Department of Mechanical Engineering

# Reducing the Embodied Carbon Content of Asphalt

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# Copyright Declaration

## Abstract

This thesis sets out research into the calculation of embodied carbon (EC) content of virgin hot mix asphalt using cradle to gate boundaries. Currently, not as much is known about the sustainable properties of asphalt when compared to other construction materials such as concrete. However with the introduction of the Carbon Reduction Commitment (CRC) and the continual rise in oil prices means that many asphalt production companies now want to know how to make the product they manufacture more sustainable. Case study data from an asphalt manufacturer was used to calculate and quantify the embodied carbon associated with each process of asphalt production; quarrying aggregate, processing aggregate, transportation of constitute materials, mixing, heating and drying. The computer programme asPECT was used to calculate the virgin EC values of the 28 different mix types provided by the case study. Average EC content of virgin asphalt was found to be 132 $kgCO_2$ equivalent /t. Over 1/3 of this arose from the energy intensive process of heating and drying.

A sensitivity study was then carried out on the virgin EC values to see how certain factors affected them. These factors included constitute transportation distances, variation in the EC of bitumen content from a different source and the addition of 30% Recycled Asphalt Planning (RAP). From the sensitivity study it was found minimising the transportation of constituent materials was very effective in reducing overall EC content. A 33% reduction in EC content occurred when the optimised factors were applied. Application of RAP to the case study mix resulted in a 5.5% reduction in EC content, this increased to a reduction of 14% when a larger range of aggregate sizes were used. By using RAP and minimising constituent material transportation, the embodied carbon content dropped to an average of 84.35 $kgCO_2$ equivalent/t, a 36% decrease from the virgin case study value. This saving would results in an increase of both economic and environmental performance for the case study company, ultimately helping to aid the reduction in asphalt’s carbon footprint.

## Acknowledgements

I would like to thank Dr Paul Strachan for all his help and guidance throughout this project. Special thanks must also go to Ali Sheikh, who provided me with all the necessary data I required to complete this project and has given up a lot of his own time to make sure my project was completed successfully. I would also like to thank Barr Ltd for their help and cooperation throughout this project, especially Gordon Hynd, Bryan Wilson and Geoff Smith. Finally I would like to thank my family and friends for their help and continual motivation throughout my academic year.

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# *1 Introduction*

It has become significantly more important in today's climate for companies and organisations to understand the impact that their products and services have on the environment. Although power generated from clean renewable sources is continually growing, fossil fuels are still used to produce the majority of the UK's energy. It is also used to power many manufacturing processes. 74% of UK power generation in 2009 was from the burning of fossil fuels *(UK Government, 2010a).* There are many tools now available to organisation to help them quantify and understand their carbon output. Life Cycle Analysis (LCA) has been developed for this purpose; it can be used to quantify energy and embodied carbon associated with the organisations products and processes. A LCA can identify where the majority of energy is used resulting in the user knowing where large quantities of embodied carbon exist. Reductions can then be made in these areas. With rising fuel prices and introduction of new governmental legislations, it is fundamental that today's organisations are able to understand and quantify the affect they have on the environment. Any reduction in their carbon usage could prove extremely beneficial for commercial success and future environmental goals.

The following investigation undertakes a LCA for *Barr Ltd*. *Barr* manufactured 53,545 tonnes of asphalt in 2010. By calculating the Embodied Carbon (EC) content of the asphalt produced will enable *Barr* to identify where carbon savings can be made, helping to reduce the organisations overall carbon footprint.

# 2 Literature Review

## 2.1 Legislation & Driver

The United Nations Framework Convention on Climate Change (UNFCCC) created the Kyoto Protocol, a global legislation that came into force on the 16th February 2005. A 5.2% reduction in six defined Green House Gas (GHG) emissions from 1990 base year target was set for 32 of the world's industrialized nations. The six GHGs defined by the Kyoto Protocol are; Carbon Dioxide ($CO_2$), Methane ($CH_4$), Nitrous Oxide ($N_2O$), Hydroflurocarbons (HFC), Perflurocarbons (PFC) and Sulphur Hexafluoride ($SF_6$). The Greenhouse Gas Protocol (GHG Protocol) is a global standardised tool used to help reduce GHG emission. Created by the World Resource Institute and World Business Council for Sustainable Development, it is being used by governments, organisations and businesses worldwide to help them account for their GHG emissions during this time when climate policies are consistently evolving *(The Greenhouse Gas Protocol, 1998)*. The International Organisation for Standardisation (ISO) adopted the GHG Protocols principles and used it in ISO 14064-I: *Specification with Guidance at the Organization Level for Quantification and Reporting of Greenhouse Gas Emissions and Removals.*

The European Union (EU) reacted to these targets by creating the '20-20-20' legislation. This was to reduce greenhouse gasses and primary energy consumption by 20% and increasing renewable energy output to 20% by 2020 (*European Union, 2006)*. In 2005, they also launched the European Union Emission Trading Scheme (EU ETS) to help meet these targets. This was aimed at helping to reduce $CO_2$ emissions from the top five major polluting industries from each member state in the EU. It works by issuing companies 'Carbon Credits'. Each carbon credit is equivalent to one tonne of $CO_2$. There are over now 12,000 companies in the EU that are involved in this trading scheme *(European Union, 2005).* The carbon credits issued at the start of each trading term will be reduced in increments, forcing these heavy polluting, energy intensive organisations to become less carbon dependant. Credits issued in 2020 will be 21% lower than those issued in 2005 *(European Union, 2005).* It gives companies flexibility in determining their carbon needs, by either investing in more efficient 'greener' machinery or by buying excess credits from other companies.

In addition to EU targets, the UK has its own carbon reduction targets. The Climate Change Act was implemented in 2008. It has set the target for an ambitious 80% decrease from the 1990 baseline year in all six Kyoto GHG including $CO_2$ by 2050 *(UK Government, 2008).* This reduction will be met by a number of approaches, including higher energy efficiencies, energy conservation and more power generated from renewable sources.

The Carbon Reduction Commitment (CRC) Energy Efficiency Scheme was introduced in April 2010, this scheme sets mandatory cap and trade rules for organisations in the UK that consume more than 6,000 MWh per year. The majority of these organisations are large public and private sector companies include many construction and material production companies such as asphalt manufacturers. They account for around 10% the UK $CO_2$ emissions, yet fall below the threshold to be included in the EU ETS (CRC is a similar scheme for smaller organisations) *(UK Government, 2010b).* Organisations taking part will have to account for their carbon emissions for that coming year, and then buy carbon allowances depending on the amount of carbon emissions they are projected to release. At the end of each year they report their actual emissions. All participation organisations and companies are then complied into a league table based on their results. The better performing companies/organisations could receive a significant boost in their commercial reputation. The cost of these allowances are repaid at the end of each year, plus or minus a bonus depending on their performance in the CRC league table *(Energy Team, 2011)*

The CRC encourages businesses to reduce their carbon output through a combination of voluntary Automatic Meter Reading (AMR), year on year comparisons and competition with similar sized organisations/companies *(Carbon Trust, 2011).* It is clear that carbon accounting and resulting emissions limits are coming into legislation. This will only intensify over time as carbon emissions legislation become more stringent in the UK and throughout the EU. Companies will have to purchase carbon allowances priced at £12/tonne between April 2010 and March 2013, if companies need to purchase more allowances, they must pay the increased price of £14/tonne. Like the EU ETU, allowances can be bought and sold depending on the company's total carbon output. After the initial introductory phase (April 2010 - March 2013), buying and selling of allowances will become auction orientated.

## *2.2 Life Cycle Assessment*

There are different options available for organisations to lower their energy usage and reduce their $CO_2$ emissions output. However, it is first important to identify and quantify their energy usage and resulting carbon emissions from this usage. After this has been achieved, energy/carbon can be reduced and carbon reduction can be incorporated into the organisation's future strategies, helping to even further reduce their carbon footprint. Initially though, a carbon footprinting analysis needs to be undertaken. Carbon footprinting is used to measure total greenhouse gasses emitted directly and indirectly by a person, product or organisation *(Carbon Trust, 2010).* The measuring unit used depends on what is being measured. Gaseous $CO_2$ emitted from a process is measured in kg or tonnes of $CO_2$ ($kgCO_2/tCO_2$). $CO_2$ and other GHGs embodied within a product can be measured in kg/tonnes of $CO_2$ equivalent ($kgCO_2e/tCO_2e$). GHGs are measured in $CO_2$ equivalent to standardise the process giving a clearer understanding which allows a like for like comparison with $CO_2$ to take place *(Carbon Trust, 2010). Table 1* below highlights the Global Warming Potential (GWP) for each of the six defined GHGs *(IPCC, 1995).*

| **GHG** | Global Warming Potential (GWP) |
|---|---|
| Carbon Dioxide ($CO_2$) | 1 |
| Methane ($CH_4$) | 21 |
| Nitrous Oxide ($N_2O$) | 310 |
| Hydroflurocarbons (HFC) | 140 – 11,700 |
| Perflurocarbons (PFC) | 6,500 – 9,200 |
| Sulphur Hexafluoride (SF6) | 23,900 |

*Table 1 – Global Warming Potential for GHGs (IPCC, 1995).*

Carbon Dioxides GWP has been standardized to 1, while Methane has a GWP of 21 as it can cause more damage to the atmosphere. Methane however exists in far smaller quantities when compared to $CO_2$ and even more so for the other GHGs such as PFCs. This means that their overall affect is significantly reduced.

Two types of embodied carbon footprinting can be undertaken; organisational embodied carbon footprint and product embodied carbon footprint. The organisational embodied carbon footprint measures all embodied carbon associated with that organisation. This includes carbon associated with energy usage in its buildings and production lines as well as carbon associated with company transportation e.g. - deliveries of materials etc. Embodied carbon associated with a product includes energy and its resulting carbon from the whole life of a product (Depending on the boundaries defined)

The finished result for an organisational embodied carbon footprint would be the amount of carbon ($tCO_2e$) the organisation would emit in one year. For a product embodied carbon footprint, the finished result would be the amount of carbon dioxide equivalent ($kgCO_2/t$) per product/ product mass. For example, the $kgCO_2e$ for 1t of concrete, or the $kgCO_2e$ for a loaf of bread. Both these footprinting analyses are extremely useful in quantifying the embodied carbon of a process/product. This then makes it possible to identify areas in a organisation/product where savings could occur.

## *2.21 Life Cycle Assessment Guidance & Tools*

One of the most important guidance documents used to undertaking an embodied carbon footprinting analysis is ISO 14040 and ISO 14044. They were created to help standardise and advise on how to carry out a Life Cycle Assessment (LCA). LCA can be used to calculate embodied carbon and embodied energy. Standardisation is critical if LCA are to be carried out, as without some form of standardisation, each LCA could vary dramatically making results completely incomparable. (*PAS 2050, 2008).* The British Standards Institute (BSI) has also published a standardisation guide for organisation on how to assess themselves and their carbon emissions. PAS 2050, which was created using the ISO 14040 and ISO 14044 standard as guidance, specifies how to conduct a LCA. It also provides further standardisation and consistency for undertaking a LCA *(PAS 2050, 2008).* Software is also available to help calculate embodied carbon such as *Eco Invent, asPECT, AggRegain and GaBi.* Many of these software's adhere to the ISO 14040/44 principles.

## *2.22 Goal & Scope Definition*

An LCA for an organisation or product can be broken up into 4 main stages; *(ISO 14040, 2006).* The first of the 4 stages is the *goal and scope*. This is where the goal of the assessment is specified, including how much detail to go into, the target audience, intended application, use of results and the reason for carrying out the analysis. *(ISO 14044, 2006)* The boundaries are defined; these should be defined in such a way to reflect the specified goal. Defining the boundaries is a very important task in the any LCA, as it determines the scope of the project. The three most common used boundaries are;

> Cradle to Grave – Refers to the environmental impact of a product from obtaining it, refining/producing it for use, distribution to site, use of product and disposal of product. (Whether it be recycled or disposed of.)
>
> Cradle to Gate – Refers to the environmental impact of a product from obtaining it and refining/producing it. The assessment ends when it leaves the factory gates.

Cradle to Site – Refers to the environmental impact of a product from obtaining it, refining/producing it and transportation from the factory to the site.

