project allows it to be used as reference in other studies employing similar designs. Therefore, the functional unit was defined as the construction of 1m² of geosynthetic or clay capping.

The CO₂ calculation methodology employed was consistent to that of the case study (Paper 3, Appendix C). It was ensured that where feasible the same data sources and CO₂ emissions factors would be used. Section 5.3.6.3 provides further details of the CO₂ emissions calculated from each of the life cycle stages outlined in the process map (Figure 5.7)

5.3.6.3 Calculations
The calculations were carried out for the three main life cycle stages considered within the system boundary (Figure 5.7): Embodied Carbon, Transport and Construction. Emissions from both utilities and mobilisation were calculated for reference however assumed to be less than 1% of the overall CO₂ emissions hence excluded from overall the carbon footprint (Table 5.7). The method adopted in calculating the CO₂ emissions from each of the three stages is also documented in Paper 3 (Appendix C).

The first stage of the calculation process was to quantify the EC of the materials employed. This accounts for all the CO₂ emissions associated with the production of the materials up until they are ready to leave the factory gate; cradle to gate. The EC values of the materials were sourced directly from the ICE database (Hammond & Jones, 2008). The only exception was for Clay, where a specific EC value calculated in Case Study 3 (Section 5.3.4.3) was employed. Separate EC values for the geomembrane and geotextile were sourced as they were formed from different materials; Linear Low Density Polyethylene (LLDPE) and PP
respectively. The use of a calculated EC value for the geotextile is discussed in Section 5.3.6.6. The EC value for each material was multiplied with the quantity required to provide the CO₂ emissions produced (Table 5.8). The calculations were all carried out in terms of the agreed functional unit (Section 5.3.6.2).

The EC of the materials includes all the emissions that satisfy the system boundary of cradle to gate. In order to progress the CO₂ calculations to cradle to site, the material associated transport emissions were calculated. The transport related emissions of the geosynthetics and clay materials were calculated as part of the comparative case study (Paper 3, Appendix C). The same method (Equation 1, Paper 3) was employed in calculating the transport CO₂ emissions from the sand employed in both the regulatory and restoration layers. The calculations were all factored and presented in terms of the functional unit (Table 5.9). Details of the calculation methodology and the emissions factors employed are presented in Paper 3.

**Table 5.8 Total embodied carbon of materials**

<table>
<thead>
<tr>
<th>Design Solution</th>
<th>Materials</th>
<th>Embodied Carbon KgCO₂e/kg</th>
<th>Quantity Kg/m²</th>
<th>Total CO₂ KgCO₂e/m²</th>
</tr>
</thead>
<tbody>
<tr>
<td>Geosynthetic</td>
<td>Geomembrane (LLDPE)</td>
<td>2.08</td>
<td>0.939</td>
<td>1.95</td>
</tr>
<tr>
<td></td>
<td>Geotextile (PP)</td>
<td>3.43</td>
<td>0.32</td>
<td>1.10</td>
</tr>
<tr>
<td></td>
<td>Restoration Soils (Sand)</td>
<td>0.005</td>
<td>2243</td>
<td>11.22</td>
</tr>
<tr>
<td></td>
<td>Regulatory layer (Sand)</td>
<td>0.005</td>
<td>672.9</td>
<td>3.36</td>
</tr>
<tr>
<td>Clay</td>
<td>Clay</td>
<td>0.0003</td>
<td>2000</td>
<td>0.60</td>
</tr>
<tr>
<td></td>
<td>Restoration Soils (Sand)</td>
<td>0.005</td>
<td>2243</td>
<td>11.22</td>
</tr>
<tr>
<td></td>
<td>Regulatory Layer (Sand)</td>
<td>0.005</td>
<td>672.9</td>
<td>3.36</td>
</tr>
<tr>
<td>Source</td>
<td>Contractor</td>
<td>All values except that of Clay (Section 5.3.4.3) were sourced from the ICE database. Values of Low Density Polyethylene and Polypropylene (orientated film) were employed for the geomembrane and geotextile respectively.</td>
<td>Contractor</td>
<td>Calculated</td>
</tr>
</tbody>
</table>

Contractor Calculated
Table 5.9 CO₂ emissions from transport of materials

<table>
<thead>
<tr>
<th>Design Solution</th>
<th>Material</th>
<th>Total Project Quantity (kg)</th>
<th>Distance (km)</th>
<th>Truckloads</th>
<th>Fuel Consumed (litres)</th>
<th>CO₂ Emissions (kgCO₂e/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Geosynthetic</td>
<td>Geomembrane</td>
<td>8990</td>
<td>368.5</td>
<td>1</td>
<td>221.4</td>
<td>0.0595</td>
</tr>
<tr>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.0193</td>
</tr>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Geotextile</td>
<td>3060</td>
<td>217.3</td>
<td>1</td>
<td>130.5</td>
<td>0.0351</td>
</tr>
<tr>
<td></td>
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<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Geosynthetic</td>
<td>Sand</td>
<td>27911000</td>
<td>1.6</td>
<td>1396</td>
<td>1350.3</td>
<td>0.3631</td>
</tr>
<tr>
<td>Clay</td>
<td>Clay</td>
<td>19144000</td>
<td>3.5</td>
<td>958</td>
<td>2038.4</td>
<td>0.5479</td>
</tr>
<tr>
<td></td>
<td>Sand</td>
<td>27911000</td>
<td>1.6</td>
<td>1396</td>
<td>1350.3</td>
<td>0.3631</td>
</tr>
</tbody>
</table>

The final stage of the CO₂ calculations was to include the construction related emissions and complete the system boundary of cradle to end of construction (Figure 5.7). The construction of both the geosynthetic and clay solutions consists of two main phases; compaction and placement. The CO₂ emissions produced from the compaction phase were calculated as part of the comparative case study and reported in Paper 3 (Appendix C). These calculations were re-worked in terms of the defined functional unit and presented in Table 5.10.

Further calculations were required to calculate the CO₂ emissions from the placement of the various layers; clay, regulatory and restoration soils. The placement of the geosynthetics can be carried out manually by hand and hence a human energy input and excluded from this study in accordance to the PAS2050 (BSI, 2011b) guidance. Additional CO₂ emissions from the welding of geosynthetics (Paper 3) were also included. Details of the calculations and CO₂ emissions produced from the construction phase are presented in Table 5.10. The calculation methodology and the emissions factors employed were coherent with that of the case study (Paper 3).
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Table 5.10 Total Construction CO₂ emissions with details of data employed in calculations

<table>
<thead>
<tr>
<th>Solution</th>
<th>Clay</th>
<th>Geosynthetic</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Compaction Phase</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Layer</td>
<td>Clay</td>
<td>Regulatory</td>
<td>Regulatory</td>
</tr>
<tr>
<td><strong>Plant</strong></td>
<td>Bomag BW 216 D-4</td>
<td>Bomag BW 216 D-4</td>
<td>Bomag BW 216 D-4/PD-4</td>
</tr>
<tr>
<td><strong>Fuel Cons. (ltr/hr)</strong></td>
<td>16</td>
<td>16</td>
<td>16</td>
</tr>
<tr>
<td><strong>Thickness of layers placed (m)</strong></td>
<td>0.25</td>
<td>0.3</td>
<td>0.3</td>
</tr>
<tr>
<td><strong>Comp. effort (m²/hr)</strong></td>
<td>1000</td>
<td>833</td>
<td>833</td>
</tr>
<tr>
<td><strong>Total no. of passes</strong></td>
<td>24</td>
<td>2</td>
<td>4</td>
</tr>
<tr>
<td><strong>Total Time (hrs/m²)</strong></td>
<td>0.024</td>
<td>0.0024</td>
<td>0.0048</td>
</tr>
<tr>
<td><strong>Fuel consumed (ltr/m²)</strong></td>
<td>0.384</td>
<td>0.0384</td>
<td>0.0768</td>
</tr>
<tr>
<td><strong>kgCO₂ per litre</strong></td>
<td>2.5725</td>
<td>2.5725</td>
<td>2.5725</td>
</tr>
<tr>
<td><strong>kgCO₂/m²</strong></td>
<td>0.9878</td>
<td>0.09878</td>
<td>0.1976</td>
</tr>
<tr>
<td><strong>Placement Phase</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Layer</td>
<td>Clay</td>
<td>Regulatory and Restoration (Sand)</td>
<td>Regulatory and Restoration (Sand)</td>
</tr>
<tr>
<td><strong>Plant</strong></td>
<td>D6 Bulldozer</td>
<td>D6 Bulldozer</td>
<td>D6 Bulldozer</td>
</tr>
<tr>
<td><strong>Fuel Cons. (ltr/hr)</strong></td>
<td>27.276</td>
<td>27.276</td>
<td>27.276</td>
</tr>
<tr>
<td><strong>Time to Place 20t (hr)</strong></td>
<td>0.05</td>
<td>0.033</td>
<td>0.033</td>
</tr>
<tr>
<td><strong>Quantity (kg/m²)</strong></td>
<td>2000</td>
<td>2915.9</td>
<td>2915.9</td>
</tr>
<tr>
<td><strong>Total Time (hrs/m²)</strong></td>
<td>0.0050</td>
<td>0.00486</td>
<td>0.00486</td>
</tr>
<tr>
<td><strong>Fuel consumed (ltr/m²)</strong></td>
<td>0.1364</td>
<td>0.1326</td>
<td>0.1326</td>
</tr>
<tr>
<td><strong>kgCO₂ per litre</strong></td>
<td>2.5725</td>
<td>2.5725</td>
<td>2.5725</td>
</tr>
<tr>
<td><strong>kgCO₂/m²</strong></td>
<td>0.351</td>
<td>0.341</td>
<td>0.341</td>
</tr>
<tr>
<td><strong>Total Construction CO₂ Emissions</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>kgCO₂e/m²</td>
<td>1.78</td>
<td>0.54*</td>
<td>Calculated</td>
</tr>
</tbody>
</table>

*Note: Geosynthetic total emissions include 0.0026kgCO₂/m² generated from fusion welding of geomembrane. See Paper 3 (Appendix C)

5.3.6.4 Results and Findings

The CO₂ emissions from the embodied, transport and construction phases were combined to give the overall emissions for both the geosynthetic and clay design solutions (Table 5.11).
The results show the clay solution to produce 4% lower CO₂ emissions than the geosynthetic solution. Over the course of the whole project this would result in a difference of just under 7.5tCO₂.

Table 5.11 Total CO₂ emissions

<table>
<thead>
<tr>
<th>Solution</th>
<th>Transport</th>
<th>Embodied</th>
<th>Construction</th>
<th>Total (kgCO₂e/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clay</td>
<td>0.91</td>
<td>15.18</td>
<td>1.78</td>
<td>17.87</td>
</tr>
<tr>
<td>Geosynthetic</td>
<td>0.48</td>
<td>17.63</td>
<td>0.54</td>
<td>18.65</td>
</tr>
<tr>
<td><strong>Total for the project (tCO₂e)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Clay</td>
<td>8.72</td>
<td>145.30</td>
<td>17.02</td>
<td>171.04</td>
</tr>
<tr>
<td>Geosynthetic</td>
<td>4.57</td>
<td>168.76</td>
<td>5.18</td>
<td>178.50</td>
</tr>
</tbody>
</table>

In both solutions the EC contributes the most towards the overall CO₂ emissions, although construction and transport phases also make a significant contribution. In this particular project the clay was sourced from a location close to the site (3.5 km) hence a reduction in transport related emissions. Often the transport distance is significantly larger and Paper 3 (Appendix C) explains how if the clay was sourced from a distance of more than 11km, the geosynthetic solution would be more sustainable. The results also highlight the importance of extending the system boundaries to include construction emissions. This is particularly evident in the clay solution, where the construction phase would produce 17tCO₂ this equates to almost 10% of the overall CO₂ emissions.

The results obtained also help to validate the findings of the case study (Section 5.3.4) reported in Paper 3. Table 5.12 presents the results obtained as part of this study and compares them to those calculated as part of the comparative case study. The original case study did not include the placement of the clay, as it was assumed to be tipped into place with very limited placement required. However if these CO₂ emissions had been included than the results of both studies would have provided the same overall difference in CO₂ emissions.
between the two solutions. There is a small 0.01tCO$_2$e difference which can be attributed to variances in the calculation process. This helps to verify and provide credibility to the framework and methodology employed in the comparative case studies (Section 5.3.3 to 5.3.5).

Table 5.12 Comparison of case study and complete CO$_2$ footprinting results

<table>
<thead>
<tr>
<th>Study type</th>
<th>Solution</th>
<th>Total (tCO$_2$e)</th>
<th>Original Difference (tCO$_2$e)</th>
<th>Clay Placement (tCO$_2$e)</th>
<th>Overall Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Comparative</td>
<td>Clay</td>
<td>21.39*</td>
<td>10.81</td>
<td>+ 3.36</td>
<td>7.45</td>
</tr>
<tr>
<td></td>
<td>Geosynthetic</td>
<td>32.20</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Complete</td>
<td>Clay</td>
<td>171.04</td>
<td>7.46</td>
<td>-</td>
<td>7.46</td>
</tr>
<tr>
<td></td>
<td>Geosynthetic</td>
<td>178.50</td>
<td></td>
<td>-</td>
<td></td>
</tr>
</tbody>
</table>

*Note: Results obtained as part of the clay EC analysis (Section 5.2, Paper 3, Appendix C)

5.3.6.5 Utilities and Mobilisation
CO$_2$ emissions from both the utilities and mobilisation were assumed to account for less than 1% of the overall CO$_2$ emissions, hence excluded from the footprinting calculations (Table 5.7). However, in order to validate these assumptions, the CO$_2$ emissions produced from both the utilities and mobilisation phases were calculated and are presented in Table 5.13. The results show that collectively the utilities and mobilisation would account for just 0.18% and 0.11% of the clay and geosynthetic CO$_2$ footprints respectively. This helps to validate the exclusion of these emissions from the system boundary of the overall CO$_2$ footprint. Examples of other studies that have calculated the emissions associated with utilities and mobilisation include that by Spray et al. (2014), who looked at the carbon footprint of road surface treatments.
Table 5.13 CO₂ emissions from utilities and mobilisation

<table>
<thead>
<tr>
<th>Utilities</th>
<th>Clay (kWh)</th>
<th>Geosynthetics (kWh)</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy Consumption</td>
<td>522.33</td>
<td>271.328</td>
<td>Contractor estimates based on average energy consumption to include lighting, cooking etc. for the duration of the works.</td>
</tr>
<tr>
<td>kgCO₂e</td>
<td>232.69</td>
<td>120.85</td>
<td>Calculated - Conversion factor for electricity of 0.44548 kgCO₂e/kWh (DEFRA, 2013) was applied.</td>
</tr>
<tr>
<td>Water (litres)</td>
<td>1000</td>
<td>1000</td>
<td>Contractor estimates</td>
</tr>
<tr>
<td>kgCO₂e</td>
<td>0.000343</td>
<td>0.000343</td>
<td>Calculated - Conversion factor for water of 3.43 x10⁻⁶ kgCO₂e/litre (EA, 2012) was applied.</td>
</tr>
<tr>
<td>Total CO₂ (kgCO₂e)</td>
<td>232.69</td>
<td>120.85</td>
<td>Calculated</td>
</tr>
<tr>
<td>% of total CO₂ footprint</td>
<td>0.14%</td>
<td>0.07%</td>
<td>Calculated - A % of the total CO₂ footprint (Table 5.11)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Mobilisation</th>
<th>Bulldozer, Vibratory Roller</th>
<th>Contractor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transport Distance (km)</td>
<td>24</td>
<td>Contractor</td>
</tr>
<tr>
<td>Fuel Consumed (litres)</td>
<td>29</td>
<td>Calculated – Based on transport distance and average fuel consumption of transport mechanism (Equation 1, Paper 3)</td>
</tr>
<tr>
<td>Total CO₂ (kgCO₂e)</td>
<td>74.65</td>
<td>74.65</td>
</tr>
<tr>
<td>% of total CO₂ footprint</td>
<td>0.04%</td>
<td>0.04%</td>
</tr>
</tbody>
</table>

5.3.6.6 Use of a Calculated Geotextile EC Value

To provide comparability, the EC data employed in this study was consistent to that of the initial case study (Paper 3, Appendix C). However, in the last phase of the EngD research, EC values for four types of geosynthetics were calculated (Section 5.4) and are reported in Paper 5 (Appendix E). These included an EC value for PP geotextile of 2.35 tCO₂e/t, which is lower
Reducing the Environmental Impact of Construction Through Use of Geosynthetics

than the ICE database value of 3.43 tCO\textsubscript{2e}/t employed in the CO\textsubscript{2} footprinting calculations. To ascertain what impact the change in EC would have on the overall CO\textsubscript{2} footprint, the calculated value was substituted into the calculations and the results presented in Table 5.14.

The use of the calculated EC value results in an overall saving of 3.41tCO\textsubscript{2e} for the geosynthetic solution, reducing the overall footprint to 175.19 tCO\textsubscript{2e}. When considering the relatively small quantity of geotextile used in this project, this is a considerable saving in CO\textsubscript{2} emissions and highlights the need for more geosynthetic specific EC values (Section 3.5.3). The impact on overall CO\textsubscript{2} footprints from the use of calculated geosynthetic specific EC values as compared to commonly employed database values is also discussed in Paper 5 (Appendix E).

Table 5.14 The effect of a calculated EC value on the total CO\textsubscript{2} footprint of the geosynthetic solution

<table>
<thead>
<tr>
<th></th>
<th>ICE database EC</th>
<th>Calculated EC</th>
</tr>
</thead>
<tbody>
<tr>
<td>PP geotextile Embodied Carbon (tCO\textsubscript{2e}/t)</td>
<td>3.43*</td>
<td>2.35</td>
</tr>
<tr>
<td>Total CO\textsubscript{2} (kgCO\textsubscript{2e}/m\textsuperscript{2})</td>
<td>18.65</td>
<td>18.30</td>
</tr>
<tr>
<td>Total Solution CO\textsubscript{2} (tCO\textsubscript{2e})</td>
<td>178.50</td>
<td>175.19</td>
</tr>
<tr>
<td>Difference (tCO\textsubscript{2e})</td>
<td>-</td>
<td>-3.41</td>
</tr>
<tr>
<td>% change in total CO\textsubscript{2}</td>
<td>-</td>
<td>-1.9%</td>
</tr>
</tbody>
</table>

*ICE database value for PP orientated film

5.3.6.7 Uncertainty Analysis
There are two sources of uncertainty in CO\textsubscript{2} footprinting analysis as described in the PAS 2050 guide (BSI, 2008b); technical uncertainty and natural variability. Technical uncertainty is created by factors such as limited data quality, wrong assumptions and other process errors in the footprint calculations itself. Natural variability is accounted for in the definition of a product CO\textsubscript{2} footprint as an average, or representative figure, hence does not need to be quantified.
The first step in assessing uncertainty is by performing a data quality assessment, which establishes those areas contributing to the uncertainty. Details of this and a more formal uncertainty analysis in the form of a Monte Carlo analysis are provided in the PAS 2050 carbon footprinting guide (BSI, 2011b). In the case of this study review of the literature (Section 3.5) and the EC analysis (Section 5.4) have already identified the EC data of the geosynthetics as an uncertainty in the CO\(_2\) footprinting study. This is also highlighted in Section 5.3.6.6 where the use of a calculated (primary) EC value of the geotextile reduced the overall CO\(_2\) footprint by almost 3.5 tCO\(_2\)e. In the case of the geomembrane there was no primary EC data available hence a secondary database value for LLDPE was sourced from the ICE database (Hammond & Jones, 2011). To understand the impact of the uncertainty in geomembrane EC on the overall CO\(_2\) footprint, a sensitivity analysis was carried out (Figure 5.9).

The results of the analysis show that a 40% change in the geomembrane EC combined with the calculated geotextile EC value (Table 5.14), can result in a 6% difference from the original geosynthetic solution CO\(_2\) footprint of 178.5 tCO\(_2\)e (Table 5.12). When comparing the results to the clay solution a geomembrane EC value of less than 1.6tCO\(_2\)e/t would make the geosynthetic solution more sustainable. The analysis helps to identify the uncertainty that exists within the data and how this can impact on the overall CO\(_2\) footprint. Further uncertainty analysis could be carried out through a Monte Carlo Analysis. However, detailed information about the likely variability around each data point is required, which is currently not available for geosynthetics. The availability of more primary EC data for geosynthetics and CO\(_2\) footprinting studies would help to address this. There are also a number of assumptions made with regards to the transport mechanisms and the EC of the fuel that will also influence the overall CO\(_2\) footprint. Therefore considering these variances, a conservative approach would be to assume an upper bound of 10% for the CO\(_2\) footprints calculated.
Reducing the Environmental Impact of Construction Through Use of Geosynthetics

Figure 5.9 The impact of a change in geomembrane EC on the overall CO₂ footprint

5.3.6.8 Conclusions

The CO₂ footprinting study extended the earlier work carried out in the comparative case study (Section 5.3.4) to provide a total CO₂ footprint for both the geosynthetic and clay solutions. The aim of the study was not only to compare both solutions in terms of total CO₂ footprints but to also demonstrate the application of a rigorous methodology that followed the PAS 2050 guidance. Consistency in EC data and LCA scope (cradle to end of construction) was maintained between the two studies to ensure comparability.

The CO₂ footprints calculated for each solution were very similar, however the clay was marginally more sustainable producing 17.87 kgCO₂e/m² compared to 18.65 kgCO₂e/m². Overall for the whole project this resulted in a difference of 7.46 tCO₂e with the clay solution 4% lower in total CO₂ emissions. In both solutions the EC contributes the most towards the overall CO₂ emissions. Analysis on the use of calculated EC values for the geotextile and clay
(Section 5.3.4) highlighted the dependence of CO$_2$ footprints on accurate EC data. Transport and construction related emissions also made a significant contribution to the overall CO$_2$ footprint, demonstrating the importance of an extended LCA system boundary of cradle to end of construction.

Emissions from both the utilities and mobilisation were excluded from the overall CO$_2$ footprint. This was based on the guidance provided in PAS2050, as it was anticipated they would account for less than 1% of the overall CO$_2$ emissions. However, in order to verify these assumptions, CO$_2$ emissions from both the utilities and mobilisation phases were calculated separately and confirmed to be below the 1% threshold.

The results obtained as part of this study also helped to validate the findings of the initial case study (Section 5.3.4) reported in Paper 3 (Appendix C). The initial case study differed in scope and methodology and did not provide a total CO$_2$ footprint for both the geosynthetic and clay solutions. However, when you compare the difference in CO$_2$ emissions between the geosynthetic and clay solutions both in terms of the total CO$_2$ and the comparative study, the results are very similar. This helps to provide credibility to the framework and methodology employed in the comparative case studies (Section 5.3.3 to 5.3.5).

**5.3.7 SUMMARY**

Objective 3 was to compare the CO$_2$ emissions between geosynthetic and non-geosynthetic solutions whilst demonstrating a rigorous framework and CO$_2$ calculation methodology. This was carried out through three case studies presented in Papers 2, 3 and 4 (Appendix B, C and D). A comparison framework (Figure 5.1) was developed and ensured that the case studies all employed a clear, coherent methodology. It was made sure that the methodology demonstrated could be easily applied to other studies and applications where geosynthetic solutions were being compared in terms of CO$_2$ emissions. In addition to the three
comparative case studies, a total CO$_2$ footprint for both the geosynthetic and clay solutions was calculated for Case Study 2 in accordance to PAS2050 (BSI, 2011a). The case studies demonstrated the CO$_2$ benefits of employing geosynthetics with the most important saving made in the total EC. The geosynthetic solutions often reduced the import of quarried material, which in turn reduced the associated EC. This also coincided with a saving in the CO$_2$ emissions from the transport of imported fill and waste material off site.

Transport CO$_2$ emissions also have a significant impact on the overall CO$_2$ footprint of a project or solution. This is demonstrated in case study 2 where locally sourced clay material could make the clay solution more appropriate in terms of lower CO$_2$ emissions. Construction emissions were also considered in case studies 1 and 2. However, most techniques are similar on both solutions producing little if any difference in CO$_2$ emissions, as highlighted by the results of the case studies. Their inclusion does however increase the scope and credibility of the study.