*(Timber Research and Development Association, 2008)*

As well as defining boundaries for time, analysis boundaries also need to be defined. This is the cut-off point for the assessment, for example, most analyses will take into account the energy used to obtain the product, and create the boundary there. (E.g. the energy used by the digger to extract the raw material from the ground) If these aren't decided upon, then the analysis could go even further and look into the amount of fuel used by the digger driver to get to work that day. Boundaries are very important and making sure they are clearly defined before the assessment takes place is critical. *Table 2* shows different guidance documents for LCA and their associated analysis boundaries (*Chishna, A et al, 2010).*

| | ISO 14040 | PAS 2050 | BRE Material Profiles[1] | University of Tennessee studies[2] | Stone Study: Scotland[3] | Stone Study: Jordan[4] |
|---|---|---|---|---|---|---|
| Boundaries include | *Cradle-to-grave* | *Cradle-to-grave* | *Cradle-to-site* | *Cradle-to-site* | *Cradle-to-site* | *Cradle-to-gate* |
| Materials (used in the production process) | ✓ | ✓ | ✓ | ✓ | | |
| Energy generated onsite | ✓ | ✓ | ✓ | ✓ | | ✓ |
| Use of electricity | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| Use of fuels on site | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| Use of fuels off site (transport) | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| Energy embodied in fuels | ✓ | ✓ | | | | |
| Energy use in offices and factories | ✓ | ✓ | ✓ | | | |
| Treatment and disposal of waste products | ✓ | ✓ | | ✓ | | |
| Recovery of used products (including reuse, recycling and energy recovery) | ✓ | ✓ | | | | |
| Manufacture of ancillary materials | ✓ | | | | | |
| Manufacture, maintenance and decommissioning of capital equipment | ✓ | | | | | |
| Manufacture, maintenance and decommissioning of capital infrastructure | ✓ | | | | | |
| Any other processes within the life cycle which are associated with GHG emissions | | ✓ | | | | |

[1] Anderson, Shiers and Steele, 2009; [2] University of Tennessee 2008a; 2008b; 2008c; [3] Venkitachalam, 2008; [4] Alshboul and Alzoubi, 2008

*Table 2 – Guidance Documents and their associated analysis boundaries* (*Chishna, A et al, 2010).*

## *2.23 Inventory Analysis*

Inventory Analysis is the second stage in the assessment. This is where all the data is collected and organised. It forms the body of information upon which the assessment depends. The data collected usually involves the quantification of energy flow in/out of the stated system boundaries. A flow diagram can be produced clarifying this. With this information, embodied carbon or embodied energy can then be calculated *(ISO 14044, 2006).* Data can be collected from a number of sources, quantitative energy bills and production rates are the most common methods used to calculate embodied carbon for a particular process in the organisation/manufacture of a product. For secondary processes (e.g. – bitumen produced in an oil refinery then used to produce asphalt in an asphalt plant), carbon inventories are used as many organisations have no means of obtaining this information from their secondary suppliers. Unfortunately though, there can be many different data ranges for the same product. It is advised that while collecting data and using an inventory, to make sure as much of it as possible is from that same inventory *(ISO 14040, 2006),* as the people who compiled the inventory will have set standards and defined boundaries that adhere to all the products listed, giving consistency and reliability to the data. If this is not possible, it is critical that data from different secondary sources is thoroughly analysed.

It is also important to use the most up to date data available. In the space of ten years, the energy used to make the same product can vary dramatically, due to a change in the manufacturing process or change in the source of the energy (e.g. Sustainable instead of fossil) *(Timber Research and Development Association, 2008).* Carbon conversion factors can also be applied to energy types such as electricity, coal, gas, transportation etc. The Department for Environment, Food & Rural Affairs (DEFRA) publishes an annual document containing up to date carbon conversion factors.

Energy used for transportation of the product also needs to be taken into account. Usually, if the product has a high embodied carbon, transportation energy is negligible. For products such as sand, the transportation energy can be significant as sand has a low embodied carbon content. (*Timber Research and Development Association, 2009)* DEFRA have set out guidelines and compiled tables to help calculate transportation energy. *(Department for Energy, Food and Rural Affairs, 2009)* Once all the data for the study has been gathered, it should be combined into an inventory, this should include everything that will be an input or output of the system. As stated earlier, it is important to evaluate the data to confirm it is from a creditable source that has adhered to *their* defined boundaries and the ISO14040 standards.

## *2.24 Impact Assessment*

The third stage is the Life Cycle Impact Assessment. (LCIA) Analysis takes place to evaluate impact potentials from the inventory drafted in the stage before, with inventory data being turned into a functional unit, such as kg$CO_2$e/t. By utilising a functional unit, the full impact of all contributing factors and inputs/outputs can be understood and accurately quantified. It will be clear by this stage if the original goal and scope set has been achieved. Sometimes modification of the goal or scope might be needed to help achieve the goal *(ISO 14044, 2006).*

## *2.25 Interpretation*

The final stage is interpretation of the results. By evaluating the inventory and the impact assessment, the processes with the least contribution of embodied carbon and embodied energy can be identified and used. A sensitivity analysis can be carried out to see what affect implementing changes has on different stages of the LCA *(ISO 14044, 2006)*.

LCA can be used for a whole number of applications, including; eco-labelling, marketing, education, reviewing processes and product design. *(Timber Research and Development Association, 2009)* Many companies use LCA to evaluate and improve themselves. It is also good publicity for them if they are ‘carbon concise’.

## *2.26 Critical Review of LCA*

Life Cycle Assessment can be a very useful tool in determining the impact a product or a service has on the environment. Unfortunately, it does have limitations. The data used can vary between different inventories, this can lead to confusion and makes a LCA difficult to undertake. Where no data is available, assumptions need to be made; again, this can make the LCA difficult and takes away from the accuracy of the study by introducing errors. Although *ISO 14040* and *ISO 14044*, along with other documents such as *PAS 2050* help to standardise the LCA, they are still loose guidelines. The UK Low Carbon Commission Innovation and Growth Team (IGT) have made recommendations that both government and industry should agree on a standardised method of measuring embodied energy and embodied carbon *(UK Government, 2010c)*

Many inventories are available including ICE *(Hammond G, Jones C, 2011).* Associated bodies also produce embodied carbon and embodied energy data for their respective materials, some of these inventories are not easily assessed and subscription costs do occur. The possibility of values from associated bodies being biased to favour their material can be a reality. It is critical that transparency is provided with their figures. *Table* 3 below shows how the embodied carbon content of a material can vary depending on which source it has been taken from.

| Source | Embodied Carbon Content ($kgCO_2e/t$) |
|---|---|
| Eurobitume | 190 |
| ICE (University of Bath) | 430 - 550 |

*Table 3 – Bitumen EC from various sources (Hammond G, Jones C, 2011. Eurobitume, 2011)*

It can be seen that the embodied carbon content from these two sources varies significantly which can prove problematic when undertaking a LCA. Both sets of secondary data should be looked into, not only determine the calculation methods used but also their credibility. Both sources need to be transparent enough to understand how the values were reached, what boundaries were applied etc. By undertaking a background analysis, one source can be favoured over another to be used in the investigation. If a choice cannot be made due to the lack of data then a sensitivity analysis should be undertaken. This will show the range of embodied carbon content a product can have when two different secondary values are used. This highlights the problems faced when undertaking a LCA. Many different sources of secondary data, all giving different embodied carbon content values for the same material. One way to solve this problem would be to create a UK or European standardised open-sourced database that is easily accessible to everyone. The EU has already begun construction of a standardised database called ELCD (European Reference Life Cycle Database). It is relatively new so the inventory list isn't very large; however it is continually expanding with new materials and processes being added to it. A database that covers such a wide geographical area however will have numerous values for one material depending on where it was produced. A product manufactured in Scotland could have a significantly different embodied carbon value when compared to the same product being manufactured in an eastern European county due to where they source their electricity from (renewable vs. fossil). This technique would substantially increase the amount of data needed and size of the database; however it will also increase its accuracy, giving it the potential as an extremely credible and therefore popular source.

A standardised, in depth life cycle inventory that is easily accessible, transparent and covers a wide geographical area (i.e. Europe) could prove an extremely powerful and beneficial tool in LCA calculation and subsequent better understanding of $CO_2$ emissions that occur through manufacturing processes etc.

## *2.3 Materials*

The UK construction industry has been targeted as one of the main areas for $CO_2$ reduction due to its high emissions output and its contributions to the UK economy *(R J Plank, 2005a).* Many constructional materials are manufactured within the UK; this significantly contributes to the UK's overall carbon emissions. *Figure 1* and *Figure 2* below show the UK's $CO_2$ emissions by sector in 1990 and 2009 respectively. From these graphs, it can be seen that 22% of the UK $CO_2$ emissions in 2009 came from the industrial sector *(UK Government, 2010d)*. Although there has been a slight decrease since 1990, this sector still contributes significantly to the UK's overall carbon emissions; any savings in this sector could be extremely beneficial to reducing the UK's carbon emissions.

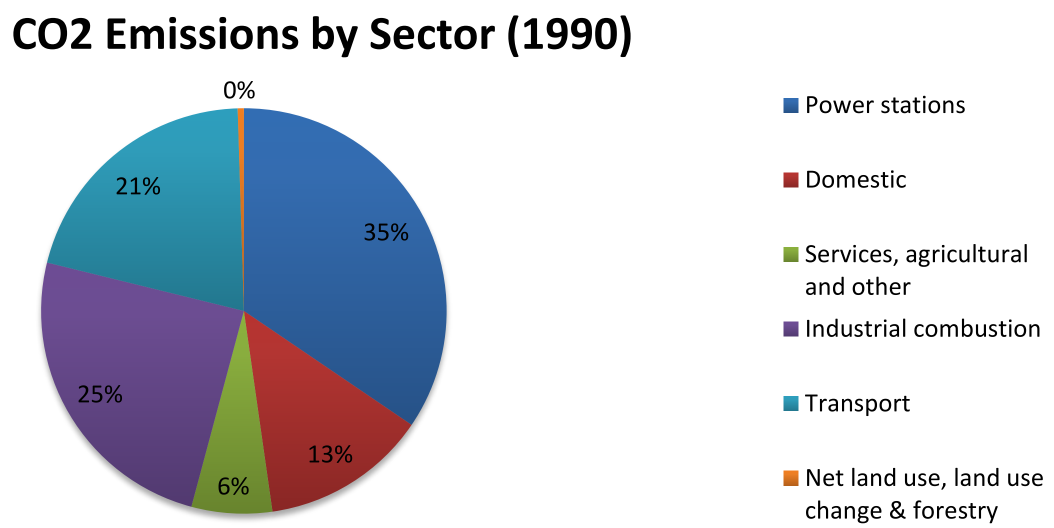



*Figure 1 – CO2 Emissions by Sector (1990)*

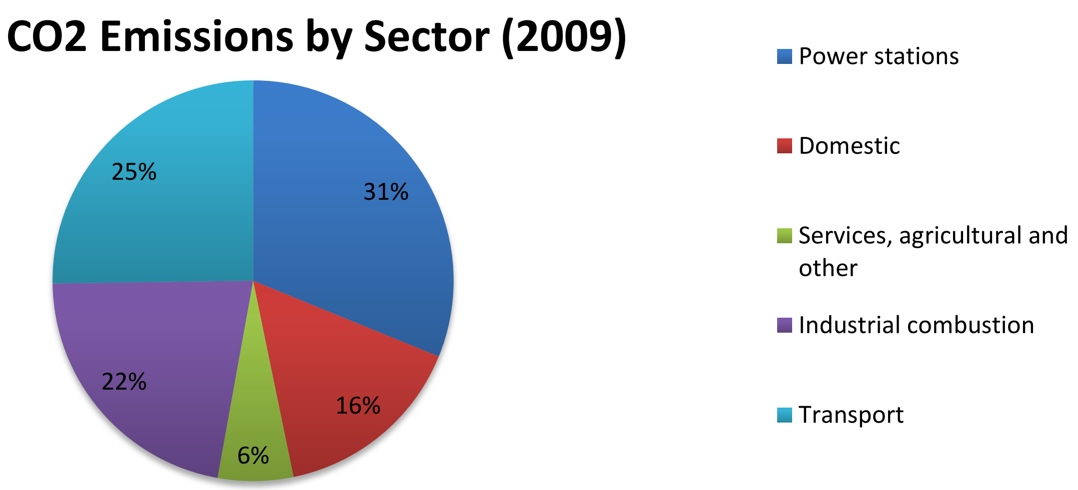



*Figure 2 – CO2 Emissions by Sector (2009)*

A component of the industrial sector in the UK is the extraction and production of heavy building materials including aggregates, concrete, cement, bitumen and asphalt. These materials continue to be used extensively in the construction industry, be it asphalt for roads or concrete for foundations and structural elements in buildings. By quantifying the energy (and resulting $CO_2$ emissions) used in the manufacture of these products, possible solutions could be applied resulting in a significant reduction in their embodied carbon content, helping to contribute to the reduction of UK's overall $CO_2$ emissions output.

## *2.31 Aggregates*

Aggregates can comprise of a mixture of igneous rock, sedimentary rock, metamorphic rock, sand and gravel. They are relied upon heavily in the UK and form the primary ingredient for the materials including asphalt and concrete. In 2009, 197.5 million tonnes of aggregates were produced in the UK *(MPA, 2010)*. Aggregate production can be separated into three different activities; extraction, haulage and processing. Extraction takes place in quarries, usually through explosive blasting. For blasting to occur, holes are first drilled into the rock face to be blasted. The depth and spacing of holes is dependent on the type and amount of rock that is to be obtained from the blasting. The most common explosives used for blasting are Ammonium Nitrate/Fuel Oil (ANFO), Emulsion and Nitro-glycerine *(OSHA, 1996)*. Once blasting has occurred, the fragmented rock is transported for processing. Processing usually takes place on-site, so only minimal transportation is required. A large primary crusher initially breaks the blasted rock down to around 200mm in size. It is then screened and classified by size, rocks that are still too large (>100mm) are sent to a secondary crusher. A tertiary crusher is also used to again further reduce the rock size *(Private Communication, Jaszewski D, 2011).* Crushers can either be powered by mains electricity of gas oil, while transportation and heavy machinery (used for haulage and extraction) are powered by gas oil *(DETR, 1998).* By the end of the crushing process numerous piles of rock containing different sizes of rock are produced, *Figure 3 (OPA, 2004)* below shows the different sizes of screens used in the UK and the classifications for asphalt and concrete. According to the Mineral Products Association (MPA), carbon emissions from the UK aggregate sector in 2009 were 4.3Kg$CO_2$/tonne of aggregate produced *(MPA, 2009b).*

Calcium carbonate, otherwise known as limestone is another major aggregate type used in the UK, it is one of the world's most abundant raw minerals. UK lime production is around 2.5 million tonnes per year *(British Geological Survey, 2006).* It can be used in many materials including glass production, animal feeds, paper, plastics, asphalt filler, foods and pharmaceuticals amongst many other things. The limestone is ground or crushed depending on the final product that is required. By firing limestone in a kiln, lime can be created, again a very useful material that can be used for many products including iron and steel, chemical products and building materials.

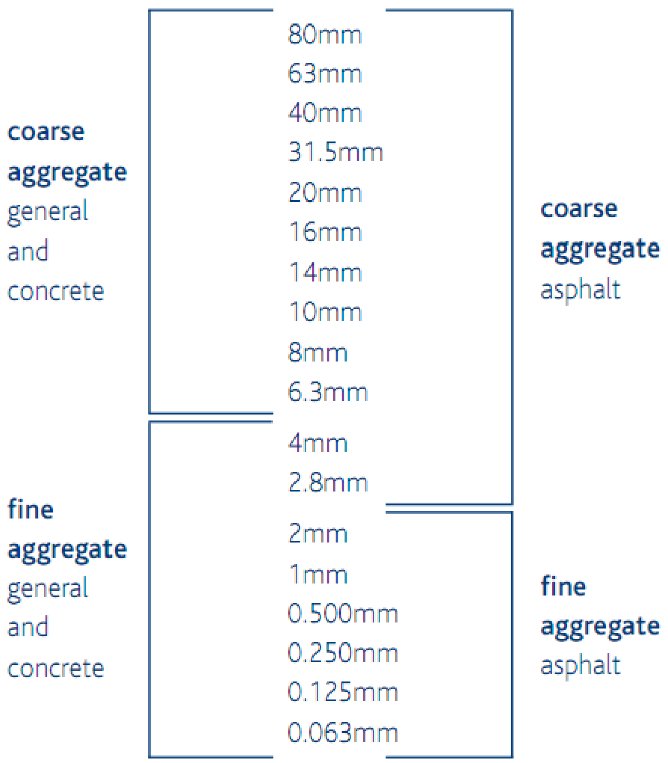



*Figure 3 – Standard UK grading sizes for Asphalt and Concrete as defined by the National Guidance Document (QPA, 2004).*

Recycled aggregate can also be used in these products. By using recycled aggregate, a lower embodied carbon content of the finished product can be achieved. Virgin aggregate is also saved, helping to conserve resources, however, it is estimated that the UK has enough aggregates to last hundreds of thousands of years at current consumption trends *(McLaren D et al, 1999).* There was more than a doubling of aggregate recycling plants in the UK in a four year period between 1997 and 2001 from 16 to 33 due to the introduction of the landfill tax *(BAA, 2005).* As of 2010, landfill tax for and including produced aggregates such as asphalt and concrete is £48 per tonne, meaning that it is extremely costly to dispose of material like this, making recycling now an extremely more viable option *(AggRegain, 2011).* In 2002, DEFRA set up the Waste & Resources Action Plan (WRAP). This initiative was set up to help promote the use of recycled aggregates in the construction industry, helping to reduce the amount sent to landfill. WRAP have produced a number of guidance tools to help minimise waste from the construction, leading to a more sustainable industry sector.

## *2.32 Concrete*

Concrete, which is made from a mixture of cement, aggregates and water, is a very versatile and accessible material, being 100% recyclable. Almost all the Concrete used in the UK is sourced from the UK, usually within close proximity to the building site itself *(The Concrete Centre, 2007).* It is the second most consumed substance on Earth, with only water being the first *(Aitken P. C, 2000),* roughly 80% of which is made from aggregates *(The Concrete Centre, 2010b).* Currently, lots of data on the sustainable credentials of concrete is available. Recent legal and environmental drivers, many of which were targeted at the built environment, have forced the concrete industry to become more environmentally friendly and be able to quantify the impact concrete production has on the environment.

In 2008, '*The UK Strategy for Sustainable Construction'* was published. This report set out targets to help the concrete industry become more sustainable, many of which were to move towards using more recyclable materials. It is hoped by 2012 that the concrete industry will be the most sustainable in the construction sector, already the industry uses more waste than it produces, meaning it is a net waste user. Currently, Recycled Aggregate & Recycled Concrete Aggregate rA & RCA) in the UK concrete industry accounts for 5.3% of total aggregates used in concrete *(The Concrete Centre, 2010b)*, however this figure varies depending on the type of concrete being produced, as concrete with higher recycled rates cannot be used as a structural material *(The Concrete Centre, 2006).* This figure is quite low, mainly due to that fact that it is heavily affected by transportation of recycled aggregate to/from the plant, if distances are too high, then the recycled content loses its purpose. The majority of recycled material used in concrete comes from the demolition of structures, currently, concrete production is significantly higher than recycled material production and this is another reason due to the lower rates of RA & RCA usage. According to the Mineral Products Association (MPA), carbon emissions from the UK ready mixed concrete sector in 2009 was 0.95Kg$CO_2$/tonne *(MPA, 2009b).*

Cement, the binder used in concrete comprises of limestone and small quantities of other materials such as clay. They are heated together in a kiln, where a temperature of 1450°C is reached. Gypsum is then added to the mix to produce cement. This process is very energy intensive due to the high amounts of energy needed to heat the content. Energy used to heat the kiln is usually natural gas; however other materials such as used tyres and sewage waste can be used to help power them, reducing the amount of fossil fuels used. This has led to a saving of 26.5% in the use of fossil fuels and has meant nearly a 40% reduction in $CO_2$ emission levels from 20 years previous *(MPA, 2009a).* However, the embodied carbon of cement still remains very high at 776.8Kg$CO_2$/tonne produced *(MPA, 2009b).* Fly Ash (FA), produced from the burning of coal and Ground Granulated Blast Furnace Slag (GGBS), a by-product from steel production can be used to replace cement. Different mixes can be used depending on the end product; FA usage can range from 6% to 55% and 6% to 80% for GGBS respectively *(The Concrete Centre, 2010a).* UK cement has reportedly over 30% of FA and/or GGBS content used in it, helping to reduce the embodied carbon content of UK concrete *(The Concrete Centre, 2010b).*

## *2.33 Bitumen*

Bitumen is another major material used in the UK construction industry, especially as a binder for the production of asphalt. 1.5 million tonnes of bitumen is produced annually in the UK, 90% of which is used in the production of asphalt *(Refined Bitumen Association, 2011).* Originating from crude oil, it is first extracted from the ground then sent to an oil refinery to be processed. The crude oil undergoes fractional distillation; lighter fractions have lower boiling point, meaning separation can take place. This produces different substances including gas, gasoline, kerosene, diesel oil and bitumen. Bitumen is one of the heaviest fractions in crude oil, to obtain it the crude oil needs to be heated to temperatures of over 525°which requires significant amounts of energy. Once the bitumen has been extracted, it is then transported to where it will be used, such as an asphalt coating plant. Energy and resulting carbon emissions are associated with every aspect of the bitumen production process including extraction, transportation and processing. In 2009, *Eurobitume* produced a Life Cycle Inventory for bitumen used within Europe. The report quantifies all GHG as well as other material and fuel uses associated with bitumen production.

## *2.34 Asphalt*

Asphalt can be used as a coating for our roads. 25 million tonnes of asphalt were produced in the UK in 2008 *(MPA, 2009b).* After the aggregate has been crushed and separated, it is turned into asphalt. This process first requires the correct mixture of aggregate (depending on the type of asphalt being produced, usually a mix of aggregate, bitumen, sand and limestone filler) to be dried out in a rotating drum, intense heat from a burner is used to dry the material, removing its moisture. Once dry, binder (usually bitumen) is added and mixed together in a coating plant, thus creating asphalt. The binder is kept in heated tanks to keep it at the correct viscosity for use. The drum in the coating plant is rotated by an electric motor, while the burner is typically fuelled by kerosene. Through private communication, it was found out that the gas oil was mixed with kerosene to a ratio of 2:1. The kerosene is cheaper than gas oil; however using high ratios of kerosene can damage the delivery pumps, reducing their working life. Gas oil is added to help lubricate the system and is also more combustible *(Private Communication, Hugh McClurg, 2011).*

Aggregate, which contains both small and large particles, ranging from 20mm to less than 0.5mm, are added into the rotating drum where it is heated up by the burner. The particles are exposed to temperatures of around 150°C. The smaller particles of which they are more of, heat up quicker and coat the larger particles, helping to reduce the time they take to heat up. Moisture is evaporated from the particles and removed in the exhaust gasses. Once the aggregate has been dried, bitumen is pumped in to the drum and spread thinly over the surface of the rotating drum coating the aggregate. Drum mixers today have very high efficiencies a low pollutant exhaust levels. *Figure 4* shows the schematic of a coating plant

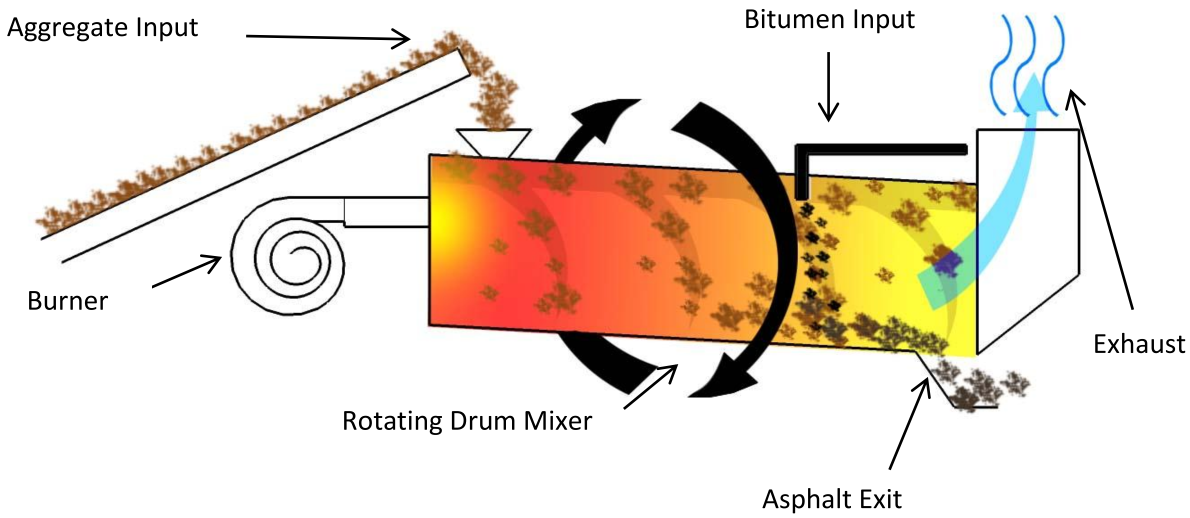



*Figure 4 – Coating Plant Schematic*

Asphalt, like concrete can be recycled. Unlike concrete however, recycled asphalt is not as common in the UK. This is due to the lack of legal and environmental drivers associated with the asphalt industry and the large amounts of aggregate present in the UK. New legislation, such as the CRC, and the rising price of crude oil has now started to affect many UK asphalt producers, resulting in the need to become more environmentally friendly and sustainable. The majority of recycling that currently takes place is using outworn asphalt as a supporting layer for a new stretches of road. It can also be disposed of in landfill. As discussed earlier, it is becoming unsustainable to use landfill for waste products due to environmental legislations and rising landfill taxes. However, outworn asphalt, often referred to when being recycled as Recycled Asphalt Plannings (RAP) can also be used as a substitute to virgin aggregate. By increasing the amount of RAP used in the asphalt mix, the EC content of asphalt can be lowered. Samples of outworn asphalt first need to be taken to determine its characteristics such as moisture content, asphalt binder content and aggregate properties. Once these characteristics are known, the removal and screening of the RAP can take place, it is then ready to be reapplied on to the road surface. There are different methods that can be used to recycle asphalt shown in *Figure 5*;