The case studies emphasised the importance of accurate EC data, especially for geosynthetics. With no geosynthetic specific EC data in the databases, substitute values based on the material composition are commonly employed. Such values may not be an accurate representation of the actual EC for a particular type of geosynthetic. Therefore, the use of accurate, reliable EC data would ensure that the most sustainable solution whether geosynthetic or non-geosynthetic is being employed. It would also strengthen the credibility and validity of any CO$_2$ analysis being carried out and highlight the benefits of geosynthetics when at their most appropriate sustainable use.
5.4 EMBODIED CARBON DATA FOR GEOSYNTHETICS

5.4.1 INTRODUCTION
Objective 4 of the research looked at sourcing EC data for different types of geosynthetics. The importance of EC data and an absence of geosynthetic specific values have already been discussed numerous times in the previous chapters. The research undertaken as part of objective 4 looked to fill this gap in the research, through contacting manufacturers and calculating a first-hand EC value for various types of geosynthetics. A total of four manufacturers contributed to the study and with their involvement and assistance, EC values for four types of geosynthetics (Table 4.4) were calculated.

The EC values were calculated to life cycle boundaries of cradle to gate in order to maintain consistency with databases such as the ICE database (Hammond & Jones, 2011). The overall methodology employed in sourcing the EC data including the initial contact made in the form of a survey (Appendix G) is discussed in Chapter 4. A more detailed methodology about the measurements and calculations undertaken as part of this study is presented in Paper 5 (Appendix E). Paper 5 reports in detail the work carried out and the findings of the study, which are summarised within this section, covering some of the main results and discussion points.

The implications of the calculated EC values were considered through re-working of the case studies. The results are presented in Table 5.16 and also discussed in Paper 5.

5.4.2 RESULTS
Results were obtained for four types of geosynthetics; two of both geotextile and geogrids (Table 4.4). Each manufacturer was able to provide data for a range of products that varied in mass and production results, within a specific type of geosynthetic. This allowed the overall energy consumption per kg of product produced to be calculated (Table 2 from Paper 5) In
order to present these results in the form of EC, the energy consumed was converted to EC values using appropriate CO$_2$ emissions factors sourced from DEFRA (2013).

![Process map for non-woven geotextile](image)

Figure 5.10 Process map for non-woven geotextile

The EC values calculated were presented to LCA boundary conditions of cradle to gate hence including any CO$_2$ emissions associated with the manufacture of the product up until it is ready to leave the factory gate (Figure 5.10 and Figure 5.11). This also includes any CO$_2$ emissions associated with the transport of materials up until the finished product. Further details of what embodied, manufacturing and transport emissions arose for each type of
geotextile/geogrid are provided in Paper 5 (Appendix E). The overall EC values are provided in Table 5.15.

The results show that the total EC of the geotextiles provided by the two manufacturers is very similar with only a 5% difference. This small difference, which arises in the manufacturing process, could be due to various reasons such as differences in energy sources employed. The total EC for both Manufacturers A and B can be averaged to give an overall value for non-woven geotextiles of 2.35 tCO$_2$e/t for cradle to gate.

**Table 5.15 Overall EC value for each type of geosynthetic**

<table>
<thead>
<tr>
<th>Manufacturer</th>
<th>Type</th>
<th>Polymer EC (tCO$_2$e/t)</th>
<th>Conversion of Granules to fibre (tCO$_2$e/t)</th>
<th>Average* Geosynthetic CO$_2$ Manufacturing (tCO$_2$e/t)</th>
<th>Total EC (tCO$_2$e/t)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Non-woven Geotextile (Needle punched)</td>
<td>1.983**</td>
<td>0.241</td>
<td>0.053</td>
<td>2.28</td>
</tr>
<tr>
<td>B</td>
<td>Non-woven Geotextile (Thermally Bonded/Needle Punched)</td>
<td>1.983**</td>
<td>0.241</td>
<td>0.189</td>
<td>2.42</td>
</tr>
<tr>
<td>C</td>
<td>Geogrid (Extruded)</td>
<td>-</td>
<td>-</td>
<td>0.987</td>
<td>2.97</td>
</tr>
<tr>
<td>D</td>
<td>Geogrid (Woven)</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>2.36</td>
</tr>
</tbody>
</table>

*Average across a range of products
**EcoInvent v2.2 database value for EC of polypropylene (granules)

There were also EC values obtained for the two types of geogrids. The extruded geogrid had an EC of 2.97 tCO$_2$e/t and 2.36 tCO$_2$e/t for the woven geogrid. Unlike the geotextiles which were formed from the same material the geogrids varied both in manufacturing processes and raw materials employed. Hence a small difference between the EC values of the two geogrids
was expected. The results from both categories of geosynthetics highlight that the biggest contribution to the overall EC of each product is made by the EC of the raw material. However, the manufacturing process still accounts for a considerable amount of the overall EC ranging from 2% to 33%.

**Figure 5.11 Process map for geogrid (extruded)**

### 5.4.3 DISCUSSION

The aim of this study was to calculate EC values for categories and types of geosynthetics. The results show that values calculated in this study have significant differences to the database values often used (Table 5.16). In the case of geosynthetics manufactured from PP,
the ICE database values commonly employed can be up to 90% higher than those calculated in this study for a PP based geotextile or geogrid. Therefore, the use of these database values in carbon footprinting studies can lead to uncertainty with regards to the correctness of the calculated emissions. The EcoInvent database (EcoInvent Centre, 2010) only present’s data for PP in granulate form, which gives a lower EC than that of a finished material and can result in underestimation of the total emission.

Table 5.16 Comparison of calculated EC values with database alternative values

<table>
<thead>
<tr>
<th></th>
<th>Calculated EC values (tCO₂e/t)</th>
<th>Database EC values (tCO₂e/t)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Polypropylene</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Non-woven geotextile (average)</td>
<td>2.35</td>
<td>ICE v2.0 (Processed)</td>
</tr>
<tr>
<td>Extruded geogrid</td>
<td>2.97</td>
<td>EcoInvent v2.2 (Non-processed)</td>
</tr>
<tr>
<td><strong>Polyester</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Woven geogrid**</td>
<td>2.36</td>
<td>ICE v2.0*</td>
</tr>
<tr>
<td></td>
<td>2.54 to 3.31</td>
<td>EcoInvent v2.2</td>
</tr>
</tbody>
</table>

*The ICE v2.0 database does not contain values for polyester materials and therefore previous studies (e.g. WRAP, 2010) have used values for General Polyethylene and Plastics (General) as alternatives.

**The EC value for the Woven Geogrid was sourced directly from manufacturer D, who did not employ database values for polyester in their calculations. The PP products all employ the non-processed value of 1.98 tCO₂e/t for the raw material in the calculations. See Paper 5 Appendix E for more details.

Similar results are obtained for the Polyester (PET) based geogrid, with an Environmental Product Declaration provided by Manufacturer D and validated by a third party in accordance to ISO 14025 (2011). The EcoInvent database in this instance presents values for PET (granulate) in two different forms (Table 1 from Paper 5). Although the values are for granulate and not a finished material they are still higher than the value calculated for the PET woven geogrid. This could be attributed to the source and literature used in obtaining the data. In this instance the ICE database does not have any specific values for PET, however, values for general plastics and PE have previously been used as alternatives (WRAP, 2010). These values for general plastics and PE follow the same trend of PP database values and are higher
than that calculated for the woven geogrid. Thus substituting these values for PET based geogrids in CO₂ studies would overestimate the results.

It is important to note that this study does not suggest the database values are inaccurate as the values stated are not direct comparisons. They are values for different forms of materials whether it be granulate or in the case of PP, injection moulding or orientated film. Due to a lack of specific EC values for geosynthetics, to date these values have commonly been employed as alternatives when working with PP based geosynthetic products. However, the values reported in this study can now be used for future carbon footprinting, to provide more rigorous construction solution assessments. The case studies (Section 5.3.3 to 5.3.5) were also re-worked using these calculated EC values where applicable and the results presented in Table 5.17.

Table 5.17 The use of calculated EC values in the CO₂ case studies (Section 5.3.3 to 5.3.5)

<table>
<thead>
<tr>
<th>Case Study</th>
<th>Original EC value (ICE database)</th>
<th>Calculated EC value</th>
<th>Difference (tCO₂e)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Geotextile* Geogrid</td>
<td>Solution (tCO₂e) Geotextile Geogrid</td>
<td>Solution (tCO₂e)</td>
</tr>
<tr>
<td>1</td>
<td>3.43 -</td>
<td>10.91</td>
<td>2.35 -</td>
</tr>
<tr>
<td>2</td>
<td>3.43 -</td>
<td>32.2</td>
<td>2.35 -</td>
</tr>
<tr>
<td>3</td>
<td>- 1.93**</td>
<td>16.16</td>
<td>- -</td>
</tr>
</tbody>
</table>

* Value for PP orientated film from ICE database (Hammond & Jones, 2011)
**HDPE geogrid employed and calculated EC values are for PET and PP geogrids hence are not comparable.

5.4.4 ACCURACY OF CALCULATED EC VALUES

The EC values were calculated using first-hand manufacturer data, however, there was still some assumptions with regards to exclusion of flows and conversion factors for electricity that would influence the accuracy of the overall EC calculated.

The CO₂ emissions factor for electricity can fluctuate from year to year, depending on the fuel mix consumed in UK power stations. In the 2014 GHG conversion factors reported by
DEFRA (2016) there was an 11% increase in the UK electricity factor from the previous year due to a significant increase in coal powered electricity generation. There are also differences in the conversion factors for electricity generated and electricity consumed. The electricity consumed factor accounts for assumed distribution and transmission losses. This is stated as 0.07033 kgCO$_2$e/kWh by DEFRA (2016) and would equate to a 15% increase on the 0.44548 kgCO$_2$e/kWh employed in the calculations (Paper 5, Appendix E). Using these values the average EC for the geotextiles could increase by 1.7% from 2.35 tCO$_2$e/t to 2.39 tCO$_2$e/t.

The uncertainty within the conversion factors alongside the assumptions made with regards to exclusion of flows anticipated to contribute less than 1% of the total EC (BSI, 2011a) could be assumed to affect the EC values by up to 5%. Factoring in the other assumptions and variances that may exist in the EC of the raw materials, fuel, and transport mechanisms, it would be fair to assume the calculated values are accurate to within 10% of the total EC. The availability of further geosynthetic EC data and studies alongside a detailed uncertainty analysis would be required to truly quantify the accuracy of the EC values calculated. In consideration of the assumptions discussed it would not be justified to report the EC values to a higher level of precision than 2 decimal places. This also matches the level of precision provided in the ICE database, which also uses a number of assumptions in calculating average EC values for different materials (Section 3.5.2.2)

5.4.5 CONCLUSIONS
This study was carried out to calculate the EC values for two categories of geosynthetics subdivided into four types; non-woven geotextile needle punched, non-woven geotextile needle punched and thermally bonded, extruded geogrid and woven geogrid. The study demonstrates that the values calculated are considerably lower than the commonly employed substitute database values.
The results from the two different geotextile manufacturers were very similar with only a 5% difference. The geotextile from Manufacturer A had an EC of 2.28 tCO₂e/t compared to 2.42 tCO₂e/t from Manufacturer B. The small difference in values can be attributed to different manufacturing processes and fuel sources. The mean value for non-woven geotextiles was 2.35 tCO₂e/t. Results for two types of geogrids were also obtained; 2.97 tCO₂e/t for the extruded and 2.36 tCO₂e/t for the woven geogrid. The variance between the two geogrids was expected due to differences in manufacturing processes, raw materials, and the use of database values for the PP granulates.

With no available specific EC values for geosynthetics, studies such as those by WRAP (2010) and the case studies reported in Section 5.3 employ database values as a substitute. In instances where PP based non-woven geotextiles or geogrids are being employed, the value for polypropylene (orientated film) from the ICE database (v1.6a) has been used as an alternative (WRAP, 2010). The ICE database (v2.0) value for polypropylene (orientated film) of 3.43 tCO₂e/t is 46% higher than that of 2.35 tCO₂e/t calculated for the geotextiles and 15% higher than the 2.97 tCO₂e/t of the geogrid.

The findings of this study highlight the importance and need for geosynthetic specific EC data. The use of specific geosynthetic data in CO₂ calculations will help to add accuracy and hence credibility to the overall carbon footprinting results. This will further highlight the sustainability benefits of geosynthetics whilst also removing any doubts or challenges that may exist with regards to the EC data employed. The publication of EC data for a range of geosynthetics would allow clients and consultants to undertake their own robust calculations. This study has provided EC values for two different categories of geosynthetics. However, there is a need to develop, add and extend this dataset to a range of other categories of geosynthetics.
5.5 SUMMARY

This chapter reported on the research undertaken and provided an overview of three main objectives (Section 5.1) that were achieved. The grouping of research tasks into core objectives helped in measuring the success and impact of the research. It provided a clearer understanding of how the aims of the research would be met. Although each objective provided key conclusions it was their collective findings that helped to fulfil the needs of the research.

Objective 2 evaluated two different calculation methodologies. Tests were run to gain an understanding on how coherent the EA (2012) carbon calculator methodology was with that employed by WRAP (2010). The results showed that both methodologies produced similar results and differences that arose were due to miscalculations or use of different EC databases. The findings from objective 2 helped provide a methodology and framework for the CO₂ comparison case studies that formed objective 3.

Objective 3 looked at comparing the CO₂ emissions between geosynthetic and non-geosynthetic solutions whilst demonstrating a developed CO₂ calculation framework. Three case studies following a coherent framework/methodology for functions of drainage, containment and reinforcement were carried out. The case studies all showed CO₂ reduction benefits of employing a geosynthetic solution. The biggest difference in the CO₂ emissions of the two solutions being compared came in the EC of the materials. This highlighted the dependence of a credible CO₂ analysis on accurate reliable EC data.

The findings of objectives 2 and 3 highlighted the importance of EC data in determining the validity of any CO₂ footprinting results. The research showed an absence of geosynthetic specific data in the commonly employed databases. Therefore Objective 4 sought to address this and source first-hand EC values for different types of geosynthetics. Through the
involvement of four manufactures, EC values for two categories of geosynthetics; geotextiles and geogrids were calculated. The use of these values in any CO₂ comparative study would provide credible results that would also help to highlight applications where geosynthetics are at their most appropriate sustainable use.

The majority of the research undertaken excluding Objective 2 is documented in Papers 2 to 5 (Appendix B to E). Therefore this chapter provided a summary of the work carried out. For a more detailed review of the work, it is recommended that the relevant EngD papers are consulted.
6 FINDINGS AND IMPLICATIONS

6.1 INTRODUCTION

This chapter draws upon the work undertaken in each of the four main objectives and presents the key findings of the research. These findings subsequently have implications for the industrial sponsors (IGS UK Chapter), the wider geosynthetic and civil engineering industry and the academic community. The chapter discusses what implications have arisen from this research and what effects this has on the various stakeholders. A critical evaluation of the research is presented, as well as how it has contributed to existing theory and practice. Finally the chapter provides some recommendations for the industrial sponsors and identifies areas of possible further research.

6.2 KEY FINDINGS

The research was broken down into four main objectives that covered a number of research areas and tasks. Each of the objectives provided some key findings that helped to fulfil the aims and needs of the research. However, these findings also contributed to the research undertaken in other objectives therefore there was constant flow of information as illustrated in the research map (Figure 1.3). These key findings, and the associated objective, are listed below:

- The biggest drivers to sustainable construction solutions come from the clients insisting on ratings of ‘excellent’ on environmental assessments of construction projects such as CEEQUAL and BREEAM. (Objective 1)

- The use of site-won or marginal fills is one of the most sustainable uses of geosynthetics. However, their use is limited due to lack of guidance and fears regarding their poor mechanical characteristics. (Objective 1)
• CO₂ calculation methodologies applicable to geosynthetic projects and currently in use are comparable with one another. However, differences exist due to the LCA scope and/or the embodied carbon data employed (Objective 2)

• A clear and rigorous calculation framework has been developed as part of this project to aid any CO₂ comparative studies. (Objective 2 and 3)

• The case studies into different functions of geosynthetics demonstrated the CO₂ reduction benefits when employing a geosynthetic solution in most, but not all cases. (Objective 3)

• The case studies highlighted the importance of reliable EC data in reducing the uncertainty and producing a validity CO₂ footprint. (Objective 3)

• Commonly employed sources of EC values such as the ICE and EcoInvent databases respectively have no specific values for geosynthetics. (Objective 1, 2, 3 and 4)

• EC values were calculated for four types of geosynthetics. The EC value for the Polyester geogrid was calculated and validated by the supplier, with the Polypropylene geogrid and geotextiles EC values calculated based on database values for the raw polypropylene granules and manufacturer data. These calculated geosynthetic specific EC values were lower than those often used as alternatives from the ICE database. Thus CO₂ studies employing database values for geosynthetics may be overestimating their EC contribution to the overall results. (Objective 4)

6.3 OUTPUTS

The main outputs of the EngD research were the six academic publications which contained rigorous CO₂ comparative case studies and primary EC data for geosynthetics. The research
also helped to identify some of the constraints and barriers to the use of geosynthetics (Raja et al., 2011).

The project produced a framework (Section 5.3.2) to compare the CO₂ emissions from geosynthetic and non-geosynthetic solutions. This framework which was demonstrated in the development of the cases studies (Section 5.3) and provides guidance for those wishing to carry out similar studies within or outside the geosynthetic industry. It highlighted the CO₂ savings from employing geosynthetics and could be used to promote sustainable, low CO₂ construction.

The most worthwhile output of the EngD research was the EC values calculated for different types of geosynthetics (Section 5.4). Their use will help to increase the accuracy of CO₂ studies that include geosynthetics. The EC data calculated could form a geosynthetic specific EC database or be included in existing databases such as the ICE (Hammond and Jones, 2011). This will help to publicise geosynthetic products and develop awareness about geosynthetics and their usage into the wider civil engineering industry.

6.3.1 CONTRIBUTION TO EXISTING THEORY AND PRACTICE

Throughout the course of the EngD research six academic papers were produced. These papers included four published conference papers, one published journal paper and a second journal paper accepted for publication, at the time of submission. Five papers were selected to be included in the appendix as they presented findings from the core objective and helped increase the impact of the research on existing knowledge. The papers and the key contributions that they made are listed:

Limitations to Designing with Marginal Fills (EngD Paper 1, Appendix A)- This paper presented a review on the use of marginal fills. The poor mechanical characteristics can often be a hindrance to their usage (Section 3.7). The paper gave an insight into how geosynthetics
could be used to overcome such characteristics, adding to the body of knowledge that marginal fills can be utilised. It also highlighted the limitations in the design codes and provided recommendations on how they could be addressed.

The sustainable use of geosynthetics: Landfill drainage case study (EngD Paper 2, Appendix B)- This paper presented a case study comparing the CO₂ emissions between three different under-drainage solutions in a landfill application, to LCA boundaries of cradle to end of construction (Section 3.4.3). The conference paper highlighted the sustainable benefits of geosynthetics in a landfill drainage application. It presented a clear, rigorous CO₂ calculation methodology which could be easily applied to other CO₂ comparative studies involving geosynthetics. The paper helps to identify and promote the use of low CO₂ solutions in other landfill projects.

Comparison of CO₂ emissions for two landfill capping layers (EngD Paper 3, Appendix C)- This journal paper presented a case study comparing the CO₂ emissions between a geosynthetic and non-geosynthetic solution in a landfill capping layer. The paper demonstrated the CO₂ savings possible from employing the geosynthetic solution. The case study followed a coherent methodology to the studies reported in Papers 2 and 4 (Appendix B and D). The detailed analysis highlighted the importance of reliable EC data and how erroneous EC values could have a significant impact on the overall CO₂ results. This was demonstrated by calculating a first-hand cradle-to-gate EC value for clay and compared to the originally sourced database value. The findings of this paper will promote the use of sustainable construction techniques in landfill capping applications and provide guidance in the CO₂ footprinting of similar solutions.

Comparison of CO₂ emissions for a reinforced soil and concrete retaining structure: A case study (EngD Paper 4, Appendix D)- This conference paper presented a case study comparing
the CO₂ emissions between a geosynthetic reinforced slope and concrete retaining wall. The paper showed the CO₂ benefits of employing the geosynthetic solution, once again demonstrating a clear detailed methodology coherent to those adopted in Papers 2 and 3 (Appendix B and C). The study also considered the possibility of post-construction CO₂ savings of the geosynthetic solution through carbon fixation of the vegetated face. The paper demonstrates the CO₂ savings in a reinforcement application adding to the existing case studies on drainage (Paper 2) and containment (Paper 3). It highlights how the developed CO₂ calculation methodology can be applied to a variety of applications, thereby promoting low CO₂ solutions.

**Sustainable construction solutions using geosynthetics: Obtaining reliable embodied carbon values (EngD Paper 5, Appendix E)** – This journal paper presents the research carried out in calculating EC values for different types of geosynthetics. Currently there is no specific EC data for geosynthetic products in the commonly employed databases. Therefore the values presented in the paper would help to increase the accuracy of any CO₂ footprinting analysis involving geosynthetics. The research presented in this paper not only contributes to existing theory and practice but also provides a basis for further research.

The main contributions from the EngD research can be summarised into three points:

- A clear CO₂ calculation methodology and comparison framework (Figure 5.1) has been developed. This can be applied to other studies looking at comparing CO₂ emissions between geosynthetic and non-geosynthetic solutions.

- CO₂ comparison case studies have demonstrated the low CO₂ benefits of applying geosynthetics in different applications and functions. These will help familiarise clients and consultants with geosynthetics and the sustainable benefits they can provide.
The EC values developed for different types of geosynthetics, will improve the accuracy of CO₂ analysis. The formation of a database or these geosynthetic values and their inclusion in construction materials databases will further publicise the use of geosynthetics as credible sustainable solution.

6.4 IMPACT ON SPONSORS

The EngD research was unique in that there wasn't a single sponsoring company but a group of companies represented through a society; The IGS UK Chapter. Therefore, the impact of the research was not confined to any one company by rather the whole geosynthetic industry in the UK. The IGS UK chapter also feeds into the global IGS, hence an impact was also made on a global scale.

Throughout the EngD research the author played an active role on the IGS UK Chapter committee. Progress updates and interim findings of the research were discussed at each committee meeting four times a year. This meant that not only was the research constantly being shaped to meet the needs of the Society but also the research had an impact from a very early stage of the EngD project. The chapter sponsors were also engaged through a dedicated evening meeting midway through the 4 year EngD programme. The evening was used to present the research up to that point and gain the feedback and input of the Chapter sponsors.

The IGS UK Chapter is formed of sponsors of differing natures offering various services such as manufacturers, suppliers, consultants and contractors. Therefore the research impacts each stakeholder in a different manner. One of the major impacts of the research came from the CO₂ comparative cases studies. It has helped the IGS UK Chapter demonstrate the sustainable benefits of geosynthetics to its Chapter sponsors and the wider geotechnical industry through collaborative evening meetings. It has provided manufacturers and suppliers the guidance to produce their own CO₂ case studies to market the sustainable benefits and applications of
their products. Similarly those Chapter sponsors that are consultants and contractors can use the case studies to raise awareness amongst clients.

Presentation of the research at international conferences under the auspices of the IGS led to an impact on a global level. It encouraged the main IGS body to approach the EngD research team to help in the formation of a script for a short IGS (2015) movie. The movie targeting clients and those outside the geosynthetics industry highlighted the sustainable benefits of geosynthetics. The author and supervisory team were acknowledged for their involvement in producing the movie, available at http://youtu.be/LIH-7djSPO0.

The biggest impact of the research on the IGS UK will come from the embodied carbon values calculated for geosynthetics. The IGS UK Chapter recognised the need to be able to accurately identify the CO$_2$ savings of employing geosynthetics. The case studies have demonstrated a framework that can be transferable to other studies. However, with no EC data for geosynthetics the overall CO$_2$ results could be challenged or questionable. Generic values for geosynthetics and common fill materials such as Clay can often be erroneous (Paper 3, Appendix C). The development of EC values for four different types of geosynthetics will allow the IGS UK Chapter sponsors to accurately forecast potential CO$_2$ savings. It will also allow the IGS UK Chapter to take the lead in developing an EC database which could be employed on a global level, initiated through the Geosynthetics International journal (Paper 5, Appendix E).