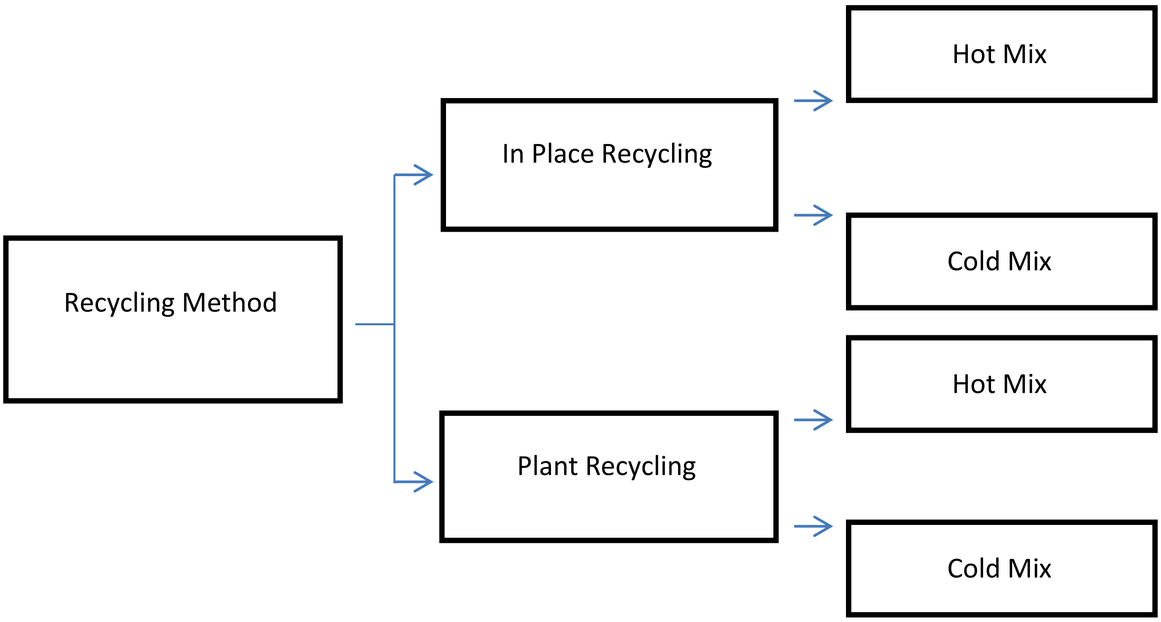



*Figure 5 – Different Recycling Methods Available*

<u>In Place Hot Mix Recycling</u>

Out worn materials are softened using infra-red heaters. This makes removal considerably easier, which is undertaken using a scarifier. Once removed, the outworn material is mixed with virgin aggregate and binder depending on mixture requirements. In Hot Mixture design when using RAP content, the virgin aggregate needs to be superheated. This is so it can later coat the RAP material and let it blend and mix together properly. As the virgin aggregate needs to be hotter, more fuel is required to reach the achieved temperatures. Although the total embodied carbon content of the asphalt will be less when using RAP content, fuel usage increases. This is one disadvantage to using RAP content *(Don Brock J, 2002).* The mixture is then laid. This method significantly reduces transportation to/from site, helping to reduce carbon emissions. However, the machinery is bulky and used in a 'train' format which requires a certain amount of space, meaning that it can only be used in certain applications (e.g. motorway construction)

In Place Cold Mix Recycling

In Place Cold mix recycling uses emulsified binder as a binding agent. Initially, the surface is scarified to remove the outworn material; it is then crushed to the required size. The crushed material is then mixed with virgin aggregate and emulsified bitumen to the correct recipe. Compaction and vibration is then used to separate the water from the mix, letting it evaporate and resulting in the mix setting. Cold mix recycling cannot be used for everything and usually takes longer to set, making it impractical for certain circumstances where time is a constraint. As this is done on site, significantly less transportation is required, saving carbon emissions for vehicle activities.

Cold Plant Mix Recycling

Cold Plant Mix Recycling is identical to Cold In Place Recycling however the recycled material is carried from the construction site to the plant where it is recycled and re produced. It is then transported back to site to be laid. As more transportation is used, higher carbon emissions are associated with this project. It can be used on smaller roads however as there are minimal space restrictions and all processing equipment is located in plant.

Hot Mix Recycling

Hot Mix Recycling is the most common of the four methods and is produced in a burner/drum mixer. Many drums used in today's asphalt production are unable to handle large quantities of RAP due to their older design. More advanced rotating drums however are available that can handle higher RAP percentages and are more efficient in their heating and mixing process. The *Double Barrel* drum mixer manufactured by *Astec Inc* has been purposely designed to handle high quantities of RAP, up to 50%. *Ammann's* Standard Parallel Drum can operate using 100% RAP. When higher percentages of RAP are being used (>15%) it is essential that testing and monitoring is carried out to ensure that the final mix stays consistent, adjustments to the virgin asphalt selected will also need to occur

*(Santucci L, 2007)*. Asphalt containing less than 15% RAP need little, if any modification to the original production process, again however monitoring is essential to make the asphalt produced is consistent *(Santucci L, 2007)*. Again with using higher RAP content, more fuel is required to superheat the virgin aggregate *(Don Brock J, 2002*). *Table 4* below shows the average RAP rate usages in six European countries;

| Country | Percentage of New Production Containing Recycling |
|---|---|
| UK | 1%* |
| France | 15% |
| Germany | 20% |
| Italy | 5% |
| Netherlands | 65% |
| Switzerland | 20% |

*Table 4 – Asphalt Recycling Rates of European Countries (*Estimated) (Quarry Management, 2009)*

It can be seen that the Netherlands, Switzerland and Germany have particularly high recycling rates, whereas the UK is the lowest. This is due to our plentiful supplies of aggregate; however this is expected to change due to tightening environmental legislation and rising fossil fuel prices *(Quarry Management, 2009).*

Another way to lower the embodied carbon of asphalt is to increase its lifespan. By doing so will decrease the times the surface needs to be renewed, leading to decrease in asphalt use and lowering its embodied carbon. Such things as designing the asphalt layers to minimise water absorption and better compacting can increase the lifespan of surface. Usually only the top layer needs to be renewed due to high wear and tear loads. By manufacturing the material to last twice as long will reduce the embodied carbon by half. By introducing more durable material, with recycled content could decrease embodied energy even further *(Tarmac, 2009).*

The UK Highway Agency, Mineral Products Association, Refined Bitumen Association and TRL Limited came me together in a joint venture to create an embodied carbon tool called *asPECT*. *asPECT* was launched in 2009, with continual upgrades until May 2011 when the final version was launched. The tool provides a methodology for the user to calculate embodied carbon content of asphalt at a particular site, by entering is specific details about the production process of the asphalt they are trying to calculate. This tool is particularly useful when it comes to calculating the embodied carbon content of asphalt. *asPECT* shall be utilised later on in this investigation to calculate the embodied carbon content of asphalt associated with a case study.

## *3 Investigation*

A Life Cycle Assessment has been under taken to quantify the embodied carbon associated with Hot Mix Plant Asphalt. Currently, only minimal information is available about the EC content associated with asphalt when compared to other building materials such as concrete. Recent legislation has put a focus on reducing emissions from the built environment. As concrete is a major construction material used in the built environment, it has come under speculation about its ‘green’ properties. In reaction to this, the construction industry including concrete associations have published material and design information about the sustainable credentials of concrete, including its embodied carbon content. This has also happened with other built environment materials such steel, timber and cement. However, with the plentiful supplies of aggregate in the UK and the lack of legislation that affects the asphalt industry, there have been no real drivers to understand and quantify the sustainable credentials and EC of asphalt. With the introduction of the CRC and rising oil prices, both of which will affect many asphalt manufacturers, there is now a need to quantify the EC associated with asphalt and ways best to reduce its value.

To obtain data for this investigation, a case study was used. *Barr Limited* was used as the case study and by using data collected by *Barr* at their quarries and asphalt coating plants; results were obtained to help understand to what degree RAP content affects the embodied carbon of asphalt. Originally a joinery business, Barr expanded significantly and by 2003 the company’s main focus was on four key areas; Construction, Manufacturing, Industrial and Environmental. *Barr* are also subject to the Carbon Reduction Commitment (CRC) described previously, so any reduction in carbon emissions in hot mix asphalt manufacturing could prove beneficial for the company. Hot mix asphalt production is at the core of their business and they have numerous production sites around central and southern Scotland providing asphalt for local authorities and private clients. This is another reason why the hot mix manufacturing method has been chosen as the focus of this investigation, as not only is it very relevant but information regarding the hot mix process will be readily available from the case study and results from the investigation could be used by Barr. Killoch, located in SW Ayrshire is one of Barr’s asphalt production plants and will be the focus of this case study. In 2010, the plant produced 53,545 tonnes of asphalt, however quarrying of aggregate is not done on site, meaning aggregate needs to be transported to Killoch for asphalt production. Aggregate used for asphalt production comes from a quarry at Sorn, located around 6 miles NE of the Killoch site. Asphalt sand, another constituent ingredient in asphalt production comes from their Ardeer site, located in 28 miles NE in Stevenston, North Ayrshire. Transportation of constituent materials will impacts the EC content of asphalt, by how much though needs to be investigated. *Figure 6* shows the location of all three sites.


*Figure 6 – Quarry and Coating Plant Locations*

## <u>*3.1 Aims & Objectives*</u>

The main aims and objectives for the investigation are as follows;

- Quantify energy/fuel usage for each process of asphalt production at the Killoch site for each type of asphalt mix produced.
- Quantify the embodied carbon per tonne of asphalt produced at the Killoch site for each type of asphalt mix produced.
- Understand and quantify what effect increasing the RAP content has on the embodied carbon of asphalt.
- Understand and quantify how varying the embodied carbon content of bitumen affects the final embodied carbon content of asphalt.
- Draw conclusions about the applicability of the calculated EC content for other locations
- Make recommendations to Barr Ltd on reducing embodied carbon in their asphalts.

## *<u>3.2 Investigation – Life Cycle Analysis</u>*

This investigation has adhered to the standards set out in *ISO 14040* and *PAS 2050* specifications. By carrying this investigation out in accordance to these specifications it keeps the LCA standardised. Standardisation is critical in LCA, as it gives clarity and transparency to the reader. It also makes undertaking any further future work easier.

Initially, the energy and subsequent embodied carbon content of the virgin asphalt mixes will be calculated using the *asPECT* software, with data from the case study After this has been quantified, data verification and sensitivity analysis will be undertaken to quantify the EC content of virgin asphalt with varying RAP content. Greater RAP uses will lead to a reduction in virgin material usage, which equates to a reduction in embodied carbon content. This analysis will look into varying levels of RAP content in asphalt, bitumen content and transportation.

To quantify the embodied carbon content of asphalt, first the asphalt production process must be mapped. This will give a clear indication of all processes, materials and transportation energy use throughout the production process. As stated above in the literature review, system boundaries are critical in any LCA. For this investigation, the *Cradle to Gate* approach will be used. *Figure 7* shows the outline process map of the asphalt production process. *Figure 8* and *Figure 9* show the process map in detail for aggregate production at Sorn and the coating plant at Killoch. The *Cradle to Gate* approach has been chosen as it quantifies the embodied carbon content of asphalt, which includes aggregate production, constituent material transportation and asphalt production. Transportation of asphalt to site, the laying and final removal of the asphalt *(Cradle to Grave)* is out with the scope of the investigation due to time constraints. Energy included in the investigation is as follows;

- Energy used for extraction of aggregates.
- Energy used by heavy machinery on site.
- Energy embodied in secondary materials (Bitumen).
- Energy used in transportation of secondary materials.
- Energy used in transportation of materials between processes.
- Energy used for processing material (Screening, crushing, drying, heating and mixing).

*PAS 2050* states that the following energy usages should be excluded from a LCA and this has been adhered to in this investigation;

- Energy embodied in the manufacture, transportation and maintenance of both fixed and mobile machinery.

- Energy used to manufacture and transport machinery grease, lubricating and hydraulic oils.

The functional unit used in this investigation will be kg of carbon dioxide equivalent per tonne of asphalt produced (kg$CO_2$e/t).

Currently, the industry has two distinct and separate ways to measure the recyclability of a product; The *Recycled Content* approach which rewards recycling, and the *Substitution Method* which rewards recyclability. The *Recycled Content* approach allocates a certain percentage of constituent materials which have been recycled/reused. (e.g. 40% recycled material, 60% virgin material), thus giving recycling credit to materials at the start of their life. The later approach awards the future recyclability of a constituent material, therefore giving an end of life recycling approach (e.g. 80% of the constitute materials can be recycled into new products at the end of the original products life). Both approaches can be used, however for this investigation, the initial approach, *Recycled Content*, is favoured. Both methods have pros and cons; there is no right or wrong method to use. The *Recycled Content* approach takes into account materials which have already undergone the recycling process, while the latter approach takes into account materials that can be recycled, however, this does not necessarily mean that come the end of the original products life that these materials will be recycled, thus leading to possible over accounting and inaccurate results.