The EngD research also had secondary unintentional yet favourable impacts. These impacts were not in the aims of this research but did however benefit the Chapter sponsors. An example of such impact was in the sourcing of the EC data. One of the manufacturers contributing to the study used the methodology employed in taking energy measurements for the research to help improve their manufacturing efficiency.
The EngD research has helped the IGS UK to correctly identify the CO₂ savings of employing geosynthetics. It puts the UK Chapter at the forefront of research into the sustainable benefits of geosynthetics and the development of an EC database for geosynthetics. However, as a ‘not for profit’ society the IGS UK have a responsibility to provide a benefit to the Chapter sponsors and individual members for sponsoring the society. The EngD research and the publications that were produced should help to fulfil some of these responsibilities. It has also placed the IGS UK in a unique position to hold a symposium on geosynthetics in sustainable engineering (IGS UK Chapter, 2015)

6.5 IMPACT ON THE WIDER INDUSTRY

The construction industry is being driven towards low carbon sustainable construction by government targets (BIS, 2013) and the growth in the ‘green building’ market (McGraw-Hill Construction, 2013). Clients, consultants and contractors are increasingly looking at techniques for reducing the CO₂ emissions from construction methods and solutions. The EngD research has demonstrated how geosynthetic solutions could help reduce CO₂ and provided a clear framework and methodology.

In order to maximise the impact, one of the case studies (Paper 3, Appendix C) was published in the Proceedings of the ICE- Engineering Sustainability journal. This journal targets a wider audience than the geosynthetic based conferences, hence helps maximise the impact of the research. The methodology demonstrated in the case study could be easily applied to other CO₂ comparative studies, helping to identify potential CO₂ savings. The case study also provides an example application where a geosynthetic solution could reduce the CO₂ emissions when compared to a non-geosynthetic solution. This raises awareness amongst those in the wider construction industry of the sustainable benefits of geosynthetics. With the aid of the case studies and the findings of the EngD research CO₂ comparisons may be carried
out on existing or new designs to understand whether the solution employed is the most sustainable.

The EngD research was also successful in developing EC data for four types of commonly employed geosynthetics. The availability of this data will help to accurately forecast the CO$_2$ emissions from geosynthetic solutions. Thus clients and consultants will be more confident that the CO$_2$ results produced for geosynthetics are accurate and credible. This EC data will also benefit other industries such as concrete and steel to compare CO$_2$ emissions with construction solutions involving geosynthetics.

Other impacts of the research included the development of a short sustainability movie (IGS, 2015) discussed in Section 6.4.

6.6 CRITICAL REVIEW OF THE RESEARCH

An important part of academic rigour is to critically evaluate the research carried out. It is necessary to reflect on the work and gain an understanding of the effectiveness of the research and how it may have been improved. This section evaluates the research against three key aspects; the aims and objectives, methodology and the research undertaken.

6.6.1 MEETING THE AIDS AND OBJECTIVES

The main aim of the research was to establish and demonstrate a rigorous framework for comparison of CO$_2$ emissions between geosynthetic and non-geosynthetic solutions. This aim was broken down into a number of research areas and tasks (Table 4.1) that were grouped together into four core objectives.

The EngD research needs to account for any changes in the research needs of the sponsor hence the aims and objectives need to provide some flexibility, as was witnessed on the completion of Objective 1. It was concluded that rather than a carbon footprinting tool, EC data in combination with a clear CO$_2$ calculation framework would have a much greater
impact for the research. Therefore the objectives and research tasks were altered to include these changes.

The EngD research was successful in meeting the aims and objectives outlined in Section 1.2 this is evident from the impact and outputs of the research (Section 6.3). This evaluation as well as possible areas of research that remain outstanding are summarised in Table 6.1.

Table 6.1 Meeting the objectives

<table>
<thead>
<tr>
<th>Objective</th>
<th>Outcomes</th>
<th>Research work outstanding</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. To understand sustainable construction and the benefits achieved through use of geosynthetics</td>
<td>Survey highlighted use of geosynthetics and barriers faced (Raja et al., 2011). Literature review (Chapter 3) provided the basis and identified the research areas and objectives.</td>
<td>-</td>
</tr>
<tr>
<td>2. To evaluate CO₂ calculation methods typically used in the geosynthetics industry</td>
<td>Tests on two CO₂ calculation methodologies provided basis for the calculation framework developed (Section 5.3.2).</td>
<td>Tests on methodologies for extended LCA boundaries</td>
</tr>
<tr>
<td>3. To compare CO₂ emissions between geosynthetic and non-geosynthetic solutions</td>
<td>Three CO₂ case studies for functions of drainage, containment and reinforcement (Papers 2-4, Appendix B –D)</td>
<td>Further case studies of other functions and to include ‘Life’ and ‘Maintenance’ phases of the LCA in the CO₂ comparison</td>
</tr>
</tbody>
</table>
| 4. To source embodied carbon data for specific types of geosynthetics     | EC data for four types of geosynthetics calculated (Paper 5, Appendix E)                        | EC data for other types of geosynthetics e.g. geomembranes

Detailed uncertainty analysis |

6.6.2 METHODOLOGY

The research methodology required a mixed-method technique (Chapter 4). The main body of research followed a quantitative technique, however, there were elements of the research that required qualitative techniques. The use of the mixed method approach worked well in helping to incorporate numerical and narrative data from both techniques into one study (Tashakkori and Teddlie, 2003).

The methodology developed allowed an effective flow of information between objectives (Figure 1.3) and provided flexibility to the research approach. However, there were specific
methods that could have been altered or improved to maximise the outputs of the research. The most significant example was the use of a survey (Appendix F) in sourcing EC data as part of the requirements of Objective 4. The survey in the form of a questionnaire received no responses due to fears regarding confidentiality of the data (Section 4.3.4). A more effective research method would have been to conduct a personal interview, thus providing a personal experience and alleviating any concerns with regards to the misuse of the data.

6.6.3 Research Undertaken

The success of the research undertaken can be measured by the academic outputs and the impact it has had on the industrial sponsor and the wider industry. However, it is still important to evaluate in more detail key elements of the research undertaken and how they may have been improved to further maximise the impact of the research. The two main areas of focus are the cases studies and the sourcing of the EC data.

The case studies were undertaken for three different functions of drainage, containment and reinforcement. The applications covered included that of landfills and retaining structures. The case studies may have helped to fulfil the needs of the research, but their impact could have been maximised further by increasing the number of applications covered. Case studies on a range of other applications such as roads, railways and hydraulics, would have had a greater impact on the wider industry. The LCA scope of the case studies could also be increased to include emissions from the ‘life’ phases of the structure. The main constraint to achieving this further work was sourcing the required project data for the case studies, as most geosynthetic manufacturers/suppliers did not have design information for the non-geosynthetic solution.

The sourcing of the EC data was limited by commercial sensitivity concerns from the IGS UK Chapter sponsors. In total EC values for four commonly employed geosynthetics were
developed. There was however, scope to increase the number of different types of geosynthetics covered in the study, which could have led to an EC database as direct impact of the research. However, there were confidentiality concerns amongst the different sponsors in sharing such data. The survey and accompanying letter (Appendix F) hoped to alleviate these concerns but this was not possible and only four out of a possible 14 manufacturers contributed to the study. The use of a different research method (Section 6.6.2) instead of the survey may have provided more beneficial results.

6.7 RECOMMENDATIONS FOR THE INDUSTRY AND FURTHER RESEARCH

The research sponsored by the IGS UK Chapter showed the initiative they were taking to identify the sustainable benefits of geosynthetics. Based on the findings of the research the EngD has a number of recommendations for the IGS UK.

The case studies (Section 5.3) produced will help the use of geosynthetics and act as a benefit to its chapter sponsors. They not only highlight the CO₂ savings of employing geosynthetics but demonstrate a framework for CO₂ comparative studies (Section 5.3.2). Manufacturers can adopt this framework and carry out job specific analyses for their clients feeding into their environmental assessment ratings such as CEEQUAL (Section 3.3.5).

There is scope for the IGS UK to produce further case studies, extending the LCA boundaries to include emissions from the ‘life’ phase of a project. An example application would be the use of geosynthetics in asphalt reinforcement of roads. In such applications geosynthetic may provide savings in materials but also reduce the amount of maintenance over the life time of the structure. The reduction in maintenance of a geosynthetic solution as compared to unreinforced asphalt layer will have considerable CO₂ savings. The reduced maintenance would also have significant cost benefits, which in the current economic climate is of upmost
importance. However, in order to carry out case studies on such applications further research is required on detailed aspects of the study such as maintenance cycles and design life.

The research has produced EC data for different types of geosynthetics and highlighted the lack of representation of geosynthetic products in commonly employed EC databases. Further research is required to calculate EC data for a range of geosynthetics products formed from various manufacturing techniques and polymers. These values can then be presented in a construction EC database or a more specific geosynthetic related database. The formation of such a database, will improve the ‘state of play’ with regards to sustainable construction in the UK. It will also see geosynthetic manufacturers become more energy efficient as they aim to produce ‘greener’ lower EC geosynthetic products.
7 REFERENCES


Reducing the Environmental Impact of Construction Through Use of Geosynthetics


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Reducing the Environmental Impact of Construction Through Use of Geosynthetics


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APPENDIX A  (PAPER 1)

Full Reference


Abstract

Some of the most sustainable and economical benefits of using geosynthetics are found in reinforcement applications. These applications allow the use of lower quality on-site material such as fine grained soils often referred to as ‘marginal fills’. This paper identifies the state of practice and understanding of designing with these soils in applications such as embankments, slopes and retaining walls. Designers often rely on published guidance documents and the paper discusses the influence BS 8006 (2010) has on the use of ‘marginal fills’ in construction and how the need for clearer more specific guidance. The study highlights that often well compacted fine grained fills placed close to optimum moisture content generate suctions, and this results in relatively high strength interaction between the fill and geosynthetic reinforcement. In cases where a fine grained fill with high moisture content is used, geosynthetic reinforcement that provides in-plane drainage may be beneficial.

Keywords – Geosynthetics, Marginal Fills, Design

Paper type – Conference
1 INTRODUCTION

In the context of this paper marginal fills are defined as lower quality, poor draining, cohesive fills with a high content of fines and often possessing low mechanical characteristics, such as low shear strength. With marginal fills often being easily available and providing both economic and sustainable benefits they are becoming a popular alternative to high quality granular fill. However there are still some uncertainties in the use and designs using these materials. This paper aims to investigate these further. There are a number of different applications in which marginal fills can be applied and this paper focuses on backfill/fill applications such as embankments/slopes and reinforced walls. The reasoning behind this is that often it is in these applications where the design and use of marginal fills lacks clarity.

The main areas of the paper relate to:
- Developing an understanding of the function of geosynthetic reinforcement and the design process.
- Understanding the current design principles and processes when applying marginal fills.
- Reviewing the guidance material provided particularly in BS 8006 (2010) to see whether there is a lack of clarity around fill material selection.

The paper aims to clarify the use of marginal fills when combined with geosynthetics and identify any factors that may be limiting their use. It will also consider ways in which these factors could be addressed.

2 REINFORCEMENT WITH GEOSYNTHETICS

2.1 INTRODUCTION

When a geosynthetic is combined with soil to provide the function of reinforcement the soil is then referred to as ‘Reinforced soil’. ‘Reinforced soil’ has improved mechanical characteristics such as increased tensile and compressive strengths. In general when a geosynthetic is used to reinforce a geotechnical structure its main task is to resist applied stresses or to prevent unacceptable deformations.

2.2 DESIGN PROCESSES

The literature reviewed presents a number of different design processes and methods. Although there are differences in the approaches and no uniformly agreed method, all the methods do however require the same general design parameters. Also all the methods show a high level of importance on the soil-geosynthetic interaction characteristics. The properties of the backfill being employed ultimately govern the stability of the structure. The majority of design methods being used are for good quality fills such as free draining granular fill, with only a few methods considering the effects of cohesive soils. There is a lack of clarity in the design process and analysis for these fine grained fills.

2.3 MATERIALS

Geosynthetics most commonly employed in reinforcement applications are geogrids, geotextiles and geocomposites. Each of these geosynthetic products can provide a variety of strength and drainage properties, dependant on their manufacturing technique. Geogrids can be woven or extruded and allow drain-age in the normal direction via high permeability.
through their apertures that are filled with soil. They provide very little lateral drainage in the plane of the geosynthetic and therefore can be considered to be impermeable in that direction.

Geotextiles used as reinforcement can provide some lateral drainage. The degree of in plane transmissivity depends on whether they are woven or non-woven and on the confining stress, with non-woven geotextiles having a higher transmissivity. For the purpose of this paper, because of their low transmissivity, woven geogrids and geotextiles can be considered to be impermeable reinforcement in the plane of the geosynthetic.

3 APPLICATION OF MARGINAL FILLS

3.1 INTRODUCTION

Use of marginal backfills has proven economical and environmental benefits, hence there are strong reasons for increased use. With proven benefits the question arises however as to why they are not being used more widely? The engineering properties of marginal fills can create concern for designers.

With a number of different design methods for traditional backfills and ambiguity on which design method is most suitable, this situation is not any clearer for marginal backfills. However there is a substantial body of evidence of applications where marginal backfills have been applied successfully. Also, with research and technological advances in the type of geosynthetics being available, the less favorable soil mechanical properties may be balanced using more technical geosynthetic products.

3.2 EXCESS PORE WATER PRESSURES

There has been significant research carried out in order to recognise the problems behind the application of marginal/cohesive fills and to provide a possible solution. One of the biggest challenges relates to poor drainage capabilities when utilising wet materials.

A noteworthy piece of research was carried out by Rowe & Jones (2000) who looked at the innovative properties of geosynthetics. They focus on the issue of wet cohesive fills and the problems that arise with their use, such as low strength, high moisture con-tent, creep and low bond strength between the reinforcement and the soil. Marginal/cohesive fills have high fines content and early research showed that the relative volume of the fine grained portion of the fill controlled the shear strength of the reinforced soil (Schlosser & Long, 1974). Soils classed as marginal/cohesive can have a wide range of different properties, with those marginal fills with lower fines content having increased shear strength properties compared to those with a higher fines content. This means that certain categories of marginal fills may be suitable for specific applications.

A number of trials/case studies have been carried out with the use of impermeable reinforcement to understand the interaction between the reinforcement and wet cohesive soils. Research by Murray & Boden (1979), Ingold (1979) and Lee (1976) led to the conclusions that the insertion of impermeable reinforcements in a clay fill can lead to excess pore water pressures at the soil-reinforcement interface. This is claimed to cause a reduction in the soil-reinforcement bond and reduces the overall strength of the structure in the short term (Rowe & Jones, 2000). A conclusion is that if there was a method of reducing or eliminating the excess pore water pressures, this would result in more stable structures. This led to the
concept of including a permeable reinforcement element which may also act as a drain-age layer.

It should be noted that many reinforced soil structures and earthworks have been successfully constructed utilising cohesive fills at near optimum moisture content and reinforcements which are defined in this paper as impermeable.

Use of marginal fills and applications as backfills in reinforced soil structures, has been researched by Mitchell & Zornberg (1995). Their work also recognises the problems surrounding pore water pressure generation and the inclusion of permeable reinforcing elements. Mitchell & Zornberg (1995) discuss an experiment carried out by the Transport and Road Research Laboratory (TRRL), U.K. This was used to investigate the feasibility of wet cohesive fills, by constructing a full-scale experimental reinforced wall. The construction and instrumentation used is described by Boden et al. (1978). The pore water pressures were measured during construction of the embankment and the tests showed the generation of high construction excess pore water pressure.

High excess pore water pressure can have a number of undesirable effects on cohesive soils. The clay minerals within the soils can often attract and absorb water leading to the soil swelling in volume. This increase in soil pore pressure and volume could lead to large deformations, reduction in shear strength and possible failure. Seasonal changes in moisture content through wetting and drying can cause significant volume changes and reduction in shear strength via a progressive failure mechanism.

The use of a reinforcing element that also enables drainage may allow control of pore water pressures through dissipation of excess pore water pressures. The reinforcing material can be permeable in the normal direction, which will allow the passage of water from the soil to that below, but more significant is the requirement for in plane drainage capacity as this reduces drainage path lengths and speeds up dissipation of excess pore pressures (Rowe & Jones, 2000). This approach of promoting lateral drainage in combination with soil reinforcement is also considered by Christopher et al. (1998). Christopher et al. (1998) provide complete design guidance for reinforced soil structures with wet marginal backfills. In this paper Christopher et al. (1998) state three adverse conditions of pore water pressure generation and/or loss of strength due to wetting, that can be of concern when reinforcing marginal/poor draining backfills. The three conditions are (see Figure 1):

a) Generation of pore water pressures within the reinforced fill
b) Wetting front advancing into the reinforced fill
c) Seepage configuration established within the reinforced fill

Christopher et al. (1998) suggest that the use of permeable reinforcements could be employed to control the three conditions mentioned. The use of permeable reinforcement does not just address stability problems but can have significant construction benefits, by helping in the compaction of the fill (Indraratna et al., 1991). An example of a particular permeable reinforcement is a nonwoven geotextile. Although a suitable nonwoven geotextile has good drainage characteristics, tests on the development of soil-reinforcement bond (Smith et al. 1979) show that nonwoven geotextiles do not have high strength or in-plane stiffness. The solution could be to combine existing materials to form a composite, for example a nonwoven geotextile with a geogrid.

The creation of a composite material that has both drainage and reinforcement functions is considered a possible solution to designing with wet marginal fills. Work by Heshmati (1993)
studied the effects of combining a drainage material with a geogrid in wet clay soil. He concluded that the drainage and reinforcement functions were both as important as each other in producing a stable structure.

Figure 1. Reinforced marginal fill: Different conditions of concern (Christopher et al., 1998)

3.3 IS THERE A NEED FOR A COMPOSITE MATERIAL?

It is clear that significant research has been carried out into the drainage properties of marginal/cohesive fills. The research shows that in order to utilise wet marginal fills there is need for a geosynthetic that provides both drainage and reinforcement functions. However although this may be true for cases of fill with high moisture content, many reinforced structures utilising marginal/cohesive fills have been constructed with the use of impermeable reinforcements.

The work carried out by Rowe & Jones (2000), Christopher et al. (1998), by Murray & Boden (1979), Ingold (1979) Lee (1976) and others (Section 3.2) focuses on the issue of excess pore water pressures. This is one of the main reasons a permeable reinforcement may be suggested, in order to dissipate these high excess pore water pressures. How-ever a number of studies have shown that for reinforced structures constructed of cohesive fills compacted close to optimum moisture content, the pore water pressure is negative following compaction.

Dobie (2010) discusses a study by Farrar (1978) which presents pore water pressure data from a highway embankment constructed using compacted London Clay. The fill was constructed over an 18 month period and pore water pressure measurements were taken straight after construction, two years and four years later. The results (Figure 2) showed that the upper 8m of the fill remained in suction and positive pore water pressures were recorded below this level. This helps to add to the conclusions made by Dobie (2010) that a well compacted clay fill is likely to be in a state of suction up to sizeable depths. Pore water pressures only become positive at the base of fills higher than 10 to 15m. This is however dependent on the moisture content at placement, with lower suctions achieved if the clay is placed at moisture contents wet of optimum.
The conclusions made by Dobie (2010) and the findings from work carried out by Farrar (1978), Penman (1978) and Liu et al (1994) indicate that in many cases high excess pore water pressure are not generated, rather the reinforced structure is in a state of suction, or negative pore water pressure. This means that the use of a composite drainage-reinforcement geosynthetic would be unnecessary and uneconomical. The more economical and practical solution would be to employ impermeable reinforcements, with other commonly used drainage methods, such as surface drains and mineral drains at the base of the fill, to control the availability and ingress of water that may result in loss of the suctions and softening of the clay over time.

In cases where the fill is very wet or high structures are constructed (greater than 15m) in-plane drainage may be of benefit. In these cases a composite material or a combination of geosynthetics providing both drainage and reinforcement may be beneficial.

3.4 DEFORMATION AND LIMIT STATE DESIGN

One of the biggest challenges associated with the use of marginal fills to build reinforced structures is the anticipated increase in horizontal and vertical deformations. These deformations can occur both during and after the construction phase, with ‘high fines’ soils more likely to deform than granular fills. Christopher & Stulgis (2005) highlight several issues that may arise from increased deformation that should be considered in the design:

- Maintaining wall alignment during and after construction
- The possible deformation of supported structures
- Down drag on the back of facing units and connections
- Increased risk of tension cracks

In order to control the short and long term deformations it is important to understand and control moisture in the soil. As Christopher & Stulgis (2005) mention, fine-gained soils placed a few percent dry of optimum often strain-soften and therefore lose strength. This leads to higher deformations and a loss in soil/reinforcement bond strength. Long term movement in dry fine-grained soils is also possible from hydro-compaction. Fine-grained soils placed wet of optimum will consolidate and thus deform over time. It is very difficult to predict the

![Figure 2. Profile of pore pressure versus depth in London Clay highway embankment (Dobie, 2010)](image)
level and amount of deformation even for structures with good quality backfill, so with marginal ‘high fines’ backfill the situation is no clearer. As Mitchell & Zornberg (1995) state, horizontal displacement depends on a number of different factors which include compaction efforts, reinforcement and facing properties.

The use of a permeable geosynthetic may help to address the drainage issues related to marginal back-fills and in turn speed up the consolidation process. However drainage does not change the magnitude of deformations. Care should be taken as incorrect use could provide a path for water to enter the structure.

It is worth considering however the application of the structure when designing for deformation. Certain applications such as an embankment that is not supporting any loads may have a higher serviceability limit state, hence higher than normal deformations may not be a concern. Dealing with each application on an individual basis will allow more designs to be carried out with serviceability limit state in mind, in particular those applications where high deformations may not be critical or lead to failure.

4 DESIGN DOCUMENTATION

4.1 INTRODUCTION

On an international level there is a range of different guidelines and standards employed in the design of reinforced soil structures. In the UK British Standards BS 8006(2010) is referred to for guidance. In order to completely understand the use of marginal fills and how they are accounted for, it is important to assess relevant guidance in currently available standards.

4.2 BS 8006:1-2010

BS 8006(2010) is the code of practice for strengthened/reinforced soils and other fills. The document goes into detail into on design methods for reinforced structures as well as the testing procedures and stability checks.

BS 8006(2010) provides detailed guidance notes for an experienced user or designer. It is more than adequate for a designer/engineer using standard fills and working on a common application. However as mentioned previously one of the biggest benefits of reinforcement via geosynthetics is that it allows the use of poorer quality site material. Not only does this have cost benefits but considerable sustainability gains. The reduction in virgin material required as well as less transport of new/waste material leads to significant carbon footprint reductions. The problem is that this document leaves a lot of uncertainty with respects to use of marginal fill materials, leading designers/engineers to use conservative approaches, implying there would be a risk employing a geosynthetic solution using marginal fills, and hence encouraging more ‘traditional’ solutions or use of high quality granular fill materials. One example of this is found in BS 8006(2010) clause 3.1.3.2., where it is stated that ‘General cohesive fill’ as defined in the Specification for Highway Works (1) should not be used in the construction of reinforced soil walls or abutments and may be used with caution in steep slopes. With marginal fills often being classed as cohesive fills, this statement is potentially prohibiting the use of marginal fills and encouraging unsustainable and uneconomical design solutions.

More work and testing needs to be carried out in order to gain data on the interaction of geosynthetics with a range of materials. This testing and experimentation should then allow the BS 8006(2010) to class materials based on their mechanical characteristics and physical
properties. This could lead to the creation of a framework, which would allow fills that are currently considered marginal to be used for specific applications, thus increasing their utilisation. This would help to reduce uncertainty and ambiguity, and allow designers to obtain the mechanical characteristics of their onsite material, and assess whether it is suitable for use with geosynthetics.

5 CONCLUSION

A review of the literature has presented some valuable findings and has clarified uncertainties surrounding the design and use of marginal fills. Although use of marginal fills provides proven sustainable and economical benefits they are still seldom utilised. Some key conclusions can be made from this review.

The design process and methods are not simple or straightforward. There are a number of different design methods available, with no uniformly agreed process. The design methods also produce a wide range of variability in the results of analyses. With few methods incorporating the use of low quality fills such as fine-grained soils.

The use of marginal fills has been the topic of extensive research. This has shown that poor drainage characteristics of a wet marginal fill can provide hindrance to its use. One possible suggested way of overcoming this problem is by including a permeable reinforcement. The permeable reinforcement may help to provide drainage in both the normal and lateral directions. In order to fulfil both the drainage and reinforcement functions, a composite product may be used. The use of such a composite material or permeable reinforcement may however be unnecessary in many applications. Studies have shown that in many instances a clay fill compacted close to optimum moisture content can produce a reinforced structure that contains significant suctions (negative pore water pressure). In these cases, reinforcement defined as ‘impermeable’ in this paper in combination with adequate drainage such as surface and toe drains would be appropriate. The need and requirement for a composite material or geosynthetic with in-plane drainage would only be in cases where fine-grained soils with high moisture content are used as fill.

The problems faced by the use of marginal fills are also highlighted in BS 8006(2010) with certain clauses prohibiting their use. There seems to be a very strict approach to the mechanical characteristic of the fills that can be used. It may be argued that in some cases the standards are employing over-cautious guidelines. With the standards being very strict on the range of fill materials that can be used, this reduces the number of potential applications.

This study has helped to identify that marginal fills could be utilised to a much higher degree. Previous work and research has helped to justify this conclusion. However further work needs to be carried out to clarify ambiguities in the design methods and selection of fills. Collating data from tests and previous work could help to develop a database of acceptable fill materials, which could be used as a reference table for engineers and designers. In order to improve the use of marginal fills, sections within guidelines such as the British Standards should be created focusing on the specific engineering properties for a wide range of reinforcement applications. It could be concluded that overall the state of understanding in the topic is good, but the state of practice is lagging behind and the authors encourage practitioners to consider the utilization of marginal fills whenever commercially and/or environmentally beneficial.
6 REFERENCES


BS8006-1:2010. Code of practice for strengthened/reinforced soils and other fills


APPENDIX B  (PAPER 2)

Full Reference


Abstract

Geosynthetics are commonly employed in landfill applications; to serve a variety of functions. One specific example is the use of geosynthetics as under-drainage placed on the base of a landfill cell, underneath the engineered geological barrier. This paper presents a case study that compares the CO$_2$ emissions produced from three different solutions for under drainage, all employing geosynthetics but using varying products and quantities. The project used for the case study employed a geocomposite drain solution, however, other alternative solutions could have been included such as a continuous gravel layer or the use of gravel trenches. The Life Cycle Analysis boundaries set for this case study were of cradle to end of construction. The calculation process required embodied carbon data, as well as transport and construction details. These calculations provided a carbon footprint for each solution and showed the geocomposite drain solution to be more sustainable than the continuous gravel blanket. The results suggested that there was little difference in CO$_2$ emissions between the gravel trenches and geocomposite solution. However, in this project the Environment Agency (England and Wales) (EA) insisted on a continuous drainage layer, hence the gravel trenches were not an allowable option.

Keywords – Landfill, Drainage, Sustainability, Geocomposite, Geosynthetics

Paper type – Conference
1 INTRODUCTION

In recent times a strong emphasis has been placed on the damaging effects of CO\textsubscript{2} on the climate. The changing climate is an issue recognised worldwide and reported on by the United Nations through the World Meteorological Organization (WMO, 2013). The UK was the first government to turn this recognition of the changing climate into legislation through the Climate Change Act (TSO, 2008) and introduced a set of legally binding targets to reduce the UK greenhouse gas emissions by at least 80% below base year (1990) levels by 2050. The UK government developed a plan of action known as the Low Carbon Plan (DECC, 2011) which highlighted the interim targets and how these would be met. Although this plan does not focus specifically on construction projects, it has emphasised the need for the industry to be more sustainable as a whole with reduced greenhouse gas emissions. For the purpose of this paper sustainability is being defined as the means to reduce CO\textsubscript{2} emissions produced.

The UK government initially focused on reducing greenhouse gas emissions from energy use in buildings, transport and industrial activity. However, the construction sector can influence up to 47% of the UK’s total CO\textsubscript{2} emissions (BIS, 2010). With this in mind the UK government has set up teams such as the Innovation and Growth Team (IGT) to look at ways the construction industry can meet the sustainability agenda (IGT, 2010) as well as developing relevant strategies (BERR, 2008). Although the legislation does not currently target specific construction projects and solutions, government backed plans such as the Construction 2025 (BIS, 2013) aim to reduce greenhouse gas emissions by 2025 from construction by 50%. These plans and targets are raising awareness amongst those in the construction sector and helping to promote research and development of sustainable, low CO\textsubscript{2} construction solutions.

The use of geosynthetics is one such solution that has shown CO\textsubscript{2} reduction and sustainability benefits by providing material savings or allowing the reuse of poor quality on site fill. This leads to reduced transport of materials on and off site, providing both CO\textsubscript{2} and cost savings. These benefits have been reported on by the Waste and Action Resources Programme (WRAP) who produced a series of case studies, comparing geosynthetic and non-geosynthetic solutions in terms of both cost and CO\textsubscript{2} emissions (WRAP, 2010). The work by the European Association of Geosynthetic Manufacturers (EAGM) also highlighted the sustainable benefits of geosynthetics (Stucki et al., 2011), however, unlike WRAP (2010) which was limited to just reinforcement applications, the EAGM covered a range of applications. An example of an application that was covered both by the EAGM and in the work by Heerten (2012) in his LCA studies was the use of geosynthetics in landfills. Although there are many functions that a geosynthetic solution can provide in a landfill application, the case study presented in this paper looks at the function of drainage. More specifically it focuses on the use of geosynthetics in the under cell drainage system, which is used to relieve groundwater pressure beneath the base of the landfill. Figure 1 (Cooper & Fowmes, 2011) illustrates the landfill lining system layers, as well as the geocomposite under drainage layer design used in the project.
The paper reports on a Life Cycle Analysis (LCA) case study which compares the CO₂ emissions produced by 3 different drainage solutions, which are illustrated in Figure 2. Although all three designs employ some form of geosynthetics, the two alternative designs also rely heavily on the use of imported granular fill. The LCA criteria that are set can vary between studies. The WRAP (2010) report employed boundaries of cradle to site, this covered all aspects from extraction/manufacture of the materials to delivery on site. In some cases the construction phase was also mentioned however it was not included as it was assumed to generate negligible CO₂. Other work by Kiani et al. (2008) which looked at the life of railway track beds worked to an extended scope of cradle to grave. The selection of the LCA criteria is governed by the aims and outcomes of the study as well the available data. In order to extend the work carried out by WRAP and provide a comparison of CO₂ emissions from the construction phase as well as the embodied and transport related CO₂, an LCA system boundary of cradle to end of construction was set. The aim of the study is to provide a CO₂ comparison between the three solutions and highlight whether the original design or the two possible alternatives would be more sustainable (Figure 2).

Figure 1. FCC Environment landfill lining system design drawing (Cooper & Fowmes, 2011)

Figure 2. The original drainage layer employed (a) and two possible alternatives (b) and (c)
2 CASE STUDY DETAILS

The case study was based on a landfill site situated in South Wales. The study focused on the under drainage of one landfill cell, which covered an area of 5617m² (see Figure 3), and compared the CO₂ emissions produced by the geocomposite drainage (GCD) design actually employed and two possible alternatives (see Figure 2). The site was selected as both the alternative solutions had been considered at the design stage of the project. Although they were classed as credible alternatives, the EA required a continuous drainage layer, hence ruling out the use of the gravel trenches. This solution was still considered in the case study in order to understand how it would have compared to the other two solutions, if there was no requirement by the EA for a continuous drainage layer. The three solutions were all assumed to have equivalent performance as a drainage layer hence the ‘use’ and ‘life’ stages of the LCA were not considered in this study. The LCA study carried out was a CO₂ comparison, and not necessarily the total CO₂ footprint of each project as the emissions associated with activities used in both solutions were omitted, for example, set-up of the site, transport of machinery and operation of site cabins and welfare.

As-built and manufacturer data were used to calculate the amount and type of materials used in the GCD design, as well as the quantity of materials that would have been used in the alternative designs (see Table 1). Only those materials listed were considered in the scope of this comparative study. Materials such as the perforated pipes used in the perimeter drains, have not been included due to being common to all solutions. Similarly, those materials used in the lining system have not been included, as they will remain common to whichever underdrainage solution is selected. In order to retain accuracy, the use of first-hand data, where available was maintained throughout the study and the various LCA stages.
Table 1. Quantity of material required for each solution

<table>
<thead>
<tr>
<th>Solution</th>
<th>Components</th>
<th>Mass per unit area (kg/m²)</th>
<th>Quantity (tonnes)</th>
</tr>
</thead>
<tbody>
<tr>
<td>GCD</td>
<td>Non-Woven PP geotextile x 2</td>
<td>240</td>
<td>1.35</td>
</tr>
<tr>
<td></td>
<td>HDPE cuspatc core</td>
<td>520</td>
<td>2.92</td>
</tr>
<tr>
<td>Continuous Gravel</td>
<td>Non-Woven PP Geotextile</td>
<td>210</td>
<td>2.37</td>
</tr>
<tr>
<td></td>
<td>Aggregate (Gravel)</td>
<td>-</td>
<td>3370.2</td>
</tr>
<tr>
<td>Gravel Trench</td>
<td>Non-Woven PP Geotextile</td>
<td>210</td>
<td>0.57</td>
</tr>
<tr>
<td></td>
<td>Aggregate (Gravel)</td>
<td>-</td>
<td>806.4</td>
</tr>
</tbody>
</table>

3 EMBODIED CARBON

The first stage of the LCA is accounting for the material embodied carbon, which is often also expressed as embodied energy. This can be defined as the carbon emitted or the energy consumed to produce a material, right the way from extraction of the raw material to the manufacture of the product, often referred to in LCA terms as “cradle to gate”. There are a number of sources for embodied carbon data, however in the UK the Inventory of Carbon & Energy (ICE) database produced by the University of Bath (Hammond & Jones, 2008) focuses specifically on the needs of the construction industry. Most of the data used in compiling the inventory was in fact data that was collected from secondary resources. The original database included materials that were specified by the Chartered Institute of Building Services Engineers (CIBSE, 2006) and initial embodied energy values taken from the handbook created by Boustead & Hancock’s (1979). The ICE database has continued to develop and now boasts a database of over four hundred different materials and their respective embodied energy/embodied carbon values. In the UK it is the preferred source of embodied carbon data and was used by WRAP (2010) and also employed by the EA in their carbon calculator (EA, 2012).

In this case study there were three main components; gravel, polypropylene non-woven geotextile and HDPE cuspatc core. The embodied carbon values for each component was sourced from the ICE database and multiplied with the quantity required to provide the CO₂ emissions produced from this phase of the LCA for each solution (see Table 2).

Table 2. CO₂ emissions from the embodied carbon of the materials

<table>
<thead>
<tr>
<th>Solution</th>
<th>Components</th>
<th>Embodied Carbon Value (kgCO₂/kg)</th>
<th>Quantity (tonnes)</th>
<th>Total CO₂ emissions (tCO₂)</th>
<th>Total (tCO₂)</th>
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<td>4.63</td>
<td>10.27</td>
</tr>
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<td></td>
<td>HDPE</td>
<td>1.93</td>
<td>2.92</td>
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<tr>
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<td>Gravel Trench</td>
<td>Polypropylene</td>
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<tr>
<td></td>
<td>Aggregate</td>
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<td>806.4</td>
<td>4.19</td>
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</tbody>
</table>

4 TRANSPORT EMISSIONS

The LCA boundaries employed for this study, as mentioned previously, is of cradle to end of construction. The embodied carbon of the materials includes all the emissions that satisfy the LCA boundaries of cradle to gate. In order to progress the LCA analysis to cradle to site, the material associated transport emissions were also calculated. The as-built data was used to
acquire transport distances of the geosynthetics and quarried aggregate. The amount of fuel consumed and then subsequently the CO$_2$ emissions produced were calculated using the transport distances.

The road transport mechanism was assumed to be a rigid 20 tonne vehicle; this was justified by the contractor and material suppliers, and was also consistent with previous work by WRAP (2010). The fuel consumption of one truck in conjunction with the CO$_2$ emissions produced per litre of fuel was used to calculate the total emissions from the road transport of materials. The road freight statistics provided an average mpg for a 17.5t to 25t rigid HGV (Heavy Goods Vehicle) of 9.4 (Department for Transport, 2012) which is equivalent to 3.33 km/ltr. The emissions value for fuelling station diesel is 2.5725 kgCO$_2$ per litre of fuel (DEFRA, 2011). Table 3 shows the total CO$_2$ emissions for the road transport of the materials. The distances stated in Table 3 are a single journey and multiplied by two in the calculations (see Equation 1) to account for the roundtrip of the trucks.

$$C = \beta(2DT/\alpha)/1000 \quad (1) \quad [\text{Equation}]$$

Where $C$= Total CO$_2$ emissions (tCO$_2$), $D$= distance of transportation (km), $Q$= Quantity of material (tonnes), $T$= Truckloads of materials $= Q/20$, $\alpha$= Fuel consumption of rigid HGV and $\beta$ = CO$_2$ emissions per litre of fuel, respectively.

<table>
<thead>
<tr>
<th>Solution</th>
<th>Components</th>
<th>Quantity (tonnes)</th>
<th>Distance (km)</th>
<th>Truckloads</th>
<th>Fuel Consumed (Litres)</th>
<th>CO$_2$ emissions (tonnes)</th>
<th>Total (tCO$_2$)</th>
</tr>
</thead>
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<td>418.4</td>
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<td>251.5</td>
<td>0.65</td>
<td>0.65</td>
</tr>
<tr>
<td>Continuous</td>
<td>HDPE</td>
<td>2.92</td>
<td>418.4</td>
<td>1</td>
<td>251.5</td>
<td>0.65</td>
<td>11.92</td>
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<tr>
<td>Gravel</td>
<td>Polypropylene</td>
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<td>418.4</td>
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<td>251.5</td>
<td>0.65</td>
<td>11.92</td>
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<tr>
<td></td>
<td>Aggregate</td>
<td>806.4</td>
<td>43.1</td>
<td>41</td>
<td>1062.8</td>
<td>2.73</td>
<td></td>
</tr>
</tbody>
</table>

5 CONSTRUCTION EMISSIONS

The final stage of the calculations is to include the construction related emissions, and complete the LCA boundaries of cradle to end of construction. Similar to the decision to not include some materials in the embodied carbon and transport calculations due to them being common to both solutions, there were also some construction processes that were not included such as the placement of geosynthetics. The placement of geosynthetics is not only common to all 3 solutions, but also produces very little CO$_2$ emissions hence can be assumed negligible. The calculations were split into three phases; excavation, placement and shifting. The GCD solution did not require any excavation or shifting of fill material, and as mentioned there were no placement related CO$_2$ emissions. Hence this meant that in comparison to the other two solutions the GCD had no construction related emissions. The actual construction can be seen in Figure 4.
The continuous gravel and gravel trench solutions required excavation and shifting of clay material, as well as placement of the gravel. The as-built and manufactured data was consulted to find out the machinery used as well as the duration of each phase of works. This information allowed the calculation of the total fuel consumed and subsequently the CO₂ emissions produced from the construction phase (see Table 4). It is important to note that in the instance of the continuous gravel solution, the 300mm excavation would have been carried out as part of the bulk excavation of the landfill cell. Hence the duration and time to excavate the 300mm layer is reduced and this also has cost and CO₂ benefits.

Table 4. CO₂ emissions produced from the construction phase

<table>
<thead>
<tr>
<th>Solution</th>
<th>Plant employed</th>
<th>Material</th>
<th>Volume work (m³)</th>
<th>Time Taken (hrs)</th>
<th>Fuel Consumption (ltrs/hr)</th>
<th>Total Fuel used (ltrs)</th>
<th>CO₂ Emissions (tCO₂)</th>
<th>Total (tCO₂)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Continuous Gravel</td>
<td>45 tonne excavator</td>
<td>Clay</td>
<td>1685.1</td>
<td>6</td>
<td>45.0</td>
<td>270</td>
<td>0.695</td>
<td>Continuous Gravel = 3.04</td>
</tr>
<tr>
<td>Continuous Gravel</td>
<td>21 tonne excavator</td>
<td>Clay</td>
<td>403.2</td>
<td>6</td>
<td>18.2</td>
<td>109</td>
<td>0.281</td>
<td></td>
</tr>
<tr>
<td>Gravel Trench</td>
<td>Bulldozer</td>
<td>Gravel</td>
<td>1685.1</td>
<td>3</td>
<td>27.3</td>
<td>82</td>
<td>0.211</td>
<td></td>
</tr>
<tr>
<td>Gravel Trench</td>
<td>21 tonne excavator</td>
<td>Gravel</td>
<td>403.2</td>
<td>8</td>
<td>13.6</td>
<td>109</td>
<td>0.281</td>
<td></td>
</tr>
<tr>
<td>Continuous Gravel</td>
<td>A30 Dumper Truck</td>
<td>Clay</td>
<td>1685.1</td>
<td>37.7</td>
<td>22</td>
<td>829</td>
<td>2.134</td>
<td></td>
</tr>
<tr>
<td>Gravel Trench</td>
<td>A30 Dumper Truck</td>
<td>Clay</td>
<td>403.2</td>
<td>9</td>
<td>22</td>
<td>198</td>
<td>0.509</td>
<td></td>
</tr>
</tbody>
</table>

Figure 4. Installation of GCD (photo courtesy of Wardell Armstrong)
6 RESULTS AND FINDINGS

The final results are compiled by combining the CO₂ emissions from each of the three LCA stages, to give a cradle to end of construction CO₂ comparison between the three solutions. The initial comparison is between the two continuous solutions and the results show that the GCD is more sustainable (see Table 5 and Figure 5). The 30tCO₂ difference between the two solutions is a considerable amount as it means the GCD solution only produces about a quarter of the CO₂ emissions that the continuous gravel solution would have produced. The GCD solution does have a slight advantage by having negligible construction emissions; however the major difference is in the embodied carbon of the materials and in the transport of the large quantities of gravel.

The EA insisted on a continuous solution, which would mean the use of gravel trenches could not be considered for this project. However, if this requirement was not in place the gravel trench solution also proves to be more sustainable than the continuous gravel layer. In fact it could be as sustainable as the GCD solution, which makes it a credible alternative if there are no specific design requirements to discount it as a viable option. The comparison does show that for all three solutions the construction emissions have little effect on the overall results. The majority of emissions are generated in the embodied carbon and transport stages of the LCA. A small increase or decrease in transport distances of bulk materials such as gravel can have significant impact on CO₂ emissions.

There is still need for more accurate material embodied carbon data, especially in for geosynthetics. Increased accuracy in the data sources could further help to show the sustainable benefits of geosynthetics but also validate and increase the accuracy of the results. In this case study a GCD solution was employed based on economic and design benefits, however, the case study results show that it was also the more sustainable option when compared to the continuous gravel solution.

Table 5. Summary of overall results

<table>
<thead>
<tr>
<th>Solution</th>
<th>Transport</th>
<th>Embodied</th>
<th>Construction</th>
<th>Total (tCO₂)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Geocomposite (GCD)</td>
<td>0.65</td>
<td>10.27</td>
<td>-</td>
<td>10.91</td>
</tr>
<tr>
<td>Continuous Gravel</td>
<td>11.92</td>
<td>25.65</td>
<td>3.04</td>
<td>40.61</td>
</tr>
<tr>
<td>Gravel Trench</td>
<td>3.38</td>
<td>6.15</td>
<td>1.07</td>
<td>10.60</td>
</tr>
</tbody>
</table>
7 CONCLUSIONS

The case study has shown a CO$_2$ comparison between three possible underdrainage solutions. The original solution applied in the project was geocomposite drainage, however the continuous gravel could also have been considered. Although the gravel trench solution could not have been used for this particular project due to requirements for a continuous layer, it also represents an alternative solution. The aim of the study was not only to provide a CO$_2$ comparison but also to demonstrate the significance of applying rigorous methodology. The issue of sustainability and low carbon construction is growing in importance and it is therefore essential to accurately forecast potential CO$_2$ savings by employing a robust approach. Selection of most designs is normally influenced by economic constraints; however, in many cases achieving both sustainability and economic benefits is not mutually exclusive.

The original GCD design employed in the project was found to be more sustainable than the continuous gravel alternative. There construction emissions produced in the installation of the GCD were assumed negligible therefore did affect the overall results. The major difference between the two solutions was the CO$_2$ emissions produced at both the embodied and transport stages. Although the GCD components have a much higher embodied carbon value per unit weight than the aggregate, the greatly reduced quantity generates much lower emissions. The transport of large quantities of gravel also produces large transport emissions and in this study over 11tCO$_2$ more than the GCD transports related emissions. However in this particular study even if the gravel was sourced from closer to the site, the GCD would still have been more sustainable.

The gravel trench solution was not applicable to this particular project, however without the requirements of a continuous drainage layer it could be a suitable alternative. It was for this reason that it was included in the comparison. The results indicate that the gravel trench solution would be very similar to the GCD in terms of CO$_2$ emissions, and more sustainable.
than the continuous gravel. Therefore, in projects without the requirement of continuous layer it would also be a sustainable solution, however the final selection of design between the gravel trench and GCD would most likely be governed by the economic benefits.

The cradle to end of construction LCA approach detailed in this paper can be used to compare the sustainability (as defined in this study by CO₂) of geotechnical design options, with and without geosynthetic elements. In this particular study all three solutions compared employed some form of geosynthetics albeit of various properties and quantities. The inclusion of construction emissions highlights that although not large compared to embodied and transport emissions, it should still be taken into consideration in any CO₂ comparative study. The use of accurate embodied carbon data is important in verifying any results produced and there is a need for the geosynthetic industry to produce more product specific data.

8 ACKNOWLEDGEMENTS

This paper was completed as part of an Engineering Doctorate project being carried out at CICE, Loughborough University. The authors would like to acknowledge the IGS (UK Chapter), CICE, Loughborough University and the EPSRC, who funded this project. The authors would also like to thank FCC Environment for the data provided.

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APPENDIX C (PAPER 3)

Full Reference


Abstract

Geosynthetics are commonly employed in landfill applications to provide containment in the capping layer, also referred to as a cover system. This paper presents a case study that compares the CO\(_2\) emissions produced from a compacted clay landfill cap as compared to one incorporating geosynthetics. The Life Cycle Analysis boundaries set for this case study were of cradle to end of construction, and including all processes from sourcing of materials through to the end of construction. As-built data provided by the contractors and manufacturers was used to calculate the carbon footprint of each solution. Comparison showed the geosynthetic solution to be more sustainable. However, deficiencies in standard database values revealed inconsistencies and a value for the embodied carbon of clay was calculated using primary data. The embodied carbon value calculated from primary data was much lower than the one initially employed and hence made the clay solution more sustainable where materials were locally available.

Key words – Geotextiles, Geomembranes; Landfill; Landfill Capping; Sustainability.

Paper type – Journal

List of notation:

\[ C = \text{Total CO2 emissions (tCO}_2\text{)} \]
\[ D = \text{distance of transportation (km)} \]
\[ Q = \text{Quantity of material (tonnes)} \]
\[ T = \text{Truckloads of materials} = \frac{Q}{20} \]
\[ \alpha = \text{Fuel consumption of rigid HGV} \]
\[ \beta = \text{CO}_2\text{ emissions per litre of fuel} \]
1 INTRODUCTION

The issues surrounding sustainability are at the forefront of modern day engineering. There has been considerable research into approaches that can produce more sustainable designs and construction processes with a growing demand for such solutions. The UK government has recognised this need by producing strategies for sustainable construction (BERR, 2008) and have also created groups such as the ‘Innovation and Growth Team (IGT)’ to look at ways in which the construction industry can meet the agreed sustainable low carbon agenda (IGT, 2010). In the context of this paper the term sustainability is defined as means to reducing CO$_2$ emissions, covering key aspects of the construction sequence from sourcing and transportation, to the re-use and wastage of materials.