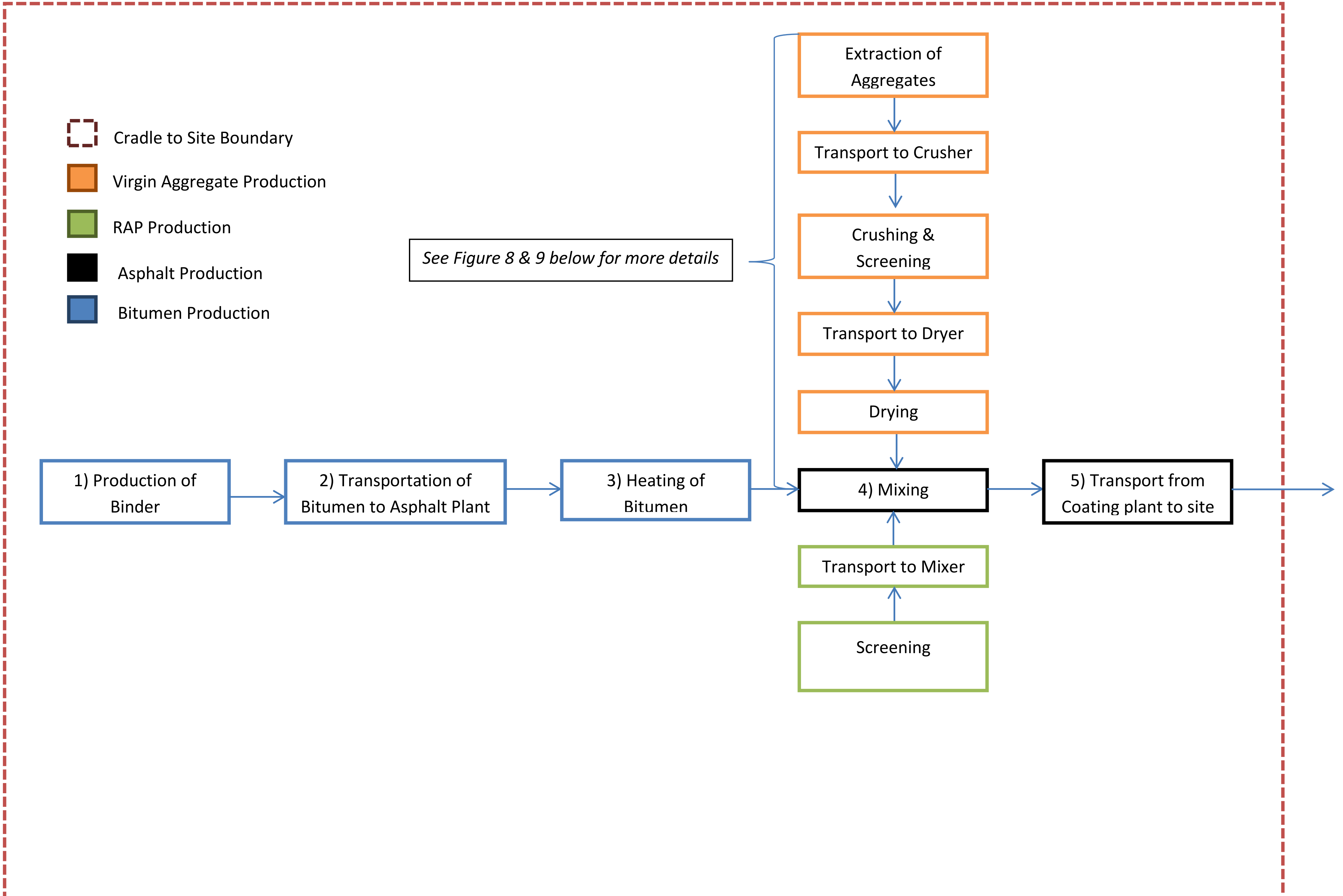



*Figure 7 – Asphalt Production Process Map (Cradle to Gate)*

**Quarrying Phase – Sorn Quarry**

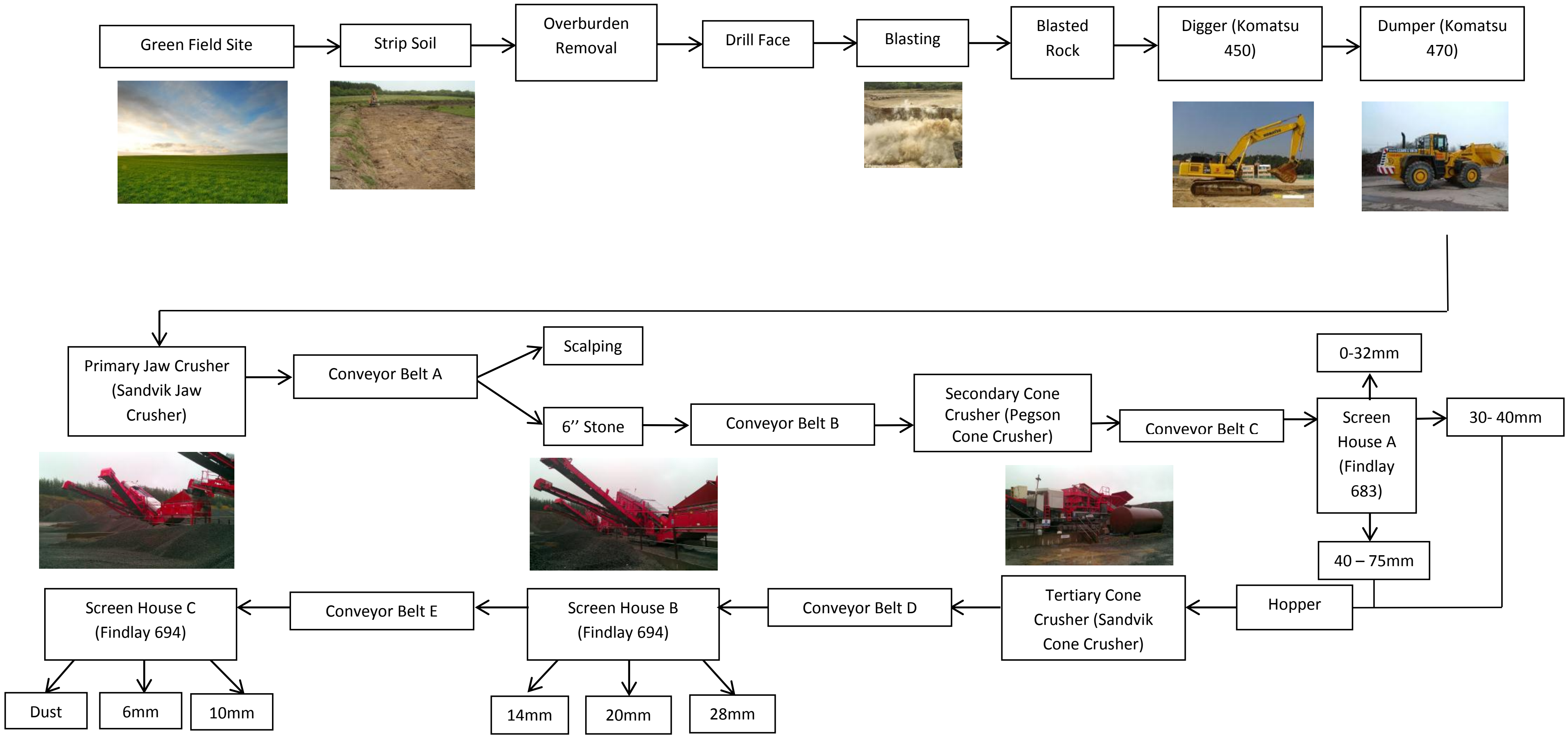



*Figure 8 – Detailed Process Map (Aggregate Production)*

**Coating Plant - Killoch**

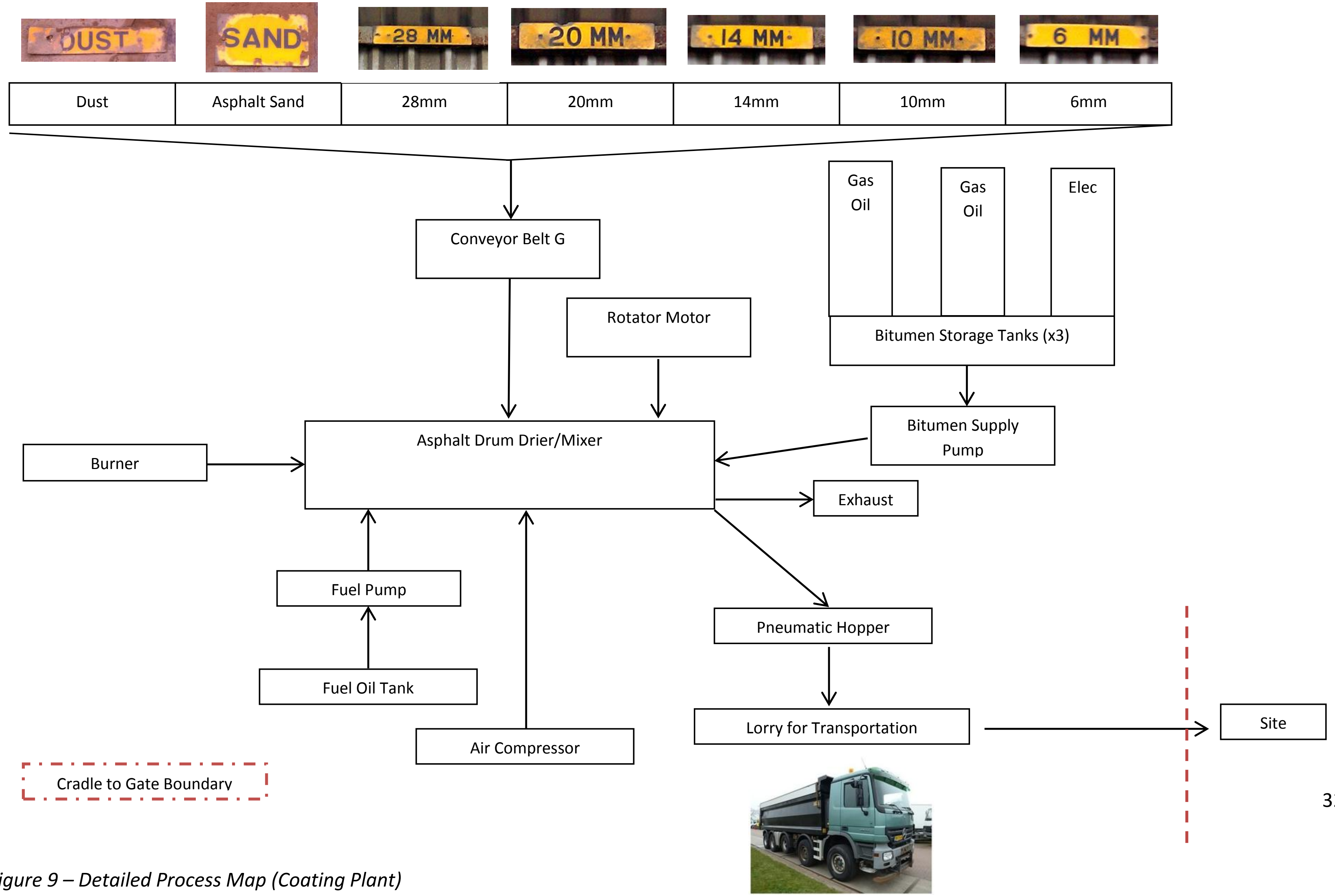



*Figure 9 – Detailed Process Map (Coating Plant)*

## *3.3 – Using asPECT to Calculate Embodied Carbon*

As stated earlier, the *asPECT* computer software tool will be used to calculate the embodied carbon content of asphalt in this investigation. Data is entered into the tool to calculate the values. asPECT is capable of calculating the embodied carbon content for numerous different types of asphalt mixes. In 2010, the Killoch site produced 28 different types of asphalt, all used for a particular type of surfacing depending on the client's needs.

asPECT has three main sections; 'Materials', 'Plants' and 'Projects'. 'Materials' section is used to create a constituent material inventory and calculate each of their associated embodied carbon contents. 'Plants' section is used to calculate the embodied carbon content of each asphalt mix produced, using the *Cradle to Gate* boundary definition. 'Projects' section is used to calculate the associated embodied carbon content of asphalt with the addition of its application and its eventual disposal/reuse (*Cradle to Grave* boundary conditions applied). Calculations undertaken by asPECT will be verified manually using the guidance and protocol documents supplied by the software. The manual calculations undertaken are shown throughout this investigation at the relevant point.

*While carrying out manual calculations to validate the asPECT software a possible bug was found that miscalculated the RAP Saving value. After discussion with the Transport Research Laboratory (TRL) it was advised that manual calculations should be used to calculate this part of the investigation. This advice has been followed and the values have been calculated out using Excel.*

## *3.4 Methodology*

A summary of the methodology used in this investigation is shown below and it will be discussed further and in greater detail in the section;

- Collect relevant data required from case study.
- Use *asPECT* (Asphalt Pavement Embodied Carbon Tool) embodied carbon tool to quantify the EC content of asphalt.
- Verify certain figures provided by Barr through the implementation of consumption monitoring at the Killoch site.
- Sensitivity analysis looking into how EC content of changes by varying the EC content of bitumen.
- Sensitivity Analysis looking into how EC content changes by varying constituent material transportation distance
- Sensitivity Analysis looking into how EC content changes by varying RAP content.