There is significant scientific evidence that links greenhouse gases and CO$_2$ emissions with the changing climate. The increase in CO$_2$ has seen global temperatures rise with the period 2000-09 being the warmest decade on record (Royal Society, 2010). This changing climate has forced many nations and governments worldwide to take action to curb the emissions of CO$_2$ and other greenhouse gases. The UK government passed legislation that is one of the world’s first long term frameworks to tackle the problems associated with climate change. ‘The Climate Change Act 2008’ introduced a legally binding target to reduce UK greenhouse gas emissions by at least 80% below base year (1990) levels by 2050 (Great Britain Climate Change Act, 2008).

The construction sector is responsible for influencing 47% of the UK’s total CO$_2$ emissions (BIS, 2010) and therefore is one of the sectors where action is required to reduce emissions. Although the legislation does not specifically target individual construction projects, Construction 2025 (BIS, 2013) sets out a vision and a plan for long-term strategic action by government and industry. The plan includes a target of reducing greenhouse gas emissions from construction by 50% by 2015. This is raising awareness amongst clients, consultants and contractors and is leading to an increased level of research and acts as a powerful driver for utilising more sustainable, reduced CO$_2$, construction solutions. One particular solution that has been shown to provide CO$_2$ reduction benefits is the use of geosynthetics, which often lessen the amount of fill material imported. Whilst WRAP (2010) highlighted CO$_2$ and cost savings from the use of geosynthetics, the scope of this work was mainly limited to soil reinforcement applications. Work by the European Association of Geosynthetic Manufacturers (EAGM) covered a wider range of applications and functions and also highlighted the environmental benefits of geosynthetics (Stucki _et al._, 2011). An example of an application covered by the EAGM is the use of geosynthetics in landfill cover systems. The benefits of which are also discussed by Heerten (2012) in studies of Life Cycle Analysis (LCA) which also provide detailed comparison of climate damaging gases produced by non-geosynthetic and geosynthetic solutions. However, published studies that compare the CO$_2$ emissions produced by geosynthetic and non-geosynthetic solutions have limitations as they do not explicitly consider the source and accuracy of a material’s embedded CO$_2$ and they employ inconsistent LCA boundary conditions.

The construction of landfill capping layers can often be carried out with a number of different solutions. Effective containment provided by the capping layer reduces infiltration and associated leachate production and enhances the production and harvesting of bio-gases that can be used as a renewable energy source (Popov, 2005). Therefore, the capping layer and its effective design can provide both economic and sustainability benefits. There are a number of commonly employed solutions that use either clay or a combination of geosynthetics as an
Reducing the Environmental Impact of Construction Through Use of Geosynthetics

effective containment layer (Koerner & Daniel, 1997). Figure 1 shows a typical section of the geosynthetic based capping layer applied in the project used in this case study, as well as a commonly employed clay based alternative. The choice of which solution to apply varies from site to site. It is dependent on factors such as design, economics, material availability and timeframe available for construction.

This paper reports on a LCA case study that compared the environmental impact in terms of CO$_2$ emissions produced by the two different solutions illustrated in Figure 1. There are a number of different LCA criteria that can be used, dependent on both the input information and the system boundaries and requirements. The WRAP case studies (WRAP, 2010) included all the emissions produced from sourcing to the transportation of the materials to site. This included the extraction manufacture and delivery to site and can be classed as an LCA system boundary of cradle to site. Clear and concise system LCA boundaries are critical in any evaluation, and ensure that like for like comparisons are made (Figure 2). Examples of how different LCA criteria are employed in research of CO$_2$ for other applications can be found in work carried out by Crishna et al (2010) and Kiani et al (2008). Crishna et al (2010) employs system boundaries of cradle to site for a study of UK dimension stone, whereas the work by Kiani et al (2008) reports a study of railway track beds using an extended scope of cradle to grave, which also includes the reuse of materials. The LCA boundaries employed in this case study were of cradle to end of construction. The two capping solutions were assumed to have equivalent performance as a containment barrier hence the ‘use’ and ‘end of life’ stages of the LCA were not considered in this study. This assumption is also justified by the work carried out by Heerten and Koerner (2008), which looked at the performance of different cover system solutions. Therefore, for this case study the total CO$_2$ emissions calculated included the embodied carbon, transport of the materials and construction related emissions. The results obtained provided a comparison of the CO$_2$ emissions produced between the two solutions. The comparison highlights which solution would be more

Figure 1. Typical section of a) geosynthetic based capping layer employed in the project and b) a possible clay based alternative design

This paper reports on a LCA case study that compared the environmental impact in terms of CO$_2$ emissions produced by the two different solutions illustrated in Figure 1. There are a number of different LCA criteria that can be used, dependent on both the input information and the system boundaries and requirements. The WRAP case studies (WRAP, 2010) included all the emissions produced from sourcing to the transportation of the materials to site. This included the extraction manufacture and delivery to site and can be classed as an LCA system boundary of cradle to site. Clear and concise system LCA boundaries are critical in any evaluation, and ensure that like for like comparisons are made (Figure 2). Examples of how different LCA criteria are employed in research of CO$_2$ for other applications can be found in work carried out by Crishna et al (2010) and Kiani et al (2008). Crishna et al (2010) employs system boundaries of cradle to site for a study of UK dimension stone, whereas the work by Kiani et al (2008) reports a study of railway track beds using an extended scope of cradle to grave, which also includes the reuse of materials. The LCA boundaries employed in this case study were of cradle to end of construction. The two capping solutions were assumed to have equivalent performance as a containment barrier hence the ‘use’ and ‘end of life’ stages of the LCA were not considered in this study. This assumption is also justified by the work carried out by Heerten and Koerner (2008), which looked at the performance of different cover system solutions. Therefore, for this case study the total CO$_2$ emissions calculated included the embodied carbon, transport of the materials and construction related emissions. The results obtained provided a comparison of the CO$_2$ emissions produced between the two solutions. The comparison highlights which solution would be more
sustainable in terms of CO₂ emissions as well as how the input data can affect the overall results. It was not in the scope of this study to include cost, however, as noted in previous research (WRAP, 2010) there can also be significant cost benefits of employing the more sustainable solution.

Figure 2. Life cycle boundaries

2 CASE STUDY DETAILS

The case study was based on a landfill site situated in the south-east of England. The study focused on capping of one landfill cell, which covered an area of 9572 m², and compared the CO₂ emissions produced by the actual geosynthetic based design employed and an alternative clay design (see Figure 1). The site was selected as both clay and geosynthetic solutions had been used to cap different landfill phases over the life of the site, thus, the clay solution was a credible alternative. The LCA study carried out was a CO₂ comparison, and not necessarily the total CO₂ footprint of each project. Therefore, the emissions associated with compatible activities used in both solutions are omitted, for example, set-up of the site, transport of machinery and operation of site cabins and welfare etc.

The quantities of materials required for this project are listed in Table 1. Only those materials are listed that were considered in the scope of this comparative study, hence, the material data of the regulatory layer and restoration soils have not been included as they are the same for both design options. As-built construction data as well as manufacturer data was used to calculate the total amount of geosynthetic and clay materials required in the capping solutions. The use of such first-hand data was maintained throughout the study and in all the LCA stages; Embodied, Transport and Construction.

Table 1. Quantities of geosynthetics and clay required

<table>
<thead>
<tr>
<th>Material</th>
<th>Area Required (m²)</th>
<th>Mass (kg/m²)</th>
<th>Bulk Density (Mg/m³)</th>
<th>Quantity (tonnes)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Geomembrane</td>
<td>9572</td>
<td>0.939</td>
<td>-</td>
<td>8.99</td>
</tr>
<tr>
<td>Geotextile</td>
<td></td>
<td>0.320</td>
<td>-</td>
<td>3.06</td>
</tr>
<tr>
<td>Clay</td>
<td></td>
<td>-</td>
<td>2.00</td>
<td>19144</td>
</tr>
</tbody>
</table>
3 EMBODIED CARBON

The first stage of the calculation process was to quantify the embodied carbon of the materials employed. This accounts for all the CO₂ emissions associated with the production of the materials up until they are ready to leave the factory site. The embodied carbon values were sourced directly from the Inventory of Carbon & Energy (ICE), a database produced by the University of Bath (Hammond & Jones, 2008). The ICE database has been developed with the construction industry in mind, hence, there are over 1700 embodied energy records covering a range of materials from aggregates to concrete and steel. This is the most comprehensive database of its kind and the preferred source of data in LCA analyses carried out in the UK. The WRAP report and calculations (WRAP, 2010) also employed data from the ICE database. However, as with any Life Cycle Inventory there are a number of assumptions made, for example, Hammond & Jones (2008b) describe how differences in manufacturing processes and assumptions based on the fuel mixes, can create a natural variation in the embodied carbon coefficients and values must be used cautiously.

The geomembrane and geotextile employed in the geosynthetic solution have different embodied carbon values. The geomembrane used was formed from Linear Low Density Polyethylene, whereas, the geotextile was manufactured from Polypropylene. In the alternative design an embodied carbon value for the clay was also required. With there being no specific embodied carbon value for clay available in the ICE database, a value of quarried aggregate was assumed as the most representative. This assumption is revisited later in this paper. The embodied carbon values used from the ICE database as well as the total CO₂ emissions produced by these materials are given in Table 2.

Table 2. Total embodied carbon of materials

<table>
<thead>
<tr>
<th>Material</th>
<th>Original design- Geosynthetic</th>
<th>Alternative design</th>
</tr>
</thead>
<tbody>
<tr>
<td>Geomembrane</td>
<td>2.08</td>
<td>Clay</td>
</tr>
<tr>
<td>Geotextile</td>
<td>3.43</td>
<td>0.005</td>
</tr>
<tr>
<td>Embodied Carbon (kgCO₂/kg)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Quantity (tonnes)</td>
<td>8.99</td>
<td>3.06</td>
</tr>
<tr>
<td>Total CO₂ emissions</td>
<td>18.70</td>
<td>10.50</td>
</tr>
<tr>
<td>Total (tCO₂)</td>
<td>29.20</td>
<td>95.72</td>
</tr>
</tbody>
</table>

3.1 TRANSPORT EMISSIONS

The embodied carbon calculated accounted for all the CO₂ emissions up until the materials leave the factory site. In terms of LCA this would be classed as cradle to gate values. In order to progress the LCA to the next stage of gate to site, transport related emissions need to be accounted for. The as-built data was used to acquire accurate transport distances. In the case of the geomembrane, which is commonly imported from Europe, the manufacturer was contacted to get details of the route and transportation methods. Table 3 provides the transport distances.
Table 3. Material transport distances

<table>
<thead>
<tr>
<th>Material</th>
<th>Method</th>
<th>Distance (km)</th>
<th>Method (2)</th>
<th>Distance (km)</th>
<th>Total (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Geomembrane</td>
<td>Road</td>
<td>368.5</td>
<td>Water</td>
<td>201.2</td>
<td>569.7</td>
</tr>
<tr>
<td>Geotextile</td>
<td>Road</td>
<td>217.3</td>
<td>-</td>
<td>-</td>
<td>217.3</td>
</tr>
<tr>
<td>Clay</td>
<td>Road</td>
<td>3.5</td>
<td>-</td>
<td>-</td>
<td>3.5</td>
</tr>
</tbody>
</table>

The amount of fuel consumed and then subsequently the CO₂ emissions produced were calculated from the data in Table 3. Using data from previous work carried out by WRAP (WRAP, 2010) as well as information from contractors and material suppliers, a rigid 20 tonne vehicle was assumed as the road transport mechanism. The fuel consumption of the one truck in conjunction with the CO₂ emissions produced per litre of fuel was used to calculate the total emissions from the road transport of materials. The road freight statistics provided an average miles per gallon for a 17.5t to 25t rigid HGV (Heavy Goods Vehicle) of 9.4 (Department for Transport, 2012) which is equivalent to 3.33 km/ltr. The emissions value for fuelling station diesel is 2.5725 kgCO₂ per litre of fuel (DEFRA, 2011). Table 4 shows the total CO₂ emissions for the road transport of the materials. The distances stated in Table 4 are a single journey and multiplied by two in the calculations (see Equation 1) to account for the roundtrip of the trucks.

Table 4. CO₂ emissions from road transport of materials

<table>
<thead>
<tr>
<th>Material</th>
<th>Quantity (tonnes)</th>
<th>Distance (km)</th>
<th>Truckloads (whole)</th>
<th>Fuel Consumed (litres)</th>
<th>CO₂ Emissions (tonnes)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Geomembrane</td>
<td>8.99</td>
<td>368.5</td>
<td>1</td>
<td>221.4</td>
<td>0.57</td>
</tr>
<tr>
<td>Geotextile</td>
<td>3.06</td>
<td>217.3</td>
<td>1</td>
<td>130.5</td>
<td>0.34</td>
</tr>
<tr>
<td>Clay</td>
<td>19144</td>
<td>3.5</td>
<td>958</td>
<td>2038.4</td>
<td>5.24</td>
</tr>
</tbody>
</table>

Equation 1

\[
C = \frac{(2DT)}{\alpha} \beta \frac{1000}{\beta}
\]

The transport route of the geomembrane also involved crossing to the UK from mainland Europe by ferry. This water transport phase generated additional CO₂ emissions. These were calculated by again consulting the data provided by the Department of Energy & Climate Change (DEFRA, 2011). The average value for ferry transport of 0.05136 kgCO₂ per tonne.km was used in combination with the transport distance of 201.2 km and a geomembrane quantity of 8.99 t to give the overall emissions for this phase of the travel. The calculations showed that the water transport phase produced 0.18 tCO₂ therefore the total transport emissions of the geomembrane was 0.75 tCO₂ combined with the 0.34 tCO₂ for the
geotextile gave a total of 1.09 tCO₂ for the geosynthetic solution. This can be compared to the 5.24 tCO₂ for the alternative clay solution calculated using Equation 1.

### 3.2 CONSTRUCTION EMISSIONS

The scope of this case study also included the CO₂ emissions that would arise from the construction phase of the project. Similar to the decision to not include some materials in the embodied carbon and transport calculations due to them being common to both solutions, there were also some construction processes that were not included such as the unloading. A significant difference in placement techniques used was related to the amount of compaction required to the different layers employed in the two design solutions. Construction of the two solutions would require varying amounts of compaction effort and hence a large difference in the fuel consumed by the roller employed. The difference in compaction effort is because the clay barrier layer has to be compacted to achieve the required permeability, whereas the deployment of geosynthetics requires limited effort. However in the geosynthetic solution the regulatory layer requires more compactive effort than the clay solution in order to prepare the layer for the placement of the geosynthetics. In order to calculate the CO₂ emissions, it was important to determine the compaction effort of the Vibratory Roller employed. Contact with the contractor as well as technical information directly from the manufacturer of the compaction plant, via their technical data sheets (BOMAG, 2013) provided a compaction effort of 250m³/hour. Table 5 shows how this compaction effort in combination with other data was used to calculate the total CO₂ emissions produced.

The construction emissions from the compaction phase of the clay solution was 10.40 tCO₂ compared to the 1.89 tCO₂ for compaction of the regulatory layer in the geosynthetic solution. Although CO₂ emissions produced from the welding of the geomembrane were envisaged to have very little effect on the overall results, for completeness this was also calculated. Welding involved the use of a fusion welder with the data stated in Table 6. The diesel generator data (Hardy Diesel, 2013) combined with that of the fusion welder (Silicon Instrumentation, 2013) provided the total fuel consumed for this phase of work and produced 0.03tCO₂. This as predicted is very small and only accounts for 1.5% of the construction emissions produced by the geosynthetic solution, with a total of 1.92tCO₂ construction emissions produced in the geosynthetic solution.
Table 5. Data employed in calculation of total construction CO\textsubscript{2} emissions

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Plant</td>
<td>Bomag BW 216 D-4</td>
<td>Bomag BW 216 D-4/PD-4</td>
<td>Bomag BW 216 D-4/PD-4</td>
<td>Contractor</td>
</tr>
<tr>
<td>Fuel Cons. (lit/ hr)</td>
<td></td>
<td></td>
<td></td>
<td>Bomag</td>
</tr>
<tr>
<td>Clay</td>
<td>Clays</td>
<td>Clay</td>
<td>Clay</td>
<td>Design</td>
</tr>
<tr>
<td>Reg</td>
<td>Reg</td>
<td>Reg</td>
<td>Reg</td>
<td>Design</td>
</tr>
<tr>
<td>Thickness of layers placed (m)</td>
<td>0.25</td>
<td>0.3</td>
<td>0.3</td>
<td>Design</td>
</tr>
<tr>
<td>Comp. effort (m²/hr)</td>
<td>1000</td>
<td>833</td>
<td>833</td>
<td>Bomag</td>
</tr>
<tr>
<td>Time for 1 pass (hrs)</td>
<td>9.57</td>
<td>11.49</td>
<td>11.49</td>
<td>Calculated</td>
</tr>
<tr>
<td>Total no. of passes</td>
<td>24</td>
<td>2</td>
<td>4</td>
<td>Contractor</td>
</tr>
<tr>
<td>Total Time (hrs)</td>
<td>229.73</td>
<td>22.97</td>
<td>45.95</td>
<td>Calculated</td>
</tr>
<tr>
<td>Fuel consumed (ltrs)</td>
<td>3675.65</td>
<td>367.57</td>
<td>735.13</td>
<td>Calculated</td>
</tr>
<tr>
<td>kg CO\textsubscript{2} per litre</td>
<td>2.5725</td>
<td>2.5725</td>
<td>2.5725</td>
<td>DEFRA</td>
</tr>
<tr>
<td>t CO\textsubscript{2}</td>
<td>9.46</td>
<td>0.95</td>
<td>1.89</td>
<td>Calculated</td>
</tr>
<tr>
<td>TOTAL (t CO\textsubscript{2})</td>
<td>10.40</td>
<td></td>
<td>1.89</td>
<td></td>
</tr>
</tbody>
</table>

Table 6. Fuel consumption of fusion welding

<table>
<thead>
<tr>
<th>Solution</th>
<th>Plant Employed</th>
<th>Wattage (kW)</th>
<th>Length of welding (m)</th>
<th>Speed of Welding (m/min)</th>
<th>Total time (hrs)</th>
<th>Fuel cons. (Litres/hr)</th>
<th>Total Fuel (litres)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Geosynthetic</td>
<td>Fusion Welder</td>
<td>1.8</td>
<td>2120</td>
<td>2.5</td>
<td>14.13</td>
<td>0.682</td>
<td>9.64</td>
</tr>
</tbody>
</table>

4 RESULTS AND FINDINGS

The results show that the geosynthetic solution produced significantly lower CO\textsubscript{2} emissions than if an alternative clay solution had been employed. In both solutions the embodied carbon contributes the most towards the overall CO\textsubscript{2} emissions, although construction and transport phases also make a significant contribution and highlight the need for the inclusion of the construction phase in LCA studies (Table 7 and Figure 3).
Table 7. Total emissions produced by both solutions

<table>
<thead>
<tr>
<th>Solution</th>
<th>Transport</th>
<th>Embodied</th>
<th>Construction</th>
<th>Total (tCO₂)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clay</td>
<td>5.24</td>
<td>95.72</td>
<td>10.40</td>
<td>111.37</td>
</tr>
<tr>
<td>Geosynthetic</td>
<td>1.09</td>
<td>29.20</td>
<td>1.92</td>
<td>32.20</td>
</tr>
</tbody>
</table>

Figure 3. A bar chart presenting the total CO₂ emissions

The contribution of both the construction and transport related emissions is higher in the clay solution than in the geomembrane solution. This result was expected as construction of the clay cap required significant compaction effort, and also a large mass of material transport would be required. The results help to demonstrate where the largest emissions are generated and they clearly show that the geosynthetic solution is more sustainable even if the clay for the cap was available on site (i.e. with no transport emissions). In this particular case study the clay was sourced from a location close to the site (3.5 km) although in many sites this could be a larger distance, hence the clay transport related emissions are low for this case study. The calculation of construction related emissions is important as it allows their contribution to the overall solution emissions to be understood, which in the clay solution were over 10 tCO₂.

The geosynthetic solution was the one employed in the actual design, and it was selected due to its cost and time benefits. However, this study shows that it was also the more sustainable solution and with the help of these findings, the client could promote the environmental benefits. The results could also help them in achieving better scores on ratings such as the CEEQUAL (2010) and also any Environmental Product Declarations (BSI, 2012).
5 ACCURACY OF THE DATA

In many cases where common construction materials are used, embodied carbon values from databases such as the one produced by Hammond & Jones (2008) are accepted as the best available source. However, in this particular study where materials such as geosynthetics have been employed there is a need for more accurate product specific data. This study suggested that for both solutions the majority of CO₂ emissions came from the embodied carbon of the materials. This is somewhat expected for the geosynthetic solution due to their energy intensive manufacture process. It would be assumed that the embodied carbon of clay would be very small as it is simply excavated and loaded for transport. This would be consistent with the values provided in the ICE database, where the value of 0.005kgCO₂/kg was used for clay, and is the value stated for quarried aggregate, which is considerably smaller than the values for other quarried materials (Table 8). Had values for soil and general clay been used, this would have provided an even higher total embodied carbon for the clay solution. These values may seem suitable based on their classification; however, they include LCA processes such as crushing and screening, which would not be associated with the clay, used in this case study.

Table 8. ICE database embodied carbon values of quarried materials (Hammond & Jones, 2008)

<table>
<thead>
<tr>
<th>Material</th>
<th>Value (kgCO₂/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quarried aggregate</td>
<td>0.005</td>
</tr>
<tr>
<td>Recycled aggregate</td>
<td>0.005</td>
</tr>
<tr>
<td>Marine aggregate</td>
<td>0.008</td>
</tr>
<tr>
<td>Bitumen</td>
<td>0.490</td>
</tr>
<tr>
<td>Bricks</td>
<td>0.240</td>
</tr>
<tr>
<td>Clay: general (simple baked products)</td>
<td>0.240</td>
</tr>
<tr>
<td>Sand</td>
<td>0.005</td>
</tr>
<tr>
<td>Soil - general / rammed soil</td>
<td>0.024</td>
</tr>
<tr>
<td>Stone: general</td>
<td>0.079</td>
</tr>
<tr>
<td>Granite</td>
<td>0.700</td>
</tr>
<tr>
<td>Limestone</td>
<td>0.090</td>
</tr>
<tr>
<td>Sandstone</td>
<td>0.060</td>
</tr>
<tr>
<td>Shale</td>
<td>0.002</td>
</tr>
</tbody>
</table>

5.1 CLAY EMBODIED CARBON ANALYSIS

The aim of this part of the analysis was to calculate an embodied carbon value for the clay and compare it to the value employed in the case study. In order to calculate a comparable value it had to have the same LCA boundaries of cradle to gate. To meet this criterion, the calculations included three key LCA stages; excavation, loading of road going vehicle and transport to site exit. The emissions generated for these processes were calculated using data provided by an earthworks contractor and is summarised in Table 9.
The calculated value for embodied carbon for the clay of 0.0003 t CO\textsubscript{2}e/tonne was considerably lower than the ICE database quarried aggregate value of 0.005 t CO\textsubscript{2}e/tonne. It was also much lower than the values for other quarried materials (Table 8) that could have been used in the case study to represent the embodied carbon of the clay material. The difference in the values between the ones calculated and those stated in Table 8 may be due to the ICE database value including processes that are not relevant for clay, such as crushing and screening. Therefore, although using database values such as for quarried aggregates may be convenient, the embodied carbon value calculated in this analysis shows it may not be the most reliable approach thus highlighting the importance of attention to detail in LCA comparisons.