### *3.41 – 'Materials'*

In this section, information about each material used in the asphalt mix is required to create the material inventory including; total annual saleable tonnage, category of material type, amount and type of explosives used to remove material from rock face, amount of fuel used by site diggers/dumpers while removing/transporting rock, overburden removal and site restoration. Once this data has been entered, the embodied carbon per tonne of that constituent material can be calculated. 'Plants' stage can then be undertaken to calculate the embodied carbon content of the different asphalts produced. *Table 5* shows the information that was input into the 'Materials' section for 10mm stone. Information used was gathered from productions invoices provided by Barr as well as discussions with quarry managers.

| Category | Value (2010) | Embodied Carbon ($KgCO_2e/t$) | Source |
|---|---|---|---|
| Saleable Tonnage | 3,856.7 Tonnes | - | Barr |
| Electricity | 0 | 0 | Barr |
| Other Fuel | 3707.8 Litres | 13,154.16 | Barr |
| Water Usage | 0 | 0 | Barr |
| Site Works | 645.9 Kg | 2,626.23 | Barr |
| Overburden Removal | 154.55 Litres | 548.30 | Barr |
| Site Restoration | 51.52 Litres | 182.78 | Barr |

*Table 5 – 10mm Stone Production Data*

Basic Data

This field requires initial basic data about the constituent material including its saleable tonnage and the category that the constituent material falls under. By selecting the appropriate category it lets the software know how that constituent material will perform in the burner. As stated earlier the smaller particles in the burner heat up first and provide the heat for the larger particles. This is important to take into account and can determine fuel consumption usage, so by selecting the category of the constituent material used will determine the final outcome of the investigation.

Electricity

Electricity used in the production of aggregates is taken from measured data provided by Barr Limited. The Sorn site used for aggregate quarrying does not use electricity other than to on-site utilities (offices) which is not accounted for in this study.

Other Fuel

Other fuel usage includes fuels used to power on site equipment such as crushers, conveyor belts, vibrating screens, diggers, dumpers and other heavy machinery. Gas oil is used to power these machinery. Figures were taken from monthly measured data provided by Barr and totalled up to get annual consumption. Quantity of each type of aggregate transported from Sorn to Killoch was also provided. To achieve fuel used for each aggregate type, several steps were taken *(Table 6)*;

*Fuel Usage – 10mm Stone Production*

*Total amount of aggregate produced at Sorn – 207,076 tonnes*

*Total amount of aggregate taken to Killoch – 29,311.3 tonnes*

*Percentage of quarried aggregate taken to Killoch =* $29{,}311.3/207{,}076$ *= 14.1%*

*Total Sorn fuel consumption – 276,625 litres*

*Fuel used to produce Killoch aggregate = 276,625 x 14.1% = 39,004.1 litres*

This figure however needs to be adjusted to take into account the difference in fuel usage between the primary and secondary crushers. From measured data provided by Barr it was found out that 65% of the aggregate processed passed through both primary and secondary crushers, while 35% of aggregate processed passed through only the primary crusher only. All aggregates used in asphalt production at Killoch passes through both crushers, so 39,004.1 litres will be multiplied by 65% to account for the fuel usage split.

*Fuel Usage Cont.– 10mm Stone Production*

*Crusher fuel split – 65%*

*Fuel Used to produce Killoch aggregate = 39,004.1 x 65% = 25,352.7 litres*

*Fuel used to produce 10mm Stone – 25,352.7 x 14.6% =* ***3701.5 litres*** *(See Table 6 below)*

*Table 6* below summaries fuel used to produce each size of aggregate used to produce asphalt at Killoch.

| Type | Amount (tonnes) | Percentage | Fuel Usage Split (litres) |
|---|---|---|---|
| 6mm | 4,710.5 | 16.1 | 4081.8 |
| 10mm | 4,286.8 | 14.6 | 3,701.5 |
| 14mm | 5,152.4 | 17.6 | 4,462.1 |
| 20mm | 1,677.7 | 5.7 | 1,445.1 |
| 28mm | 694.9 | 2.4 | 608.5 |
| Dust | 12,789.0 | 43.6 | 11.053.7 |
| | | | |
| TOTAL | 29,311.3 | 100.0 | 25,352.7 |

*Table 6* - Fuel Usage of each Aggregate Size

Water Usage

No mains water is used in the aggregate production process.

Site Works

Site works include amount of explosives used to remove rock from the rock face. This figure was taken from blasting logs for 2010 at the Sorn site, which used emulsion explosives. Each log gives total amount and type of explosives used, as well as $m^3$ and weight of rock to being blasted, summarised in *Table 7*

| Date | Explosive (kg) | Volume of Rock ($m^3$) | Tonnes of Rock (t) |
|---|---|---|---|
| 16/12/2009 | 6,037 | 10,318 | 26,826 |
| 19/05/2010 | 9,737 | 15,335 | 39,872 |
| 21/07/2010 | 825 | 1,894 | 4,924 |
| 22/07/2010 | 9,853 | 17,162 | 44,621 |
| 02/11/2010 | 4,921 | 8,730 | 22,699 |
| | | | |
| TOTAL | 31,373 | 53,439 | 138,942 |

*Table 7 – Amount of Explosives used in 2010*

The amount of explosives used for each constituent material was then multiplied by the embodied carbon content of the explosive type used. The emissions factor associated with emulsion explosives is 3900 $kgCO_2e/t$ for its manufacture and 166.6 $kgCO_2/t$ given off when detonated, thus giving a total of 4066.6 $kgCO_2e/t$. The protocol document that comes with the software states that no other GHG emissions data is available for the detonation value, hence why the measurement is in $kgCO_2$/tonne. Both measurement units however can be used interchangeably when only calculating embodied carbon content.

Below shows the calculation applied to quantify the amount of explosives used and the embodied carbon associated with the blasting for each type of stone bound for Killoch.

*<u>2010 Site Works, Sorn - 10mm Stone</u>*

*Total Amount of Explosives Used – 31,373 kg*

*Explosives used for Killoch stone – 31,373 x 14.1% = 4392.2 kg (14.1% taken from 'Other Fuel')*

*Explosive used for 10mm Stone – 4424 x 0.146 = 641.3 kg (0.6413 tonnes)*

*Associated embodied carbon – 0.6413 x 4066 =* ***2626.23*** $\boldsymbol{kgCO_2/t}$

*Table 8* below summarises explosives used for each size of stone as a constitute material for the asphalt production at Killoch.

| Type | Percentage | Explosives Used (kg) |
|---|---|---|
| 6mm | 16.1 | 707.1 |
| 10mm | 14.6 | 641.3 |
| 14mm | 17.6 | 773.0 |
| 20mm | 5.7 | 250.4 |
| 28mm | 2.4 | 105.4 |
| Dust | 43.6 | 1915.0 |
| | | |
| TOTAL | 100 | 4392.2 |

*Table 8 – Amount of Explosives used for each constituent material.*

Overburden Removal

Overburden removal includes removal of land situated on top of the usable rock; this usually consists of soils and clays. Diggers and dumpers are used to remove this before blasting takes place. Overburden removal may take place once every few years; certain quarries may only undertake overburden removal once in the quarry's lifetime. It has been calculated by Barr's Geotechnical Engineer that the volume of overburden removed at Sorn throughout its lifetime will be 305,760 $m^3$. This equates to roughly 580,944 tonnes of top soil material. Unfortunately fuel consumption and tonnage removed has not been logged during overburden removal at Sorn. Private communications were held with Gordon Hynd, who is the Operations Manager for Barr, regarding overburden removal and site restoration. After discussions it has been decided that the fuel consumption figure for overburden removal at Sorn will be based on machinery operating for one week per year removing top soil. This is an average value which will provide accurate results using the minimal amount of information available. Below shows how the fuel usage figure for overburden removal was calculated.

*Average Daily Fuel Consumption (Based on 3 Dumpers, 1 Excavator and 1 Dozer) – 1350 L*

*(Dumper (x3) – 200 L/day, Excavator – 400L/day, Dozer – 350 L/day)*

*Overburden Removal Days per Year – 5.5*

*Annual Fuel Usage At Sorn – 1350 x 5.5 = 7425 L*

*Fuel Split For Killoch - 7507.5 x 14.1% = 1046.9 L*

*Table 9* summarises fuel used for overburden removal associated with Killoch for each stone size.

| Sizes | Percentage | Overburden (litres) |
|---|---|---|
| 6mm | 16.1 | 168.55 |
| 10mm | 14.6 | 152.85 |
| 14mm | 17.6 | 184.25 |
| 20mm | 5.7 | 59.67 |
| 28mm | 2.4 | 25.12 |
| Dust | 43.6 | 456.45 |
| | | |
| TOTAL | 100 | 1046.9 |

*Table 9 – Fuel Required for Overburden Removal Associated with Killoch.*

Site Restoration

As site restoration has not yet taken place at Sorn, only an estimate of the volume of top soil needed to restore the site can be made. Through discussion with Gordon Hynd and Barrs Geotechnical Engineer it can be estimated that roughly a third of the volume will be put into Sorn, which equates to 101,920 $m^3$ of top soil. Using the fuel consumption rates from machinery in the *'Overburden'* section above, the fuel usage required for site restoration can be calculated. *Table 10* summarises the fuel required for restoration associated with Killoch.

| **Sizes** | **Percentage** | **Restoration (litres)** |
|---|---|---|
| 6mm | 16.1 | 56.81 |
| 10mm | 14.6 | 51.52 |
| 14mm | 17.6 | 62.10 |
| 20mm | 5.7 | 20.11 |
| 28mm | 2.4 | 8.47 |
| Dust | 43.6 | 153.84 |
| | | |
| TOTAL | 100 | 352.85 |

*Table 10 – Fuel Required for Restoration Associated with Killoch.*

## *3.42 – 'Plants'*

This section requires information and measured annual data about the coating plant used to produce the asphalt. Data required includes total asphalt production, total electricity usage, water usage, heating and drying fuel usage, materials transported to plant and mixtures. Once all the required data has been entered, a completed embodied carbon content value is calculated. Each individual mix will be assigned its embodied carbon content as well as an average embodied carbon content being calculated.

Total Asphalt Production

Annual saleable tonnage in 2010 is 53,545 tonnes. This was achieved by totalling of each specific asphalt mix provided by Barr

Electricity Usage

An annual electricity usage of 283,210 kWh has been applied. This includes electricity used to power pumps, heating elements (bitumen tank) and motors. The data has come from coating plant monthly meter measurements in 2010.

Other Fuel Usage

Gas oil is also used for two other processes in asphalt production at Killoch; heating the bitumen tanks and powering the on-site vehicles such as diggers and dumpers. Killoch has three bitumen tanks; two gas oil fired tanks and one electrically heated tank *(Figure* 9*).* If the temperature of the bitumen falls below 120°C then degradation and thickening will occur, meaning it cannot be used for asphalt production. In 2010, the fuel consumed by gas oil fired bitumen heaters was 31,328 litres *(Table 10).*

Gas oil used by on-site vehicles in 2010 was 28,565 litres. Gas oil usage is measured each time a vehicle is refuelled at the Killoch site.

Water Usage

No mains water is used in the asphalt coating plant.