### Table 9. Data and Calculation of Clay Embodied Carbon

<table>
<thead>
<tr>
<th>Process</th>
<th>Plant Details</th>
<th>Fuel Cons.</th>
<th>Embodied Carbon</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Excavation and Loading</td>
<td>Komatsu PC450 (45t) 10 hours taken, 2800 m\textsuperscript{3} (5180 tonnes) clay (Bulk density of 1.85 Mg/m\textsuperscript{3}) moved</td>
<td>0.087</td>
<td>0.224</td>
<td>Contractor, DEFRA (2011)</td>
</tr>
<tr>
<td>Shifting</td>
<td>20t Road Going Dumper Truck 0.8 km journey to site entrance (1.6 km roundtrip)</td>
<td>0.024</td>
<td>0.06</td>
<td>Department for Transport (2012), DEFRA (2011), Contractor</td>
</tr>
</tbody>
</table>

| Total Embodied Carbon (t CO\textsubscript{2}e/tonne) | 0.0003 |

### 5.2 IMPACT OF CLAY EMBODIED CARBON ANALYSIS ON CASE STUDY RESULTS

The sensitivity of the case study results to the possible clay embodied carbon values is illustrated in Figure 4. The use of the embodied carbon value of calculated clay results in a reduction of around 90 t CO\textsubscript{2} as compared to using the value obtained from the ICE database. Using the lower value makes a considerable difference, resulting in the clay capping solution being more sustainable for this application (see Figure 5). It is considered that the calculated clay embodied carbon value is more reliable than the ICE database value for material that is excavated and transported without the need for additional processing, which is often the case in materials used in landfill liner and capping applications.
This analysis has shown that the ranking of design options in terms of CO$_2$ emissions can be dependent on the source and accuracy of material embodied carbon data. In this study, the geosynthetic solution is more sustainable if ICE database embodied carbon values are used for the clay but using calculated embodied carbon values for the clay reverses the ranking. In certain cases when the clay is available on site or only has to be transported a short distance (such as in this case study), it may be both more economical and sustainable to employ the clay solution. Based on this case study and the calculated embodied carbon value of clay, Figure 6 shows at what transport distance the use of the geosynthetic solution would be more sustainable in terms of CO$_2$ emissions. In this case study if the clay had been imported from a distance of 11 km or more the geosynthetic solution would become more sustainable. This is still a relatively short distance when compared to many other sites and the distances they typically import clay from. This comparison does not consider the relative cost of the two
solutions and the distance of clay transport may well influence the selection of design option based on cost.

![Figure 6. The effect of transport distance of clay on overall emissions](image)

6 CONCLUSIONS

This case study has shown a comparison of CO$_2$ emissions for two commonly employed containment solutions in the landfill industry. The aim of the study was not only to provide a comparison of the CO$_2$ emissions but also to illustrate the importance of applying rigorous methodology and accurate data collection. With sustainability being given increasing importance in construction it is essential to accurately forecast potential CO$_2$ savings by employing a robust approach. Selection of the design will be influenced by economic constraints; however, in many cases achieving both sustainability and economic benefits is not mutually exclusive.

The original geosynthetic design for this case study site was found to be more sustainable than an alternative clay solution. This conclusion was based on embodied carbon data commonly employed in the UK. However, the value of embodied carbon of the clay compared to the construction and transport emissions was questionable. There is no embodied carbon value for clay fill in the ICE database (Hammond & Jones, 2008) and therefore the designer has to select a value for general quarried materials.

In order to investigate the accuracy of the clay input values, further analysis of the embodied carbon of clay fill was carried out. The analysis involved calculating an embodied carbon value of clay directly from contractor data. The calculated value was considerably lower than the original value employed in the case study and also much lower than other quarried material values stated in the ICE database. The use of this revised value in the case study had a major effect on the results, making the clay solution a more sustainable alternative.

In this particular case study the transport distance of the clay fill was very short, hence minimising the transport CO$_2$ emissions. However, many sites import clay from greater distances, and in these cases using geosynthetics to form the barrier layer will be a more sustainable solution. If the clay in this particular case study had been imported from a distance of greater than 11 km, the geosynthetic solution would have generated lower CO$_2$ emissions.
The cradle to end of construction LCA approach detailed in this paper can be used to compare the sustainability (as defined in this study by CO₂ emissions) of geotechnical design options, with and without geosynthetic elements. The need for accurate input data such as the embodied carbon values is highlighted by the case study. Inaccurate data or values based on assumptions, can affect the overall results by a significant amount, making one solution seem more sustainable than another. Work is ongoing to review and revise geosynthetic embodied carbon data and to develop further case studies for reinforcement, drainage and pavement applications.

ACKNOWLEDGEMENTS

This paper was completed as part of an Engineering Doctorate project being carried out at CICE, Loughborough University. The authors would like to acknowledge the IGS UK chapter, CICE, Loughborough University and the EPSRC, which collectively funded this project.

REFERENCES


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APPENDIX D (PAPER 4)

Full Reference


Abstract

A 4 year Engineering Doctoral project has recently concluded at Loughborough University sponsored by the International Geosynthetics Society; UK Chapter. The aim of the project was to understand the environmental benefits of using geosynthetics and how they can reduce the CO\textsubscript{2} footprint of construction projects. Previous studies have shown geosynthetics to offer both cost and carbon savings when being employed in reinforcement applications, such as reinforced soil structures. This paper presents a case study that compares the CO\textsubscript{2} emissions produced from a reinforced soil and concrete retaining structure. The Life Cycle boundaries set for this case study were of cradle to site, including all CO\textsubscript{2} emissions from the sourcing of the raw material up until the finished product reaches the construction site. As-built data provided by the contractors and manufacturers was used to calculate the carbon footprint of each solution. Comparison showed the geosynthetic solution to be more sustainable, whilst also highlighting the carbon fixation benefits of employing a vegetated structure.

Keywords – Sustainability, Geosynthetics, Geogrids, Reinforcement, MSE

Paper type – Conference
1 INTRODUCTION

The changing climate and the risk it poses to human societies and natural systems has become an international concern and there is strong scientific evidence to suggest the earth is warming (Royal Society, 2010). The long-term impact of climate change would amongst other things include droughts, flooding and extreme weather events (IPCC, 2014) and a need to curb the effects of climate change and reduce global warming has been recognised by the United Nations. Research studies have shown that increased greenhouse gas emissions, and more specifically CO₂ emissions, are responsible for global warming (IPCC, 2013). Recognition of the problems and effects of increased CO₂ emissions, has led to legally binding emission targets in the form of the Kyoto Protocol (UN, 1998). This has then forced signatories of the protocol to take action and set legislation and emissions targets. Examples of this are the Emissions Trading System (ETS) set by the European Union (EU, 2013) and ‘The Climate Change Act 2008’ legislation set by the UK government (TSO, 2008).

The introduction of legislation and targets to curb CO₂ emissions has influenced how industries operate and encouraged them to be more sustainable. Although sustainability covers a wide variety of environmental factors, in this study it is defined as a means to reducing CO₂ emissions. One industry that makes a significant contribution to the overall global CO₂ emissions is the manufacturing and construction industry. It is estimated to account for 15% of the world’s CO₂ emissions (WRI, 2008). The construction industry has responded to this by taking measures to become more sustainable and is producing strategies to reduce their CO₂ emissions. Additionally, major clients such as the Asian Development Bank have taken initiatives to monitor and reduce their CO₂ emissions from transport projects. Whilst also developing a methodology for carbon footprinting of road projects (ADB, 2010). This drive for sustainable construction has led to research studies on sustainable construction solutions; one such solution is the use of geosynthetics. Case studies into the use of geosynthetic solutions have shown that they can provide considerable cost and CO₂ savings, when compared to more ‘traditional’ non-geosynthetic solutions (WRAP, 2010). These findings were back up by Heerten (2012) who also highlighted the CO₂ and energy savings of employing geosynthetic solutions. The use of geosynthetics when compared to more traditional alternatives does not only yield cost and CO₂ savings but also has other environmental benefits such as reduced acidification (Stucki et al., 2011), for a range of applications. One application that often provides CO₂ savings is reinforcement as it often allows the reuse of on-site material and hence leading to considerable cost and CO₂ savings.

This paper presents a Life Cycle Analysis (LCA) case study which compares the CO₂ emissions produced by a geosynthetic reinforced soil structure and a concrete retaining wall. The as-built project was constructed using a geosynthetic solution with a vegetated face; this is compared to a traditional design using concrete and steel (see Figure 1). The traditional design; a concrete wall reinforced with steel was designed in accordance to Eurocode 2 (Mosley et al., 2007). The study employed LCA system boundaries of cradle to site to compare the CO₂ emissions between the two solutions, accounting for CO₂ emissions from the extraction of the raw material right through till the finished product arrives on site. The scope and boundary conditions of LCA studies can vary depending on the data available and the end outcome required. There are examples of other studies such as that by Kiani et al. (2008) on railway track beds that worked to an extended system boundary of cradle to grave. However, in this study the two designs were assumed to have equivalent performance in the ‘use and life phases’ and negligible construction emissions based on other similar studies (WRAP, 2010). Therefore, based on the life cycle assumptions, scope of the study and data
availability an LCA boundary condition of cradle to site was employed. In order to maintain consistency with other studies the principles and framework suggested in BS EN ISO 14040:2006 (BSI, 2006) were followed.

2 CASE STUDY DETAILS

The case study was based on a road alignment project in the south of Wales, UK. Part of the project involved the construction of a geosynthetic solution (see Figure 1) which could also have been constructed with a commonly perceived traditional design. A concrete retaining structure is a credible alternative as these are extensively used in similar situations (Koerner et al., 1998). However, in this particular case study, the improved aesthetics of a vegetated face was an added benefit due to the location of the site. An LCA comparison of the CO₂ emissions was carried out to understand whether the solution employed was more sustainable than the non-geosynthetic alternative. The LCA study was a comparison of the CO₂ emissions produced from each solution and not the total carbon footprint of each project. For this reason CO₂ emissions that were common to both solutions such as those arising from site mobilisation and preparatory works were omitted. This was maintained through both the LCA phases covered in this study; embodied, transport and construction.

Table 1. Quantity of materials for each solution

<table>
<thead>
<tr>
<th>Solution</th>
<th>Component</th>
<th>Material</th>
<th>Quantity (tonnes)</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Geosystem</td>
<td>Geosynthetic</td>
<td>Geogrid HDPE</td>
<td>0.27</td>
<td>Geosynthetic supplier</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Bodkins HDPE</td>
<td>0.02</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Turf Liner LDPE</td>
<td>0.15</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Steel Panels</td>
<td>2.05</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Steel</td>
<td>Steel Brace bars</td>
<td>0.17</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Steel Fixing Pins</td>
<td>0.02</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Class 1a fill¹</td>
<td>Gravel</td>
<td>1064</td>
<td>Contractor</td>
</tr>
<tr>
<td>Reinforced Wall</td>
<td>-</td>
<td>Concrete</td>
<td>306</td>
<td>Calculated</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Steel reinforcement</td>
<td>3.74</td>
<td></td>
</tr>
</tbody>
</table>

¹ As specified by the Highways Agency (2009)
The original reinforced soil solution had a length of 55m, maximum height of 3.3m and total face area of 130m². A range of materials were used in the construction of this solution which included geosynthetic and steel elements as well as the import of class 1a gravel fill. The non-geosynthetic solution would not require any imported fill and would be made up of two main components; concrete and steel reinforcement. Throughout the study first hand data was employed where possible in order to maintain consistency and accuracy, therefore, the type and quantities of materials used were sourced from as-built contractor’s and manufacturer data, see in Table 1.

3 EMBODIED CARBON

Embodied carbon can be defined as the amount of CO₂ emissions released in the manufacture of a product/material (Hammond & Jones, 2008). This includes everything from the extraction of the raw material up until the completed product or material is ready to leave the factory site. Embodied carbon values represented to these LCA conditions are often referred to as ‘cradle to gate’. The term ‘Embodied Energy’ is often used interchangeably with embodied carbon, depending on how the data is to be presented whether in terms of energy consumed or CO₂ emissions emitted. Embodied carbon/energy values for materials employed in the construction industry are available from databases such as the Inventory of Carbon & Energy (ICE) V 2.0 (Hammond & Jones, 2011). The ICE database provides embodied energy/carbon values for more than 200 construction materials and is one of the most comprehensive databases of its kind. In the UK it is the primary source of embodied carbon data for construction projects. Examples of its use can be seen in the case studies carried out by WRAP (2010) as well as in carbon footprinting tools developed by the Environment Agency (EA, 2012).

In this case study a range of different materials were employed from HDPE geogrids to LDPE turf liner, each of which have a different embodied carbon value. The ICE database was used to source embodied carbon values for all the materials listed in Table 1. The values sourced are generic for a type of material and not product specific. For example there is no specific embodied carbon value listed for an LDPE Turf Liner instead a representative value for all LDPE’s is used. The embodied carbon values were then multiplied by the quantities of each material to give an overall embodied carbon/CO₂ emissions (see Table 2). The results from the embodied carbon phase of the LCA shows that the geosynthetic solution produces less CO₂ emissions than the concrete wall solution. However these results only account for ‘cradle to gate’ emissions. They do not include the CO₂ emissions associated with the transport of the material to site or those generated due to construction activities.
Table 2. The total embodied carbon for each solution

<table>
<thead>
<tr>
<th>Solution</th>
<th>Component</th>
<th>Material</th>
<th>Embodied Carbon (tCO₂/t)</th>
<th>Quantity (tonnes)</th>
<th>CO₂ per material (tCO₂)</th>
<th>Total Carbon emissions (tCO₂)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Geosystem</td>
<td>Geosynthetic</td>
<td>Geogrid HDPE</td>
<td>1.93</td>
<td>0.27</td>
<td>0.52</td>
<td>12.4</td>
</tr>
<tr>
<td></td>
<td>Bodkins HDPE</td>
<td></td>
<td>1.93</td>
<td>0.02</td>
<td>0.05</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Turf Liner LDPE</td>
<td></td>
<td>2.08</td>
<td>0.15</td>
<td>0.31</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Steel Panels</td>
<td></td>
<td>2.77</td>
<td>2.05</td>
<td>5.68</td>
<td></td>
</tr>
<tr>
<td>Steel</td>
<td>Steel Brace bars</td>
<td></td>
<td>2.77</td>
<td>0.17</td>
<td>0.46</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Steel Fixing Pins</td>
<td></td>
<td>2.77</td>
<td>0.02</td>
<td>0.06</td>
<td></td>
</tr>
<tr>
<td>Class 1a fill</td>
<td>Gravel</td>
<td></td>
<td>0.005</td>
<td>1064</td>
<td>5.32</td>
<td></td>
</tr>
<tr>
<td>Reinforced Concrete Wall</td>
<td>Concrete</td>
<td></td>
<td>0.12</td>
<td>306</td>
<td>36.72</td>
<td>42.0</td>
</tr>
<tr>
<td></td>
<td>Steel reinforcement</td>
<td></td>
<td>1.4</td>
<td>3.74</td>
<td>5.24</td>
<td></td>
</tr>
</tbody>
</table>

4 TRANSPORT EMISSIONS

The transportation of the materials from the ‘factory gate’ to the construction site is the next stage of the LCA. Therefore, in order to progress the study from ‘cradle to gate’ to ‘cradle to site’ the transport emissions had to be combined with the embodied CO₂ emissions (Table 2). The as-built and manufacturer data was used to calculate the transport distances, amount of fuel consumed and subsequently the CO₂ emissions produced. The transportation was all carried out by road and the method was assumed to be a rigid 20t HGV (Heavy Goods Vehicle) for both solutions; supported by contractors and manufacturers and consistent with other case studies by WRAP (2010) and Raja et al. (2014).

The quantity of material and transport distances were used to calculate the number of truckloads required to transport each material. This was then combined with the fuel consumption of one truck based on an average of 3.33km/ltr (9.4mpg) for a rigid 20t HGV (Department for Transport, 2012) to calculate the total fuel consumed. Combining this with the CO₂ emissions value for diesel of 2.5725 kgCO₂ per litre of fuel (DEFRA, 2011) gave the overall transport related CO₂ emissions for each material. The calculation process is demonstrated in Equation 1 and the overall results summarised in Table 3. Please note that the distances stated in Table 3 are for a single journey and multiplied by two in the calculations to account for a round trip of the truck.

\[ T = \beta(2DL/\alpha)/1000 \]  \[ 1 \]

Where T= Total CO₂ emissions (tCO₂), D= distance of transportation (km), Q= Quantity of material (tonnes), L= Truckloads of materials = Q/20, \( \alpha \)= Fuel consumption of rigid HGV and \( \beta \)= CO₂ emissions per litre of fuel, respectively.
Table 3. Total transport CO₂ emissions for each solution

<table>
<thead>
<tr>
<th>Solution</th>
<th>Materials</th>
<th>Quantity (tonnes)</th>
<th>Distance (km)</th>
<th>Truckloads</th>
<th>Fuel Consumed (Litres)</th>
<th>CO₂ emissions (tonnes)</th>
<th>Total (tCO₂)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Geosynthetic</td>
<td>Geogrid HDPE</td>
<td>0.27</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
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<td>54</td>
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<td>16</td>
<td>53.8</td>
<td>0.14</td>
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5 RESULTS AND DISCUSSION

The results of the individual LCA phases were combined to give an overall CO₂ comparison between the two solutions. The comparison shows that the geosynthetic solution is more sustainable than the alternative reinforced concrete wall solution. The geosynthetic solution produces 16.2 tCO₂ compared to the 42.2 tCO₂ produced by the concrete solution (see Figure 2). The biggest difference between the two solutions arises in the embodied carbon of the materials. Although the geosynthetic solution required a large quantity of imported granular fill, the other materials with considerably higher embodied carbon were required in much smaller quantities. In comparison the concrete may have a smaller embodied carbon value than the geosynthetics, however, it was required in much larger quantity hence giving increased CO₂ emissions.

The transport of the materials in the concrete solution produced only 0.2 tCO₂ and had minimal impact on the overall results. In the geosynthetic solution the transport of materials produced 3.8 tCO₂ which is much higher than that produced in the concrete solution. It also accounted for nearly a quarter of the overall CO₂ emissions for the geosynthetic solution. This is predominantly due to the transport of granular fill which accounted for almost 2.7 tCO₂. This project imported a relatively smaller amount of granular fill as a whole when compared to other projects such as those covered by WRAP (2010). However, the transport emissions calculated highlight that they can have a significant impact on overall results. Therefore increasing the amount of reused fill will not only have embodied carbon savings but also considerable transport CO₂ savings. Such CO₂ savings will also be backed up by savings in cost. Conversely had material not been available locally CO₂ and cost savings may diminish.

The results obtained show that although the geosynthetic solution may have been selected on preference of cost and aesthetics, it was also the more sustainable solution. The study presented a worst-case scenario for the geosynthetics and assumed the concrete wall solution would re-use the onsite fill. In some instances, fill would also have been imported for the concrete wall solution dependant on the geometry, site conditions and soil parameters. No ‘cut’ and associated off-site removal was required in either solution. However, in instances
where any ‘cut’ is required the associated transport CO₂ emissions should also be included in the study.

The results of this study show the sustainable benefits of employing a geosynthetic solution however it also highlights the importance of accurate embodied carbon data. There is still a lack of geosynthetic specific embodied carbon values. The sourcing and availability of such data would further increase the accuracy of CO₂ calculations and footprinting in the geosynthetic industry.

![Figure 2. Summary of overall CO₂ emissions](image)

### 6 CARBON FIXATION OF VEGETATION

Carbon fixation is the absorption of carbon into organic compounds by living organisms (Park & Allaby, 2013). Photosynthesis in plants is a prime example of carbon fixation as CO₂ is absorbed from the atmosphere and stored as chemical energy. Carbon fixation by vegetation combined with reusable energy techniques has allowed the development and research of zero-carbon infrastructure and communities. A study by Chung & Chung (2011) demonstrated how carbon fixation from the vegetation on the campus at Tajen University could be used to balance the CO₂ emitted from the power and fuel used.

The geosynthetic solution was found to be more sustainable and although it was vegetated for aesthetic reasons, this vegetation could also have significant environmental benefits. It would also continue to provide CO₂ savings post-construction in comparison to the reinforced concrete wall solution. The amount of CO₂ absorbed by the vegetation can be dependent on a number of variants such as geographic location, season and size/type of vegetation. However based on NASA data it was assumed that on average the vegetation in the UK absorbed 1.46 kgCO₂/m²/year (Earth Observatory, 2014). Therefore the geosynthetic solution would have a vegetated face area of 130m² which on average would absorb 0.189 tCO₂/year. Figure 3 highlights that after 85 years, 16.2 tCO₂ would have been absorbed by the vegetation on the
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geosynthetic solution, thus the comparative CO₂ emissions would be zero. However this study does not calculate the overall CO₂ footprint for each solution. Therefore after 85 years the geosynthetic solution would not be carbon neutral, it will simply have a comparative value of 0 tCO₂ when compared to the 42.2 tCO₂ produced by the reinforced wall solution. Dependant on what the overall CO₂ footprint for the geosynthetic solution is and its design life, eventually it will become a carbon neutral structure.

![Figure 3. Carbon fixation of the vegetated geosynthetic wall](image)

7 CONCLUSIONS

The case study has shown a CO₂ comparison between a geosynthetic and concrete solution. The as-built solution employed in the project was a geosynthetic reinforced retaining slope, however, a reinforced concrete retaining wall could have been a credible alternative. The results of an LCA analysis showed that the geosynthetic solution produced 60 % lower CO₂ emissions in comparison to the concrete solution. Although the geosynthetic solution required the import of fill material, the embodied carbon of the fill was relatively low when compared to that of the concrete and steel. Therefore, the use of large amounts of concrete and steel in the concrete solution gave it much higher CO₂ emissions.

The transport related emissions for both solutions may appear small in comparison to the embodied carbon emissions due to the scale and size of the projects. However, in the geosynthetic solution it still accounted for a quarter of the overall CO₂ emissions. This in main can be attributed to the import of over 1000 tonnes of fill material which alone require 54 truckloads in comparison to the 17 truckloads required in the transport of concrete and steel reinforcement. Therefore, even for a project of this size the import of fill can have a
significant impact on the overall CO₂ emissions and emphasises the sustainable benefits of re-using material, and reducing transport of material on and off site.

The case study was carried out to LCA boundary conditions of cradle to site. However there is scope in further studies to extend the LCA boundaries to cradle to end of construction or cradle to grave. In this case the construction techniques and methods were examined for each solution with the aid of manufacturer and contractor information. The majority of techniques and processes would have produced very small if any CO₂ emissions, as well as some of them being common to both solutions. Therefore the extension of the study to cradle of end of construction would have had very little impact on the overall results.

The geosynthetic solution had the benefit of being able to allow the growth of vegetation on the slope, giving it an aesthetic advantage over the concrete solution. Moreover, the growth of vegetation can also provide environmental benefits and help to further reduce CO₂ emissions in the ‘life’ phase of the structure. Carbon fixation in vegetation through photosynthesis absorbs CO₂ from the atmosphere. Therefore, the use of a vegetated structure would continue to provide CO₂ savings in comparison the concrete solution.

8 ACKNOWLEDGEMENTS

This paper was completed as part of an Engineering Doctorate project being carried out at CICE, Loughborough University. The authors would like to acknowledge the IGS (UK Chapter), CICE, Loughborough University and the EPSRC, who funded this project

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APPENDIX E  (PAPER 5)

Full Reference


Abstract

Changing climate and the damaging effects of CO₂ on the environment, has led to awareness throughout the construction industry of the need to deliver more sustainable solutions. Robust and rigorous carbon footprinting procedures for assessing solutions and projects can help to identify where action can be taken to reduce CO₂ emissions. It also promotes the marketing of those solutions and methods that produce lower CO₂ emissions. Geosynthetics often provide a cost efficient alternative to more ‘traditional’ construction techniques. Recently, work by the Waste & Resources Action Programme (WRAP) in the UK has shown that geosynthetic solutions can also produce much lower CO₂ emissions. However, there are still questions as to the reliability of such calculations. Although the methodologies employed are relatively consistent worldwide, the accuracy of the embodied carbon data available for use in calculations remains uncertain. Geosynthetic products are not specifically included in the embodied carbon construction materials databases most commonly employed in Europe, and often generic values for Polypropylene (PP) and Polyethylene (PE) are used. This paper presents a study where the embodied carbon data for geosynthetic products was calculated using first-hand manufacturing process data. The values calculated for two categories of geosynthetics were considerably lower than commonly employed database values. Non-woven geotextiles had an average embodied carbon value of 2.35 tCO₂e/t, with values for example geogrids of 2.97 tCO₂e/t for extruded and 2.36 tCO₂e/t woven.

Keywords – Geosynthetics, CO₂, Carbon footprinting, Embodied Carbon, Energy

Paper type – Journal (Submitted for Review)
1 INTRODUCTION

Global warming and climate change has become a concern worldwide. The increased frequency of extreme weather events and natural disasters has increased awareness amongst governments and compelled many into taking action. Increased awareness and decisions to take action gained impetus in 1988 when the Intergovernmental Panel on Climate Change (IPCC) was established by the United Nations Environment Programme and World Meteorological Organisation. The IPCC was formed to deliver a global scientific view on the current state of knowledge in climate change and its potential impacts both environmental and socio-economic (IPCC, 2014). International action was further strengthened in 1992 when the United Nations Framework Convention on Climate Change (UNFCCC) was established, which is an international treaty between 195 countries (United Nations, 1992). The UNFCCC encouraged industrialised nations to reduce greenhouse gas (GHG) emissions; leading to the Kyoto Protocol (United Nations, 1998) that set legal emissions commitments on 37 industrialised nations including the UK, other countries in the European Union (EU) and Australia amongst others.

The main factor attributed to climate change is the rise in GHG’s (EPA, 2014). Although there are a number of gases that fall under the banner of GHG’s, the biggest single contribution is made by carbon dioxide (CO₂), which accounts for 76% of the world’s GHG emissions (ECOFYS, 2013). The influence of CO₂ on total GHG emissions has made it the primary target in acting on climate change. One example is the European Union who have been actively involved in reducing CO₂ emissions and GHG’s by introducing the Emissions Trading System (ETS). Launched in 2005 it works as a ‘cap and trade’ principle limiting the amount of CO₂ emissions and GHG produced by energy using installations such as power plants and the manufacturing industry. The EU ETS operates in its 28 member countries, and also includes Iceland, Norway and Lichtenstein, and covers around 45% of the EU’s GHG emissions (European Union, 2013).

The rising global focus on reducing CO₂ emissions over a range of sectors is also impacting on the construction industry. Targets for sustainable low carbon construction are being set by countries worldwide and as in the case of this study, sustainability is being defined as a means of reducing CO₂ emissions. The construction industry’s drive for sustainable practices is focused on reducing CO₂ because this contributes to national targets for reducing emissions. However, it should be noted that this addresses only one part of the accepted concept of sustainability encompassing environmental, economic and social aspects. The Asian Development Bank (ADB) is an example of a client/investor that is focusing on the issue of reducing CO₂ emissions from construction and specifically focused on transport projects (ADB, 2010a). The ADB have also taken this a step further and subsequently developed a methodology for carbon footprinting of road projects (ADB, 2010b). Similarly, individual nations such as the UK are actively promoting sustainable construction practice, by producing strategies (BERR, 2008) and setting up dedicated groups such as the ‘Innovation and Growth Team’ to meet the low carbon agenda (IGT, 2010).

The growing emphasis on sustainable low carbon construction has stimulated research and ‘green’ construction worldwide (McGraw-Hill Construction, 2013). Research to date ranges from carbon footprinting of construction projects to the CO₂ saving benefits of employing certain solutions and products. One such group of solutions that have shown to provide CO₂ savings is the use of geosynthetics. Studies such as those by WRAP (2010) have demonstrated that geosynthetic solutions provide significant CO₂ and cost savings when compared to more traditional construction solutions. The case studies produced by WRAP
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(2010) covered a range of applications from embankments to reinforced walls. However, the scope was limited to the function of reinforcement and Life cycle boundary conditions of cradle to site (see Section 3.2). The European Association of Geosynthetic Manufacturers (EAGM) analysed four case studies (Stucki et al., 2011) to include the functions of reinforcement, drainage and filtration. Geosynthetic and traditional solutions were compared in eight environmental impact categories for Life Cycle Analysis (LCA) boundary conditions of cradle to grave. The impact categories were: cumulative energy demand, climate change (global warming potential), photochemical ozone formation, particulate formation, acidification, eutrophication, land competition and water use. The EAGM case studies not only extended the WRAP work on range of functions and applications but also highlighted the environmental benefits of employing geosynthetics across this range of environmental measures. The WRAP (2010) and Stucki et al. (2011) findings were supported by Heerten (2012) in his study that compared CO\textsubscript{2} and Cumulative Energy Demand (CED) between geosynthetic and traditional solutions in road and steep slope applications. In all these studies the calculation of CO\textsubscript{2} emissions for construction solutions follow a similar methodology and vary only on the Life Cycle boundaries and conditions set. However, as the embodied carbon data employed is derived from general database plastic values, there is the possibility of introducing inaccuracies into the calculations, and hence conclusions drawn from these studies.

There is a dearth of geosynthetic specific embodied carbon data contained within construction material databases across the world and this threatens the credibility of reported CO\textsubscript{2} savings possible from the use of geosynthetic based solutions. The aim of the study reported in this paper was to carry out analysis of embodied carbon values for the manufacture of common categories of geosynthetics. The paper reports the methodology employed in calculating an embodied carbon value for two categories of geosynthetics: geotextiles and geogrids. These categories contain four types of geosynthetics, which were further broken down into products and materials used. The average embodied carbon values calculated for the different types of geosynthetics were compared to values currently included in the commonly used databases.

2 EMBODIED CARBON DATA FOR GEOSYNTHETICS

The embodied carbon (EC) of a material can be defined as the amount of CO\textsubscript{2} emissions released in the extraction, manufacture and transport of the material. Often in reported EC studies the term embodied energy (EE) is used interchangeably with EC, depending on what form of analysis is being carried out. Embodied energy represents an embodied carbon equivalent value in terms of the energy used in these processes. Primarily, studies calculate EE of a material as this can be easily measured using appropriate energy meters. These EE values can then be converted to EC values using appropriate conversion factors derived from knowledge of the processes used to make the energy (i.e. coal, nuclear, hydro power generation) consumed in the manufacturing process (DEFRA 2013). Embodied carbon of a material is calculated as tonnes of CO\textsubscript{2} per mass of material (e.g. tCO\textsubscript{2}/t). Where the embodied carbon values are obtained from calculated embodied energy (e.g. see Section 4.2.1), the unit descriptor is tCO\textsubscript{2}e/t.

The representation of an EC value is dependent on which LCA stages are selected. For instance, EC values might represent all the CO\textsubscript{2} emissions up until the factory gate (cradle to gate) or once the material has reached its end location (cradle to site). An example demonstrating how boundary conditions can be applied is provided by Crishna et al. (2011) in
their study of EE and CO₂ of dimension stone. The EC data in combination with CO₂ emissions from other LCA phases such as construction, maintenance and waste give the overall carbon footprint of a project. However, the inclusion of different phases and activities is dependent on the scope of the study and the LCA boundary conditions set. EC values stated for materials in databases and inventories are often quantified for cradle to gate. The reasoning behind this is that it allows those employing the values to add on project specific transport emissions, which are governed by mode of transport and distances, rather than having this included within material embodied carbon values. An example of a database that states all its values as cradle to gate is the Inventory of Carbon and Energy (ICE) database v2.0 (Hammond & Jones, 2011).

The ICE database (Hammond & Jones, 2011) is one of the most comprehensive sources of EC data for construction materials worldwide. Formed by extracting data from peer-reviewed literature, the ICE database lists EE and EC information for over 200 different materials that are commonly used in the construction industry (Hammond & Jones 2008a). It has been employed in a variety of embodied carbon studies including work by Hughes et al. (2011) on earthworks and Zhang et al. (2011) on a typical bridge deck replacement. The ICE database has also become the primary source of data for a range of construction carbon footprinting tools, such as the one developed by the Environment Agency for England and Wales (Environment Agency, 2012). An alternative to the ICE database is a European life cycle analysis database called ‘EcoInvent v3.0’ (EcoInvent Centre, 2013). Unlike the ICE database, which specifically focuses on the EE/EC of materials, the EcoInvent database provides data for a wide range of life cycle indicators. As reported in Section 1, this range of indicators was used in the Life Cycle Assessments performed in the EAGM study (Stucki et al. 2011).

The EcoInvent and ICE databases both provide embodied carbon values for plastics that are used in the manufacture of geosynthetics and these reported values are comparable. This similarity is due to both databases obtaining values through review of the same sources of literature such as the work carried out by Boustead (2005) for Plastics Europe. However, there are differences between the databases in the form and description of the material data. Table 1 presents data from both ICE databases v2.0 and v1.6 and provides corresponding data from v2.2 of the EcoInvent Centre (2010). It should be noted that the EcoInvent v2.2 and v3.0 values for plastics are unchanged as they are obtained from the same literature (e.g. Boustead, 2005). Based on the material descriptions in the ICE database the EcoInvent data is only able to provide comparative values for a subset of the materials listed. There are also differences between the two ICE versions, with the materials listed in Table 1 having higher embodied carbon values in the latest dataset (v2.0) than in the earlier version (v1.6). The variation in embodied carbon data for materials can be attributed to a number of factors such as different boundary conditions, manufacturing differences and product specifications (Menzies et al. 2007). The values provided have not accounted for variances in finished product and instead an average EC value for specific materials such as High Density Polyethylene (HDPE) is reported. The assumptions and generalised categorisation of the materials presented in these commonly used databases leads to uncertainty with regards to the relevance and validity of this published data when used for geosynthetic products.

As geosynthetic products have no specific representation in the ICE or EcoInvent databases, the values do not account for product specific information obtained from the manufacturing process. An example would be sourcing a value for a polypropylene (PP) based geotextile from the ICE database. It can be seen from Table 1 that there are two possible alternatives values for PP. However, neither of these specifically represents a geotextile. It is arguable that the manufacturing processes included in the calculation of embodied carbon for orientated
film or injection moulded products are not applicable for a geotextile. Use of these generic values for a PP geotextile in a carbon footprinting analysis of a construction solution may give incorrect and inconsistent results. This degree of variability and uncertainty could lead to challenges to the validity of such calculations from those outside the geosynthetic industry, especially when analyses show the geosynthetic solution to be more sustainable.

3 METHOD FOR CALCULATING EMBODIED CARBON VALUES

3.1 INTRODUCTION

The process of calculating an embodied carbon value for a geosynthetic product relies on energy measurements as well as embodied data for the materials. This study focused on two categories of geosynthetics: geotextiles and geogrids. Data for several products of two different types of both geotextiles and geogrids were sourced to produce embodied carbon values for each type and category. In order to effectively carry out the study, energy consumption was measured on the production lines used to manufacture the products. The energy consumed is then converted to the total CO₂ produced by applying the relevant factors based on the fuel mix employed. Co-operation of the manufacturers was required to source the relevant data with four global operating manufacturers contributing to this study. The participating manufacturers provided energy readings and data for product manufacturing lines, and material masses where a range of products have been studied. This produced data covering a range of commonly used geosynthetic products.

3.2 LIFE CYCLE BOUNDARIES

In order to calculate a complete EC value, all the phases of the life cycle have to be considered up until the product leaves the factory gate; adhering to the life cycle boundaries of cradle to gate. Presenting the values to these boundary conditions allows the outputs of this study to be compared to the ICE and EcoInvent database values. It also facilitates the use of the values in studies calculating carbon footprints of construction solutions incorporating geosynthetics. For example, if a study is using life cycle boundaries of cradle to site, emissions from transport of the material to site can be added to the product embodied carbon value in order to meet the life cycle boundary conditions. Figure 1 illustrates the different life cycle boundary conditions related to the manufacture and use of geosynthetics.

As this study worked to LCA boundaries of cradle to gate, alongside the EC data for the material and the process related CO₂ emissions there was the need to consider emissions related to transport of materials to the manufacturing plant. The EC values of polymer pellets are stated as cradle to gate, and hence already account for any transport CO₂ emissions up until the pellets are to ready leave the original factory gate. However, there is a need to account for the CO₂ emissions that arise from the transport of the polymer pellets from the manufacturer to the geosynthetic product manufacturer. This transport phase is dependent on a manufacturer’s capabilities. For instance, one of the geotextile manufacturers in this study used polymer pellets directly in their process to manufacture staple fibres, whilst another used polymer pre-processed into staple fibres by a supplier directly in their manufacturing process (see Section 3.3). Therefore, additional transport from the staple fibre manufacturer to the geosynthetic manufacturer had to be considered in the second example.
3.3 PROCEDURE FOR MEASUREMENTS

Prior to carrying out any measurements of energy used in the manufacture of specific products it was important to identify the embodied carbon of the raw material being used. In the case of the geotextiles and the extruded geogrid this was PP. The EcoInvent database provides a cradle to gate embodied carbon value for PP granules (EcoInvent Centre, 2010) therefore, it was not necessary to replicate this calculation for the raw material (Table 1). This value was then combined with the amount of carbon produced in the manufacture of the geosynthetic products (e.g. geotextiles and extruded geogrids, e.g. Table 2) to give an overall value. Similar steps are followed for the woven geogrid, which employs polyester as the raw material.

Four geosynthetic manufacturers contributed to this study; two provided data on the production of non-woven geotextiles, one on extruded geogrids and another on woven geogrids (Table 2). In the case of the geotextiles, each manufacturer employed a different manufacturing process. The geotextiles from manufacturer A were needle-punched, whereas Manufacturer B predominately used thermal bonding, although production lines could employ a mixture of both methods. As previously discussed Manufacturer A had the polypropylene delivered as staple fibre bales and Manufacturer B did this conversion in house requiring measurement of the energy consumed buy this phase of the manufacturing process. Energy usage was measured using a, Socomec Countis E50 electrical energy meter, with an accuracy of 0.5%, at the supply source of the manufacturing line. On completion of a batch of staple fibres, the amount of energy consumed per kg of material produced was calculated. This measurement procedure was repeated for products with a range of masses per unit area in order to provide data for a variety of commonly used products. The amount of energy consumed was then converted to a carbon dioxide equivalent (Equation 1) using conversion factors presented by DEFRA (2013).

A similar methodology was employed to calculate the embodied carbon for the extruded and woven geogrids but full details of the energy measurements for the manufacturing process were not available for publication in this paper, therefore they are not reported separately in Table 2. Manufacturers C and D carried out all the necessary energy measurements and life cycle calculations in house and provided an average embodied carbon value for categories of geosynthetics (Table 5). These include all processes involved in the manufacturing process (e.g. surface treatments). The authors reviewed the calculations to ensure a consistent methodology was employed to that used for the geotextiles and outlined above.

4 CALCULATE EMBODIED CARBON VALUES

4.1 TRANSPORT CO2 EMISSIONS

The transport CO2 emissions of the materials (Figure 1) were calculated based on a methodology employed in previous carbon footprinting studies such as those by Raja et al. (2014a) and WRAP (2010). This was only applicable to the geotextiles as the embodied carbon values sourced for the geogrids from manufacturers C and D already accounted for such transport related emissions. A road transport mechanism (20t rigid Heavy Goods Vehicle) was assumed with a fuel consumption of 3.33km/litre (Department for Transport, 2012). This in conjunction with a CO2 emissions value for diesel of 2.60 kgCO2 per litre of fuel (DEFRA, 2013) and actual material transport distances were employed in Equation 1.
The results presented in Table 3 demonstrate that the transport of the PP material produces very little in terms of CO₂ emissions when compared to the embodied carbon of the material itself.

\[ C = \frac{\beta(2D/\alpha)}{1000Q} \]  
(Equation 1)

Where \( C \) = Total CO₂ emissions per tonne (tCO₂/t), \( D \) = distance of transportation (km), \( Q \) = Quantity of material (tonnes), \( \alpha \) = Fuel consumption of rigid HGV and \( \beta \) = CO₂ emissions per litre of fuel.

### 4.2 MANUFACTURING PROCESS CO₂ EMISSIONS

#### 4.2.1 RELATING EMBODIED ENERGY AND EMBODIED CARBON

Results were obtained for the four types of geosynthetics: two types of geotextiles and two types of geogrids. Each manufacturer was able to provide data for a range of products that covered varying masses and production results. This allowed the overall energy consumption per kg of product produced to be calculated (Table 2). In order to present these results in the form of EC, the energy consumed had to be converted to EC values using appropriate CO₂ emissions factors. This was achieved by combining the energy readings with the conversion factors for electricity of 0.44548 kgCO₂e/kWh and gas 0.18404 kgCO₂e/kWh (DEFRA, 2013) in Equation 2. These conversion factors are based on UK energy values and represent the direct emissions at the point of use of the fuel or generation of electricity. They do not account for indirect emissions associated with factors such as extraction of the gas; setting up of a power plant etc. The factors are susceptible to change and can vary worldwide. For instance a country employing more renewable energy sources would subsequently produce less CO₂ per unit of energy.

\[ E \times \alpha = C \]  
(Equation 2)

Where \( E \) = Energy consumed (kWh/t), \( \alpha \) = Conversion Factor (tCO₂/kWh) and \( C \) = Embodied Carbon (tCO₂)

#### 4.2.2 GEOTEXTILES

Manufacturers A and B provided data for a range of geotextile products with varying mass per unit area. The manufacturing energy measurements were recorded for each roll of product produced and repeated numerous times in order to account for any variability in the manufacturing process.

Table 2 includes the CO₂ emissions generated from the conversion of the fibres to a finished geotextile for both manufacturers. The process to produce the staple fibres involves the extrusion, spinning and stretching of granules to create fibres and then cutting and pressing of the fibres to create bales. Manufacturer B carried out all these processes on site using a mix of different energy supplies; electric and gas. The data provided by Manufacturer B allowed an average carbon emissions value for this phase to be calculated (Table 4). The same energy mix was assumed for the geotextile production as used in the conversion of the fibres by Manufacturer B. This value combined with the averaged manufacturing process emissions (Table 2) and the raw material embodied carbon gave an overall embodied carbon value for the non-woven geotextiles from each manufacturer (Table 5). The values in Table 5 also include all material related transport emissions that are required to fulfil the LCA criteria of...
cradle to gate. Although the values for transport related CO\textsubscript{2} emissions are small (Table 3) compared to the embodied and manufacturing emissions they have been included to maintain consistency in the study. The average mass per unit area for each type of manufactured geosynthetic is reported in Table 2. The results suggest that for geotextiles with a larger mass per unit area, less energy is consumed when measured per tonne of geotextile produced.

The total embodied carbon values calculated for the geotextiles provided by the two manufacturers are very similar with only a 5\% difference. This small difference arises in the manufacturing process and is primarily due to differences in energy sources employed. Manufacturer A relies solely on grid electricity, whereas Manufacturer B also uses natural gas. However, machine and process efficiencies will also contribute to the difference in CO\textsubscript{2} emissions. The total embodied carbon for the products produced by Manufacturers A and B can be averaged to give a representative value for non-woven geotextiles of 2.35 tCO\textsubscript{2}e/t for cradle to gate.

4.2.3 GEOGRIDS

Manufacturers C and D carried out the measurement independently providing an overall embodied carbon value for their products, which were calculated to life cycle boundary conditions of cradle to gate (Figure 1). This meant a carbon emissions value specific to the manufacturing process was not available for publication, although as noted in Section 3.3 a review of the methodologies they used showed them to be comparable with this study. Manufacturer C provided values for three different mass per unit areas of geogrid. The raw material embodied carbon value of polypropylene (Table 1) was the same as used for the geotextiles and was sourced from data contained in the EcoInvent database (EcoInvent Centre, 2010). Manufacturer D presented data for one geogrid product formed from polyester. For the geogrids, the overall EC values calculated and supplied by the manufacturer account for the raw material embodied carbon, its transport to the manufacturing plant and the carbon emissions from the manufacturing process.

The extruded geogrid had an EC of 2.97 tCO\textsubscript{2}e/t and the woven geogrid 2.36 tCO\textsubscript{2}e/t. Unlike the geotextiles which were formed from the same material the geogrids varied both in manufacturing processes and raw materials employed. Hence a difference between the embodied carbon values of the two geogrids was expected. As for the geotextiles, variances in energy sources employed and machine efficiencies will also contribute to the differences.

4.2.3 SUMMARY OF MANUFACTURING CO\textsubscript{2} EMISSIONS

The results from both categories of geosynthetics highlight that the biggest contribution to the overall embodied carbon of each product is made by the embodied carbon of the raw material. However, the manufacturing process still accounts for a considerable amount of the overall embodied carbon of up to 33\%.

5 COMPARISON OF GEOSYNTHETIC SPECIFIC AND DATABASE VALUES

The aim of this study was to calculate embodied carbon values for categories and types of geosynthetics. Currently, the commonly used databases do not provide geosynthetic specific values hence there is a degree of ambiguity and uncertainty regarding the accuracy of carbon
footprinting of projects including geosynthetics. Table 6 presents a comparison of the geosynthetic EC values calculated in this study with the generic values currently available from databases; both are for cradle to gate LCA boundaries. The comparison shows that values calculated in this study have significant differences to the database values. In the case of geosynthetics manufactured from PP, the ICE database values commonly employed can be up to 90% higher than those calculated in this study for a PP based geotextile or geogrid. Therefore, the use of these database values in carbon footprinting studies will overestimate calculated emissions. EcoInvent Centre (2010) only present data for PP in granulate form, which does not represent the embodied carbon of a finished product.

A similar trend was obtained for the Polyester based geogrid. The EcoInvent database in this instance presents values for PET (granulate) in two different forms (Table 1). Although the values are for granulate and not a finished material they are still higher than the value calculated for the polyester woven geogrid by Manufacturer D. The ICE database does not have any specific values for Polyester however, values for general plastics and polyethylene have previously been used as alternatives (WRAP, 2010). These values for general plastics and polyethylene are all higher than that calculated for the woven geogrid. Thus using any of these alternative material embodied carbon values to represent polyester based geogrids would overestimate the total CO$_2$ of the geosynthetic based solution.

It is important to note that this study does not suggest the database values are inaccurate as the values stated are not direct comparisons. They are values for different forms of materials whether it be granulate or in the case of polypropylene, injection moulding or orientated film. Due to a lack of specific embodied carbon values for geosynthetics, these values have commonly been employed as alternatives for geosynthetic products. However, the values reported in this paper can now be used for future carbon footprinting, to provide more rigorous construction solution assessments.

6 SIGNIFICANCE OF MATERIAL EMBODIED CARBON ON PROJECT CARBON FOOTPRINTING

The importance of using accurate EC data for geosynthetics can be demonstrated by re-working of case studies reported by WRAP (2010) and Raja et al. (2014b) using specific EC values for geotextile and geogrids calculated in this study. WRAP (2010) detail a case study from the Commonhead Junction Improvement project in Swindon, UK. The case study focused on the construction of an embankment for a dual two-lane flyover and compared the cost and CO$_2$ emissions of geosynthetic base and more established solutions. The geosynthetic solution involved the use of a geogrid to reinforce site-won material as compared to the originally proposed solution that required the import of granular material. The polyester geogrid employed accounted for 30.56 tCO$_2$, just less than 10% of the overall emissions for the solution. The embodied carbon data was sourced from the ICE database v1.6 (Hammond & Jones, 2008b), which has no stated value for polyester and uses a value for general polyethylene of 1.94 tCO$_2$/t (Table 1). This ICE v1.6 value is lower than the value calculated for a polyester geogrid of 2.36 tCO$_2$/t (Table 5) and, therefore, the revised project CO$_2$ savings calculated are lower than those originally calculated. The impact of employing the geosynthetic specific calculated value increases the CO$_2$ emissions to 37.21 tCO$_2$, an increase of 22% for this case study.

Raja et al. (2014b) present a case study that compared the carbon dioxide emissions produced from a compacted clay landfill cap with a solution incorporating polypropylene based
geosynthetics. The lifecycle analysis boundaries set for the case study were cradle to end-of-construction. As-built data provided by contractors and manufacturers were used to calculate the carbon footprint of each solution and the comparison showed the geosynthetic solution produced less CO\(_2\) emissions. The use of a database EC value of 3.43 tCO\(_2\)e/t for the polypropylene based geotextiles overestimated the total CO\(_2\) emissions when compared to using the calculated average geotextile EC value of 2.35 tCO\(_2\)e/t. The Raja et al. (2014b) case study overestimated the CO\(_2\) emissions from the embodied carbon of the geotextiles by 45%.