Heating & Drying Fuel

Heating and drying fuel used in the burner is mixture of gas oil and kerosene/ furnace fuel. In 2010, 511,310 litres of fuel were consumed in the coating plant. *Table 11* below shows the total fuel used for each month and the total annual consumption. Gas oil and kerosene are replaced with furnace fuel from May to November, then gas oil /kerosene resume in December. This fuel replacement was mainly due to cheaper fuel pricing, thus also explaining the change back to gas oil/kerosene mix. Both mixes perform the same and have very similar properties, so they can be classed together. asPECT assumes fine and coarse aggregate has a 5% moisture content.

| | Burner | | | Bitumen Tanks |
|---|---|---|---|---|
| **Month** | **Gas Oil (l)** | **Kerosene (l)** | **Furnace Fuel (l)** | **Gas Oil (l)** |
| Jan | 4,885 | 7,328 | - | 2,963 |
| Feb | 7,336 | 11,049 | - | 2,065 |
| Mar | 27,880 | 41,850 | - | 3,200 |
| Apr | 64,488 | - | - | 3,300 |
| May | - | - | 40,670 | 2,300 |
| Jun | - | - | 41,600 | 2,950 |
| Jul | - | - | 84,150 | 3,250 |
| Aug | - | - | 67,784 | 1,700 |
| Sep | - | - | 39,900 | 2,300 |
| Oct | - | - | 40,500 | 2,500 |
| Nov | - | - | 21,800 | 2,800 |
| Dec* | 5,045 | 5,045 | - | 2,000 |
| | | | | |
| SUB TOTAL | 109,634 | 65,272 | 336,404 | 31,328 |
| **TOTAL** | **511,310** | | | **31,328** |

*Table 11 – Killoch Fuel Usage (Burner & Bitumen Tanks)*

Material Transportation

Three properties are assigned to each material delivered to the Killoch site, distance travelled to Killoch site, type of delivery vehicle used and the utilisation of the vehicle. A utilisation factor of 50% means the delivery vehicle (e.g. Rigid 3.5t – 7.5t truck) will be full outbound (to Killoch) and empty inbound (home depot), utilisation factors vary constantly, however for this investigation a 50% utilisation method will be applied to all delivery vehicles, this value is suggested both by asPECT and DEFRA. *Table 12* shows the relevant data input for each delivered material to the Killoch site. With all this taken into account, the embodied carbon associated with the delivery of these materials is calculated through multiplying the distance travelled with the specific emission output of the transport vehicle being used. These figures are readily available from *DEFRA.* A screenshot of the *'Materials to Transport'* tab is shown in *Figure 10.*

| Material | Delivery Distance (km) | Delivery Method | Utilisation Factor (%) |
|---|---|---|---|
| Aggregate | 10 | Truck (Rigid 17t >) | 50 |
| Asphalt Sand | 45 | Truck (Articulated >3.5t – 33t) | 50 |
| Bitumen | 288 | Truck (Articulated >3.5t – 33t) | 50 |
| Filler (Hydrated Lime) | 40.5 | Truck (Rigid 3.5t – 7.5t) | 50 |

*Table 12 – Material delivery data*

This equation below is used to calculate embodied carbon associated with delivery of constituent materials;

$$kg\ CO_2e\ per\ journey =$$
$$Distance\ travelled\ (vehicle\ km)\ x\ \left[DEFRA\ 50\%\ Load\ Factor\left[Total\ GHG\ \left[\frac{kgCO_2e}{vkm}\right]\right]\right]$$
$$-\left((f-50\%)x\ DEFRA\ 0\%\ Load\ Factor\left[\frac{kgCO_2e}{vkm}\right]\right)$$

*Transport Research Laboratory, 2011*

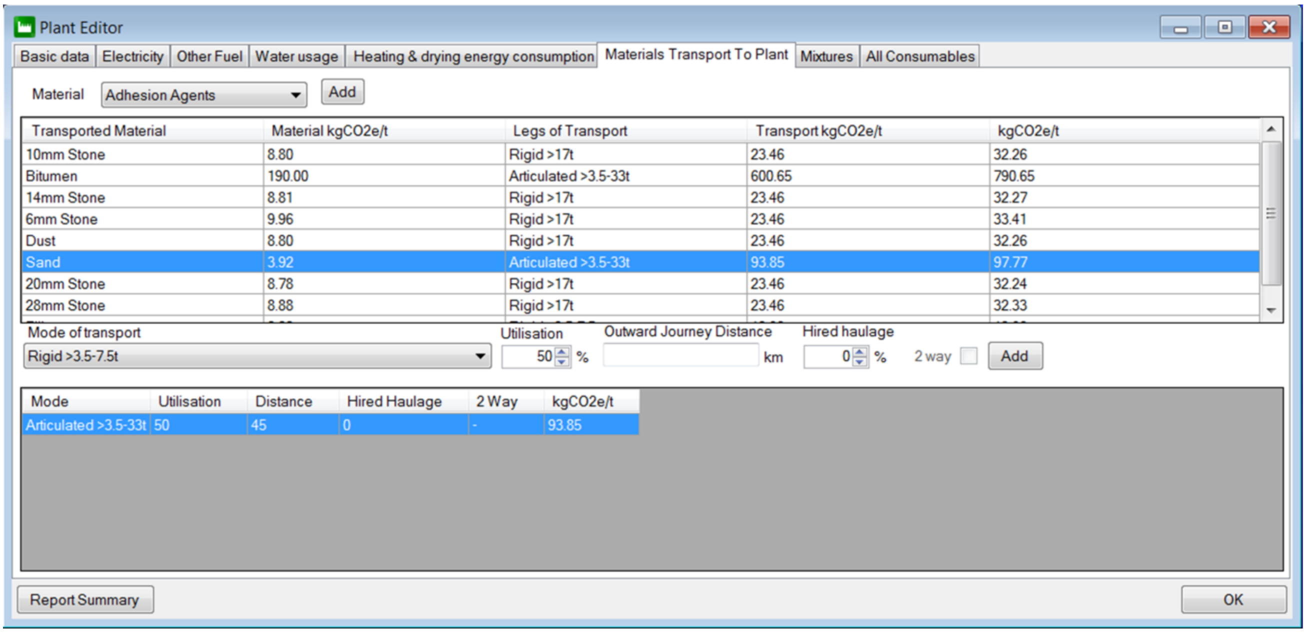



*Figure 10 – 'Material Transport To Plant' Tab*

Below is a manual example of some the calculation to quantify embodied carbon due to the transportation of constituent materials and their respective results. Once the embodied carbon for each constituent material has been calculated, it is divided up depending on the percentage of that material in the asphalt mix. An example is shown in the following section *Mixtures.*

*<u>Transport - Asphalt Sand</u>*

*Delivery Distance – 45km*

*Delivery Method – Truck (Articulated >3.5t – 33t)*

*Utilisation Factor – 50%*

*DEFRA 0% Load Factor – 0.836 kg$CO_2$e/vehicle km*

*DEFRA 50% Load Factor – 1.043 kg$CO_2$e/vehicle km*

*Kg $CO_2$e per journey = (45 x 2) x (1.043 kg$CO_2$e/vkm – ((50% - 50%) x 0.83 kg$CO_2$e/vkm))*

*= **93.87kg$CO_2$e/t***

<u>Mixtures</u>

All 28 mixtures produced at Killoch in 2010 are listed in *Table 13* with their respective constituent materials in percent. These constituent materials are input into the 'Mixtures' tab in asPECT to create the mixture profiles. For an asphalt mix to exist, 100% of constituent materials must be allocated. As well as constituent materials being allocated, the total annual production and production rate in tonnes/hour of that asphalt mix also needs to be known, both these figures have come from Barr. 60t/h has been chosen as it represents an average production rate. Realistically production rate varies depending on a number of variable including ambient temperature and moisture content.

Once all the above data has been associated with its respective constituent materials, the total EC of each mix can be calculated. The total EC content is a sum of all the processes used in asphalt production. *Equation* 1 below is used by asPECT to calculate the total embodied carbon in a mix.

$$CO_2 Asphalt\ Mixture = Constituent\ CO_2e + Transport\ CO_2e + Mix\ CO_2e + Heat\ CO_2e$$

*(Transport Research Laboratory, 2011)*

*Equation 1 – Total Embodied Carbon Content of Mixture Equation*

This can be seen in *Figure 11* where a breakdown of the final value is given, including embodied carbon associated with aggregate production, transportation, heating and drying, non-heating processes and saving made from RAP.

As stated earlier, the *Recycled Content* approach for recyclability is the favoured method for this investigation. asPECT awards RAP 0 $kgCO_2e/t$ at the start of its life when it is first deposited from its previous source. Any energy used in their processing following their first deposit will be accounted for (e.g. screening, transportation, heating and mixing). However, asPECT also applies the *Substitution Method* in a 60:40 split (Recycled Content: Substitution Method). According to asPECT, this not only rewards RAP being used in current asphalt mix but also recognises that asphalt has a very high future recyclability rate, although the bigger weighting has been given to the use of RAP in current asphalt production to help incentivise it. This shall be further explained in Section *3.63 – RAP Content*

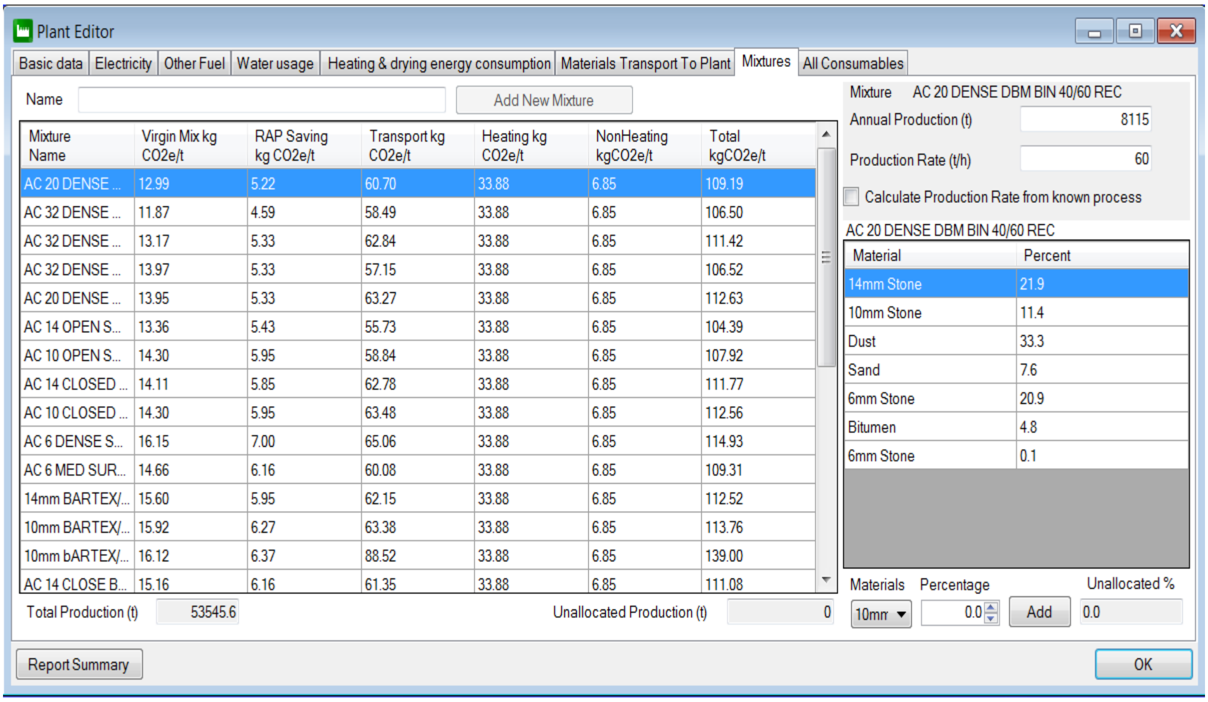



*Figure 11 – 'Mixtures' tab showing asphalt mixture make up*

| Mix | Name | Annual Production Tonnage | Tonnes/Hour | Bitumen | 20mm | 14mm | 10mm | 6mm | Dust | Asphalt Sand | Filler |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | *AC 20 Dense DBM Bin 40/60 Rec* | 8115 | 60 | 4.9 | | 21.9 | 11.4 | 20.9 | 33.3 | 7.6 | |
| 2 | *AC 32 Dense DBM Base XX/YY Rec* | 4566.8 | 60 | 4.2 | 16.3 | 9.6 | 12.5 | 8.6 | 18.2 | 9.6 | |
| 3 | *AC 32 Dense DBM Bin XX/YY Rec* | 142 | 60 | 4.9 | 16.2 | 9.5 | 12.4 | 18.1 | 29.5 | 9.5 | |
| 4 | *AC 32 Dense HDM Bin 40/60 Des* | 523 | 60 | 4.9 | 22.8 | 11.4 | 12.4 | 15.2 | 30.4 | | 2.9 |
| 5 | *AC 20 Dense HBM Bin 40/60 Des* | 51.4 | 60 | 4.9 | | 21.9 | 11.4 | 21.9 | 29.5 | 7.6 | 2.9 |
| 6 | *AC 14 Open Surf XX/YY* | 875 | 60 | 5.0 | | | 37.1 | 38.0 | 20.0 | | |
| 7 | *AC 10 Open Surf XX/YY* | 104.2 | 60 | 5.5 | | | | 74.7 | 19.8 | | |
| 8 | *AC 14 Closed Surf XX/YY* | 345.6 | 60 | 5.4 | | | 23.7 | 41.6 | 23.7 | 5.7 | |
| 9 | *AC 10 Closed Surf XX/YY* | 2129.4 | 60 | 5.5 | | | | 65.2 | 23.6 | 5.7 | |
| 10 | *AC 6 Dense Surf XX/YY* | 4662.4 | 60 | 6.5 | | | | 30.9 | 62.6 | | |
| 11 | *AC 6 Med Surf XX/YY* | 122.6 | 60 | 5.7 | | | | 45.3 | 49.0 | | |
| 12 | *14mm Bartex (Torpave) HT Thin Surf Styrlt* | 165.8 | 60 | 5.5 | | | 47.3 | 19.8 | 22.7 | | 4.7 |
| 13 | *10mm Bartex (Torpave) HT Thin Surf Styrlt* | 1011.5 | 60 | 5.8 | | | | 67.8 | 22.6 | | 3.8 |
| 14 | *10mm Bartex (Torpave) MT Thin Surf Styrlt* | 1092.8 | 60 | 5.9 | | | | 60.2 | 30.1 | | 3.8 |
| 15 | *AC 14 Close Barpave Surf XX/YY* | 759.2 | 60 | 5.7 | | | 25.5 | 34.9 | 32.1 | | 1.9 |
| 16 | *AC 10 Close Barpave Surf XX/YY* | 8133.2 | 60 | 5.8 | | | | 63.1 | 29.2 | | 1.9 |
| 17 | *AC 6 Dense Barpave Surf XX/YY* | 1174.6 | 60 | 6.8 | | | | 30.9 | 62.6 | | |
| 18 | *HRA 50/10 Base/Bin/Reg 40/60* | 5.8 | 60 | 6.4 | | | | 44.0 | 28.1 | 21.5 | |
| 19 | *HRA 15/10 F Surf XX/YY Rec* | 1037.6 | 60 | 8.8 | | | | 15.5 | 13.7 | 52.0 | 10.0 |
| 20 | *HRA 30/10 F Surf XX/YY Rec* | 102 | 60 | 7.7 | | | | 28.6 | 14.8 | 42.5 | 6.5 |
| 21 | *HRA 30/14 F Surf 40/60 Rec* | 108.8 | 60 | 7.7 | | | 25.8 | | 16.6 | 41.5 | 8.3 |
| 22 | *HRA 30/14 F Surf 40/60 Des* | 8538.4 | 60 | 7.2 | | | 26 | | 16.7 | 41.8 | 8.4 |
| 23 | *HRA 35/14 F Surf 40/60 Des* | 884.2 | 60 | 6.8 | | | 30.8 | | 15.8 | 39.1 | 7.5 |
| 24 | *HRA 55/10 F Surf 40/60 Des* | 7.6 | 60 | 5.8 | | | | 55.6 | 10.4 | 23.6 | 4.7 |
| 25 | HRA 45/10 F Surf 40/60 Prop Des | 819.8 | 60 | 6.3 | | | | 42.6 | 10.3 | 35.6 | 5.2 |
| 26 | HRA 45/14 F Surf 40/60 Prop Des | 10 | 60 | 6.3 | | | 42.6 | | 10.3 | 35.6 | 5.2 |
| 27 | AC 14 EME2 BASE/BIN 15/25 Des | 7395 | 60 | 4.8 | | 23.0 | 17.0 | 51.0 | | | 4.2 |
| 28 | 15% 0/6 HRA Surface Course | 662.2 | 60 | 8.8 | | | | 15.5 | 13.7 | 52.0 | 10.0 |