These examples provide motivation for carrying out further studies of the type reported in this paper to obtain specific embodied carbon values for other geosynthetic products. The availability of such data will increase the accuracy of carbon footprinting of construction solutions incorporating geosynthetic products. It will also reduce the opportunity for challenges to the validity and accuracy of comparisons between geosynthetic solutions and those employing other construction materials and approaches.

7 CONCLUSIONS

There is a lack of geosynthetic specific embodied carbon data in the literature for use in construction project carbon footprinting calculations. The use of generic material values obtained from commonly used databases can have significant impact on the accuracy of carbon footprinting results. The study reported in this paper was carried out to calculate the embodied carbon values for two categories of geosynthetics subdivided into four types; non-woven geotextile needle punched, non-woven geotextile needle punched and thermally bonded, extruded geogrid and woven geogrid. The geosynthetic type specific values calculated are lower than the commonly employed ICE and EcoInvent database values.

The paper reports embodied carbon values for geotextiles and geogrids to the life cycle boundary conditions of cradle to gate. The methodology involves making energy measurements during production, converting these to embodied carbon values, and combining these with embodied carbon data for the raw materials and any transport associated emissions. In the case of the geotextiles, energy measurements for converting polypropylene granules through to manufacture of the end product were obtained from various production lines operated by two manufacturers. A similar methodology was employed for the geogrids, however this was carried out by the geogrid manufacturers themselves. The overall energy consumed in producing a tonne of each geotextile or geogrid was then converted to a CO\(_2\) equivalent using appropriate energy to carbon conversion factors set out by DEFRA (2013).

The results from the two geotextile manufacturers were very similar with only a 5% difference. The geotextile from Manufacturer A had an embodied carbon of 2.28 tCO\(_2\)e/t compared to 2.42 tCO\(_2\)e/t from Manufacturer B. The difference in values can be attributed to different manufacturing processes and fuel sources. Manufacturer B used a combination of electricity and gas and employed both needle-punching and thermal bonding techniques, compared to Manufacturer A that used electricity and needle punching. The mean value for non-woven geotextiles was 2.35 tCO\(_2\)e/t. Results for two types of geogrids were also obtained; 2.97 tCO\(_2\)e/t for the extruded geogrid and 2.36 tCO\(_2\)e/t for the woven geogrid. The difference between the two geogrids is expected due to differences in raw materials and manufacturing processes employed.

With no specific embodied carbon values available for geosynthetics until this study, WRAP (2010) and Raja et al. (2014a, 2014b) used database values. In instances where polypropylene
based non-woven geotextiles or geogrids are being employed, the value for polypropylene (orientated film) from the ICE database is commonly used. This ICE database value of 3.43 tCO₂e/t is 46% higher than that of 2.35 tCO₂e/t calculated for the geotextiles and 15% higher than the 2.97 tCO₂e/t of the geogrid. There are also instances where the lack of specific embodied carbon data has led to values of alternative materials of similar properties being employed. In the absence of information for polyester, WRAP (2010) used a value for general polyethylene.

This study highlights the importance and need for geosynthetic specific embodied carbon values. The use of these values in construction project CO₂ calculations will aid accuracy and hence credibility to project carbon footprinting results. This will further highlight the sustainability benefits, in terms of reduced embodied carbon, of geosynthetic based solutions whilst also minimising doubts or challenges that may exist with regards to the basis for the embodied carbon values employed. The publication of embodied carbon data for an extensive range of geosynthetics would allow clients and consultants to undertake their own robust calculations. This study has provided embodied carbon values for two different categories of geosynthetics. However, there is a need to develop, add and extend this dataset to a range of other categories of geosynthetics. Geosynthetic manufacturers are encouraged to extend the findings of this study to include data for their own products. The availability of comprehensive data would allow production of a geosynthetics embodied carbon inventory and extension of exiting databases to include geosynthetics.

8 ACKNOWLEDGEMENTS

This paper was completed as part of an Engineering Doctorate project being carried out at CICE, Loughborough University. The authors would like to acknowledge the IGS (UK Chapter), the Corporate Sponsors that provided data, CICE, Loughborough University and the EPSRC, who funded this project.

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EcoInvent Centre. (2013). *EcoInvent data v3.0*. Ecoinvent reports No. 1-25, Swiss Centre for Life Cycle Inventories, Duebendorf, Switzerland.


Reducing the Environmental Impact of Construction Through Use of Geosynthetics


TABLES AND FIGURES

Table 1- Embodied carbon values for different plastics from ICE (Hammond & Jones, 2011) and EcoInvent v2.2 (EcoInvent Centre, 2010)

<table>
<thead>
<tr>
<th>Material</th>
<th>Embodied Carbon (kg CO₂e/Kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>ICE v2.0, 2011</td>
</tr>
<tr>
<td>General Plastic</td>
<td>3.31</td>
</tr>
<tr>
<td>General Polyethylene</td>
<td>2.54</td>
</tr>
<tr>
<td>High Density Polyethylene (HDPE)</td>
<td>1.93</td>
</tr>
<tr>
<td>HDPE Pipe</td>
<td>2.52</td>
</tr>
<tr>
<td>Low Density Polyethylene (LDPE)</td>
<td>2.08</td>
</tr>
<tr>
<td>LDPE Film</td>
<td>2.60</td>
</tr>
<tr>
<td>Polypropylene, Orientated Film</td>
<td>3.43</td>
</tr>
<tr>
<td>Polypropylene, Injection Moulding</td>
<td>4.49</td>
</tr>
<tr>
<td>Polypropylene, Granules</td>
<td>-</td>
</tr>
<tr>
<td>Polyester, Granules</td>
<td>-</td>
</tr>
<tr>
<td>Polyester, Granules – bottle grade</td>
<td>-</td>
</tr>
</tbody>
</table>
Table 2. CO₂ emissions from manufacturing phase (Note: The breakdown of carbon emission values from Manufacturers C and D are not available)

<table>
<thead>
<tr>
<th>Manufacturer</th>
<th>Type</th>
<th>Product</th>
<th>Material</th>
<th>Mass (kg/m²)</th>
<th>Energy (electricity) kWh/t</th>
<th>Carbon emissions (tCO₂e/t)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Non-woven Geotextile (Needle punched)</td>
<td>1</td>
<td>PP</td>
<td>0.371</td>
<td>144.689</td>
<td>0.064</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2</td>
<td>PP</td>
<td>0.366</td>
<td>143.155</td>
<td>0.064</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3</td>
<td>PP</td>
<td>0.539</td>
<td>109.966</td>
<td>0.049</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4</td>
<td>PP</td>
<td>0.642</td>
<td>107.422</td>
<td>0.048</td>
</tr>
<tr>
<td></td>
<td></td>
<td>5</td>
<td>PP</td>
<td>1.120</td>
<td>101.343</td>
<td>0.045</td>
</tr>
<tr>
<td></td>
<td></td>
<td>6</td>
<td>PP</td>
<td>1.233</td>
<td>110.110</td>
<td>0.049</td>
</tr>
<tr>
<td>B</td>
<td>Non-woven Geotextile (Thermally Bonded/Needle Punched)</td>
<td></td>
<td></td>
<td></td>
<td>Electricity (kWh/t) 222</td>
<td>Gas (kWh/t) 620</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Gas (kWh/t) 315</td>
<td></td>
</tr>
<tr>
<td>C</td>
<td>Geogrid (Extruded)</td>
<td>1</td>
<td>PP</td>
<td>0.232</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2</td>
<td>PP</td>
<td>0.290</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3</td>
<td>PP</td>
<td>0.320</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>D</td>
<td>Geogrid (Woven)</td>
<td>1</td>
<td>PET</td>
<td>0.530</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>
Table 3. CO₂ emissions for transport of PP materials for geotextile manufacture

<table>
<thead>
<tr>
<th>Manufacturer</th>
<th>Material</th>
<th>Transport Phases</th>
<th>Cumulative Transport Distances (km)</th>
<th>Fuel Consumed (litres)</th>
<th>Total CO₂ (tCO₂/t)</th>
</tr>
</thead>
</table>
| A            | PP       | • PP Pellets to Fibre Manufacturer  
              |          | • PP Fibres to Geosynthetic Manufacturer            | 94.1                  | 56.5                | 0.007              |
| B            | PP       | • PP Pellets to Geosynthetic Manufacturer           | 56                                  | 34                     | 0.004              |

Table 4. Carbon emissions for conversion of Polypropylene granules to staple fibres (Manufacturer B)

<table>
<thead>
<tr>
<th>Energy Source</th>
<th>Consumption (kWh/t)</th>
<th>Carbon emissions (tCO₂/t)</th>
<th>Total (tCO₂/t)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electricity</td>
<td>450</td>
<td>0.200</td>
<td>0.241</td>
</tr>
<tr>
<td>Gas</td>
<td>222</td>
<td>0.041</td>
<td></td>
</tr>
</tbody>
</table>
Table 5. Overall embodied carbon for each product

<table>
<thead>
<tr>
<th>Manufacturer</th>
<th>Type</th>
<th>PP embodied carbon (tCO$_2$e/t)</th>
<th>Granules to fibre (tCO$_2$e/t)</th>
<th>Average Manufacturing Carbon emissions (tCO$_2$e/t)</th>
<th>Total Embodied Carbon (tCO$_2$e/t)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Non-woven Geotextile (Needle punched)</td>
<td>1.983</td>
<td>0.241</td>
<td>0.053</td>
<td>2.28</td>
</tr>
<tr>
<td>B</td>
<td>Non-woven Geotextile (Thermally Bonded/Needle Punched)</td>
<td>1.983</td>
<td>0.241</td>
<td>0.189</td>
<td>2.42</td>
</tr>
<tr>
<td>C</td>
<td>Geogrid (Extruded)</td>
<td>-</td>
<td>-</td>
<td>0.987</td>
<td>2.97</td>
</tr>
<tr>
<td>D</td>
<td>Geogrid (Woven)</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>2.36</td>
</tr>
</tbody>
</table>
Reducing the Environmental Impact of Construction Through Use of Geosynthetics

Table 6 - Comparison of calculated embodied carbon values with commonly employed database values for cradle to gate LCA boundaries

<table>
<thead>
<tr>
<th>Geosynthetic Material</th>
<th>Calculated EC values (tCO₂e/t)</th>
<th>Database EC values (tCO₂e/t)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Polypropylene</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Non-woven geotextile</td>
<td>2.35</td>
<td>3.43 to 4.49, 1.98</td>
</tr>
<tr>
<td>Extruded geogrid</td>
<td>2.97</td>
<td></td>
</tr>
<tr>
<td>ICE v2.0</td>
<td></td>
<td>EcoInvent v2.2</td>
</tr>
<tr>
<td><strong>Polyester</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Woven geogrid</td>
<td>2.36</td>
<td>2.54 to 3.31, 2.71 to 2.90</td>
</tr>
<tr>
<td>ICE v2.0*</td>
<td></td>
<td>EcoInvent v2.2</td>
</tr>
</tbody>
</table>

*The ICE v2.0 database does not contain values for polyester materials and therefore previous studies (e.g. Wrap 2010) have used values for General Polyethylene and Plastics (General) as alternatives.

Figure 1. Life cycle boundaries employed in CO₂ analysis of geosynthetics
APPENDIX F  (EMBODIED CARBON SURVEY)

Centre for Innovative and Collaborative Construction Engineering
Loughborough University, Leicestershire, LE11 3TU, UK
Tel: +44 (0)1509 228549  Fax: +44 (0)1509 223982
E-mail: cice@lboro.ac.uk  www.lboro.ac.uk/cice

Dear Corporate Sponsors,

You may already be fully aware with the aims and objectives of the EngD research, however, a summary of the project is attached. The project is currently focusing on the issue of embodied carbon and the validity of data used in carbon footprinting of projects. The research thus far has shown that the currently accepted methods used to calculate carbon footprints of a project show little variance and the real issue lies behind the reliability of the data employed. There is no doubt that in most projects geosynthetic solutions are far more sustainable in terms of carbon emissions than commonly employed ‘traditional’ solutions. This is backed up by the work carried out by WRAP and EAGM. However reliability of the embodied carbon data employed could ultimately affect the acceptance of the carbon footprinting results. It leaves a window of opportunity for those providing ‘traditional’ solutions to challenge the CO2 emission totals calculated and hence the claims of the geosynthetic industry.

The EngD research is now looking to source embodied carbon data from corporate sponsors for a variety of geosynthetics. This data will then be used in the future framework, tool or method produced. Using this first-hand data from manufacturers will provide credibility to the tool and carbon emissions results produced.

It is important to note that this data will be kept confidential and anonymous, it will not be used to compare between manufacturers but instead, to create statistical information (e.g. mean, range and standard deviation) on embodied carbon values for different geosynthetic products i.e. geogrids, geotextiles. Dependant on the quality and level of data obtained, embodied carbon values for geosynthetics with different properties will be provided. For example, embodied carbon values will be provided for different strengths, sizes and forms of geogrids. In order to begin to form a reliable and defensible data set I have attached a few questions in the form of a short survey. These questions will help in starting the process, however, it is acknowledged that it may require further communication in order to clarify any issues that surround the answers or data provided. This communication or sourcing of data could extend to a short visit to your office (if you were willing to host such a visit, this could be discussed at a later date).

The overall aim of this part of the research is to collate data that will not be challenged for reliability or credibility and will help to reinforce the conclusions made by WRAP and EAGM that geosynthetic solutions have significant sustainable and carbon reduction benefits.
This data will then be used to extend the WRAP work to include the construction phase of the project (i.e. cradle-end of construction). Moreover, this will be carried out for a range of common applications.

We trust that you are in support of the project and your assistance is greatly appreciated. Should you have any queries regarding the information required please don’t hesitate to get in contact with me.

Yours Faithfully

Jamil Raja,  
Research Engineer  
Loughborough University & IGS UK Chapter  
Email: J.Raja@lboro.ac.uk
Reducing Environmental Impact of Construction though the use of Geosynthetics- Questionnaire

Jamil Raja, Loughborough University, IGS UK chapter, Email: j.raja@lboro.ac.uk

1. Do you have Embodied Energy or Embodied Carbon Values for your products?

2. Could you please state the Embodied Carbon/ Embodied Energy value of your products, in particular for the products that fall in to the following categories:
   i. Geogrid
      a. Uniaxial
      b. Biaxial
   ii. Geotextile
      a. Woven
      b. Nonwoven
   iii. Geomembrane
   iv. Geocomposites

   It is kindly requested that you provide as much information as possible about each product including material, strength and geometric characteristics.

3. If the values provided in question 2 are in terms of Embodied Energy can you provide the fuel mix used in production, as well as the factors applied for the amount of energy produced by specific fuels?

4. If the values provided in question 2 are in terms of Embodied Carbon, can you please state how they were calculated? Clearly stating the calculation procedure, how it was measured as well as the fuel mix used in the production.

5. For each value can you please state what Life Cycle Assessment (LCA) criteria it represents, for example are they cradle to site, cradle to gate, cradle to distribution centre? If you have values for different stages of LCA then can you please state these?

6. If any travel related energy or emissions are included in your values, can you please describe how these were calculated, stating any values and assumptions made?

7. Please provide the information requested for as many of the products you supply or produce.
APPENDIX G (RETAINING WALL DESIGN)

Design of Retaining Wall in Accordance to Eurocode 2 (EN 1992)

Proposed retaining wall design:

Design parameters sourced from contractor:

$\rho = \text{Density of backfill} = 1900 \text{ kg/m}^2$ and $S = \text{Surcharge} = 12 \text{kN/m}^2$

The design is required to:

1) Check the stability of the Wall
2) Determine bearing pressure at ULS
3) Design the bending reinforcement

1. Stability

Horizontal Force:

$P_a = K_a \rho gh$

Where $K_a = \text{Coefficient of active pressure} = 0.33$, $g = 9.81 \text{N}$ and $h = \text{depth considered} = 3.7 \text{m}$

Therefore:

$P_a = 0.33 \times 1.9 \times 9.81 \times 3.7$

$P_a = 23 \text{ kN/m}^2$

Allowing for the minimum required surcharge of $12 \text{kN/m}^2$ an additional horizontal pressure of $P_s$ acts uniformly over the whole depth $h$: 
\( P_s = K_a x 12 = 4 \text{ kN/m}^2 \)

Therefore the total horizontal force on 1m length of wall is given by:
\[ H_{k(\text{earth})} = 0.5P_s h = 0.5 \times 23 \times 3.7 = 42.6 \text{ kN} \]
\[ H_{k(\text{sur})} = P_s h = 4 \times 3.7 = 14.8 \text{ kN} \]

**Vertical loads:**

- **a)** Permanent loads
  - Wall \( = 0.5(0.4 + 0.3) \times 3.3 \times 25 = 29 \text{ kN} \)
  - Base \( = 25(0.4 \times 2.4 + 0.5 \times 0.6) = 31.5 \text{ kN} \)
  - Earth \( = 1.5 \times 3.3 \times 1.9 \times 9.81 = 92.3 \text{ kN} \)
  - Total \( = 152.8 \text{ kN} \)

- **b)** Variable loads
  - Surcharge \( = 1.5 \times 12 = 18 \text{ kN} \)

- **i)** Overturning (taking moments about point A at the edge of the toe):
  \[ \text{Overturning (unfavourable)} = \gamma f \frac{H_{k(\text{earth})}}{3} + \gamma f \frac{H_{k(\text{sur})}}{2} \]
  \( \gamma f \) for the earth pressure and 1.5 for the surcharge pressure
  \( = \frac{(1.1 \times 42.6 \times 3.7/3) + (1.5 \times 14.8 \times 3.7/2)}{} \)
  \( = 98.9 \text{ kNm} \)
  
  For the restraining (favourable) moment a factor of 0.9 is applied to the permanent loads and 0 to the variable surcharge load.
  
  Restraining moment \( = \gamma f (29 \times 0.7 + 31.5 \times 1.2 + 92.3 \times 1.65) \)
  \( = 0.9 \times 210.4 \)
  \( = 189.4 \text{ kNm} \)
  
  Thus the criterion for overturning is satisfied.

- **ii)** Sliding:
  
  It is necessary that \( \mu(1.0G_k + 1.0V_k) \geq \gamma f H_k \) for no heel beam
  
  For the sliding (unfavourable) effect a partial factor of 1.35 is applied to the earth pressure and 1.5 to the surcharge pressure.
  
  Sliding force \( = 1.35 \times 42.6 + 1.5 \times 14.8 \)
  \( = 79.7 \text{ kN} \)
  
  For the restraining (favourable) effect a factor of 1.0 is applied to the permanent loads and 0 to the variable surcharge load. Assuming a value of coefficient of friction \( \mu = 0.45 \).
  
  Frictional resisting force \( = 0.45 \times 1.0 \times 152.8 \)
  \( = 68.8 \text{ kN} \)
Sliding force exceeds resisting force, hence resistance must also be provided by the passive earth pressure acting against the heel beam:

\[ H_p = \gamma_f x 0.5K_p \rho a^2 \]

where \( K_p \) is the coefficient of passive pressure, assumed to be 3.5 for this granular material and \( a \) is the depth of the heel.

\[ H_p = 1.0 \times 0.5 \times 3.5 \times 1.9 \times 9.81 \times 0.6^2 \]

\[ = 11.7 \text{ kN} \]

Therefore total resisting force is:

\[ = 68.8 + 11.7 \]

\[ = 80.5 \text{ kN} \]

Which exceeds the sliding force.

2. Bearing pressures at ULS

Bearing pressures are given by:

\[ P = \frac{N}{D} \pm \frac{6M}{D^2} \]

Where \( M \) is the moment about the base centreline. Therefore:

\[ M = \gamma_f (42.6 \times 3.7/3) + \gamma_f (14.8 \times 3.7/2) + \gamma_f \times 29(1.2 - 0.7) - \gamma_f \times 92.3 \times (1.65 - 1.2) \]

\[ = 1.35 \times 52.5 + 1.5 \times 27.4 + 1.35 \times 14.5 - 1.0 \times 41.5 \]

\[ = 90.1 \text{kNm} \]

Therefore, bearing pressure at toe and heel of wall

\[ P_1 = \frac{(1.35 \times (29 + 31.5) + 1.0 \times 92.3)}{2.4} \pm \frac{6 \times 90.1}{2.4^2} \]

\[ P_1 = 169.4 \text{ and } P_2 = -21.4 \text{ kN/m}^2 \]

3. Bending Reinforcement

i) Wall:

Horizontal force

\[ = \gamma_f 0.5K_p \rho gh^2 + \gamma_f P_h \]

\[ = 1.35 \times 0.5 \times 0.33 \times 1.9 \times 9.81 \times 3.3^2 + 1.5 \times 4 \times 3.3 \]

\[ = 45.2 + 19.8 = 65 \text{ kN} \]

Considering the effective span, the maximum moment is

\[ M_{Ed} = 45.2 \times (0.2 + 3.3/3) + 19.8 \times (0.2 + 3.3/2) \]

\[ = 95.4 \text{ kNm} \]
\[
\frac{M_{Ed}}{bd^2f_{ck}} = \frac{95.4 \times 10^6}{1000 \times 330^2 \times 30} = 0.03
\]

For which \( l_a = 0.95 \) hence the Area of Steel (\( A_s \)):

\[
A_s = \frac{95.4 \times 10^6}{0.95 \times 330 \times 0.87 \times 500} = 700 \text{ mm}^2/\text{m}
\]

**Provide H20 bars at 300mm centres (\( As = 1050 \text{ mm}^2/\text{m} \))**

ii) Base

Using bearing pressures calculated earlier (\( P_1 = 169.4 \) and \( P_2 = -21.4 \text{ kN/m}^2 \)):

\( P_3 = -21.4 + (169.4 + 21.4)1.5/2.4 = 97.9 \text{ kN/m}^2 \)

**Heel:** Taking moments about the stem centreline for the vertical loads and bearing pressures

\[
M_{Ed} = \frac{1}{y_f} \times 31.5 \times (2.4/2 - 0.7) + \frac{1}{y_f} \times 92.3 \times 0.95 + 21.4 \times 1.5 \times 0.95 - 97.9 \times 0.75 \times 0.7
\]

\[
= 1.35 \times 15.75 + 1.0 \times 87.7 + 30.5 - 51.4
\]

\[
= 88.1 \text{ kNm}
\]

Therefore:

\[
\frac{M_{Ed}}{bd^2f_{ck}} = \frac{88.1 \times 10^6}{1000 \times 330^2 \times 30} = 0.03
\]

For which \( l_a = 0.95 \) hence the Area of Steel (\( A_s \)):

\[
A_s = \frac{88.1 \times 10^6}{0.95 \times 330 \times 0.87 \times 500} = 646 \text{ mm}^2/\text{m}
\]

**Provide H20 bars at 300 mm centres (\( As = 1050 \text{ mm}^2/\text{m} \))**

**Toe:** Taking moments about the stem centreline

\[
M_{Ed} = \frac{1}{y_f} \times 31.5 \times 0.45 \times 0.5/2.4 - 169.4 \times 0.5 \times 0.45
\]

\[
= - 34.1 \text{ kNm}
\]

Therefore:

\[
\frac{M_{Ed}}{bd^2f_{ck}} = \frac{34.1 \times 10^6}{1000 \times 330^2 \times 30} = 0.01
\]

For which \( l_a = 0.95 \) hence the Area of Steel (\( A_s \)):

\[
A_s = \frac{34.1 \times 10^6}{0.95 \times 330 \times 0.87 \times 500} = 250 \text{ mm}^2/\text{m}
\]

This is lower than \( A_{s(min)} = 0.15 bd/100 = 495 \text{ mm}^2/\text{m} \)

**Provide H12 bars at 200 mm centres (\( As = 566 \text{ mm}^2/\text{m} \))**

Steel should also be provided in the compression face of the wall in order to prevent cracking – say H10 bars at 200mm centres each way (\( As = 393 \text{ mm}^2/\text{m} \))