Below is a manual example of *Equation 1.*

Mix 1 - AC *20 Dense DBM Bin 40/60 Rec*

| | | |
|---|---|---|
| *Coarse Aggregate – 54.3% (4406.5 tonnes)* | *Transportation – 23.46 kg$CO_2$e/t* | *E.C – 3.9 kg$CO_2$e/t* |
| *Dust – 33.3% (2702.3 tonnes)* | *Transportation – 23.46 kg$CO_2$e/t* | *E.C - 3.9 kg$CO_2$e/t* |
| *Sand – 7.6% (616.7 tonnes)* | *Transportation – 93.85 kg$CO_2$e/t* | *E.C – 3.9 kg$CO_2$e/t* |
| *Bitumen – 4.8% (389.5 tonnes)* | *Transportation – 600.65 kg$CO_2$e/t* | *E.C – 190 kg$CO_2$e/t* |

**Application of 5% Moisture Content to Aggregate Materials*

Constituent kg$CO_2$e/tonne

*((Aggregate x (1+5%)* [kg]) x E.C [kg$CO_2$e/t]) + ((Sand) x (1+5%)* [kg]) x E.C [kg$CO_2$e/t]) + ((Bitumen [kg]) x E.C [kg$CO_2$e/t])*

*(Transport Research Laboratory, 2011)*

*((4406.5 + 2702.3) x (1+5%) [kg]) x 3.9 [kg$CO_2$e/t]) + ((616.7) x (1+5%) [kg]) x 3.9 [kg$CO_2$e/t]) + ((389.5 kg]) x 190 [kg$CO_2$e/t])*

*= 103777.15 /8115kg*

*=* ***12.99 kg$CO_2$e/t***

*RAP Saving kg$CO_2$e/tonne*

*Equation shown in Section 3.63*

*((12.99 – (0.95 x (4.8 x 190) +(100 – 4.8) x 4.3 x 1.05) – 4))*

*= 4.0*

*(0.4 x 4.0)*

*=* ***1.6 kg$CO_2$e/t***

*Transport kg$CO_2$e/tonne*

*((Aggregate x (1+5%)* [kg]) x Transport [kg$CO_2$e/t]) + ((Sand) x (1+5%)* [kg]) x Transport [kg$CO_2$e/t]) + ((Bitumen [kg]) x Transport [kg$CO_2$e/t])*

*(Transport Research Laboratory, 2011)*

*((4406.5 + 2702.3) x (1+5%) [kg]) x 23.46 [kg$CO_2$e/t]) + ((616.7) x (1+5%) [kg]) x 101.03 [kg$CO_2$e/t]) + ((389.5 kg]) x 649.59 [kg$CO_2$e/t])*

*= 492499.35 /8115kg*

*=* ***60.69 kg$CO_2$e/t***

*Heating $kgCO_2e$/tonne*

$((Annual\ Fuel\ Usage\ [L])/(Hourly\ Production\ Rate\ [t/h]))/((Annual\ Production\ Rate\ [t])/(Hourly\ Production\ Rate)[t/h])$ *x Gas Oil*

*(Transport Research Laboratory, 2011)*

*= (511,810 L / 60 t/h) / (53,545.6 t / 60 t/h)*

*= 9.545 x 3.550*

*= **33.88 $kgCO_2e$/t***

*Non Heating $kgCO_2e$/tonne*

*((Annual Electricity [kWh] x E.C [$kgCO_2e$/t]) + (Other Fuels [L] x E.C [$kgCO_2e$/t])) / (Annual Production Rate [t])*

*(Transport Research Laboratory, 2011)*

*= (283,210 [kWh] x 0.5156 [$kgCO_2e$/t] + (101,340.05 + 111,142.35) [L] x 3.550 [$kgCO_2e$/t])*

*= 427, 875 / 53,546.6*

*= **6.85 $kgCO_2e$/t***

*Total $kgCO_2e$/tonne for* AC *20 Dense DBM Bin 40/60 Rec*

$CO_2 Asphalt\ Mixture = Constituent\ CO_2e + Transport\ CO_2e + Non\ Heating\ CO_2e + Heat\ CO_2e$

*= 12.99 – 1.6 + 60.69 + 33.88 + 7.99*

*= **113.95 $kgCO_2e$/t** (Differs From asPECT answer below due to possible programming error is asPECT described earlier on)*

## *3.6 Sensitivity Analysis*

A sensitivity study will be undertaken in three areas;

-Varying transportation distance of constituent materials to Killoch.

-Varying the embodied carbon content of bitumen.

-Adding different amounts of RAP to the virgin asphalt mix to see how the final embodied carbon content of the asphalt varies.

This analysis should hopefully highlight ways in which the embodied carbon content of the asphalt can be reduced, thus making it more environmentally friendly. Both sensitivity analyses will be applied to the all 28 mixes to achieve accurate results.

### *3.61 Transportation Distance*

A sensitivity study will be carried out to see what affect varying the transportation distance of constituent materials has on the total embodied carbon content of the asphalt. Materials included will be Aggregate Stone, Dust and Bitumen. This study will give a better understanding on the affect transportation has on embodied carbon content. *Table 14* shows the study which will be carried out.

| Sensitivity Study | Material | Current Outbound Distance (km) | New Outbound Distance (km) |
|---|---|---|---|
| 1 | Stone Aggregate, Dust | 10 | 0 |
| 2 | Stone Aggregate, Dust | 10 | 20 |
| 3 | Bitumen | 288 | 100 |
| 4 | Bitumen | 288 | 500 |
| 5 | Stone Aggregate, Dust, Bitumen | 10 / 288 | 0 / 100 |
| 6 | Stone Aggregate, Dust, Bitumen | 10 / 288 | 20 / 500 |

*Table 14 – Summary of Transport Sensitivity Study*

*Sensitivity Study 1* represents aggregate production and asphalt production on the same site, therefore eliminating transportation of aggregate from quarry to coating plant (Sorn – Killoch).

*Sensitivity Study 2* represents the location of the quarry/coating plant being moved slightly further afield, for example, Kilmarnock. Barr have plans to open a new RAP capable plant in Kilmarnock, thus increasing the relevance of this study.

*Sensitivity Study 3* represents a shorter transportation distance for bitumen; this could represent bitumen coming from a different supplier, for example from the Grangemouth refinery located near

Falkirk. As bitumen is made from crude oil, it is susceptible to price fluctuations. A change of supplier providing a better price is not uncommon practice.

*Sensitivity Study 4* represents a greater transportation distance for bitumen, again for the reasons noted above concerning price fluctuation and change of supplier.

*Sensitivity Study 5* is a combination of *Sensitivity Study 1* and *Sensitivity Study 3* and it represents a minimum transportation distance for both materials.

*Sensitivity Study 6* is a combination of *Sensitivity Study 2* and *Sensitivity Study 4* It represents a maximum transportation distance for both materials.

Transportation distances can be modified in the *'Materials Transport to Plant'* tab by selecting the material and changing the outbound distance.

## *3.62 Bitumen Content*

The embodied carbon content of bitumen will be varied to see what affect this has on the final value of the asphalt mixes. Currently, asPECT provides a pre-set value for bitumen, which is 190.0 $kgCO_2e/t$. This figure has been taken from *Eurobitume*. However, as discussed earlier the value for bitumen can vary depending on the source it is taken from and so a sensitivity analysis will be carried out to determine the range of embodied carbon that asphalt has when applying different embodied carbon contents of bitumen. *Table 15* shows the embodied carbon content range of values used in the analysis.

| Sensitivity Study | Bitumen EC ($kgCO_2e/t$) | Source |
|---|---|---|
| 1 | 430 | ICE |
| 2 | 490 | ICE |
| 3 | 590 | ICE |

*Table 15 – Summary of Bitumen Sensitivity Study*

As the embodied carbon content of the bitumen is known, it can be entered directly into the *'Create from $CO_2$ Figure'* section of the '*Materials'* tab without having to know production rates and fuel usages involved in its manufacture. This is show below in *Figure 12*.

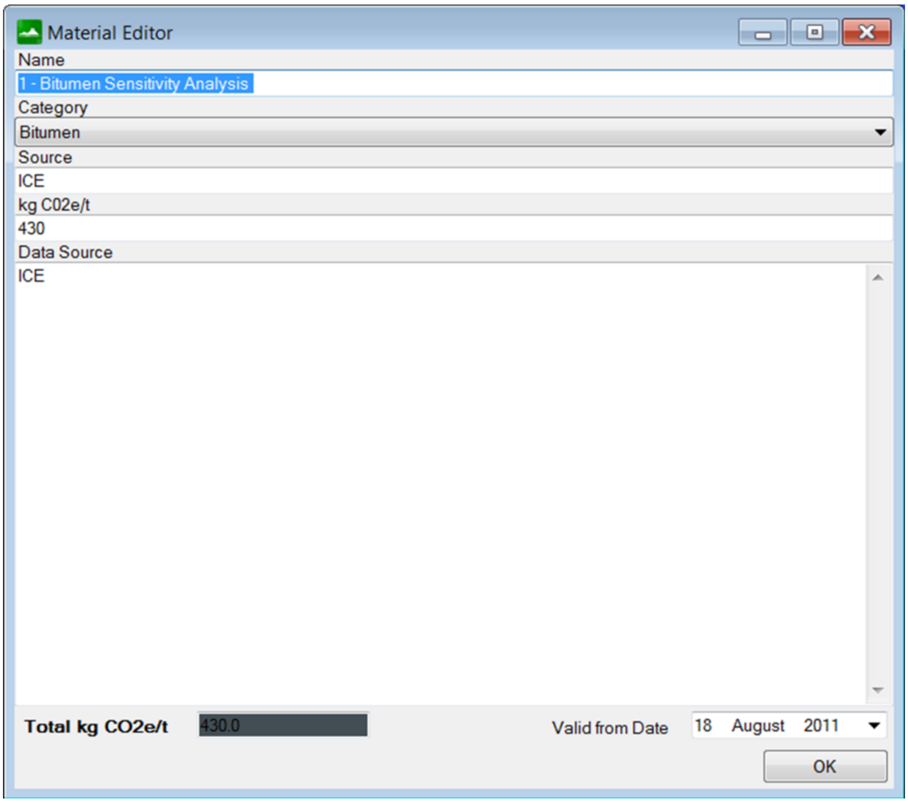



*Figure 12 – 'Create from $CO_2$ Figure' Tab (Bitumen Sensitivity Analysis)*

All 28 asphalt mixtures have to be re-calculated to include the application of three new bitumen values being applied; all other values in asPECT will remain the same.

## *3.63 RAP Content*

Currently Barr do not produce asphalt with RAP content, however, future plans to construct and open a new coating plant that is able to handle RAP are being considered. Barr are stockpiling unprocessed RAP from previous sources for future use which is stored at their Killoch site. Once the RAP is ready to be used, it has to be screened and sorted into specific sizes which will most likely be 14mm and 20mm. Any asphalt mix that uses these sizes of stone will be able to have up to 30% of their virgin aggregate replaced with RAP. The RAP stockpiled at Killoch has an average bitumen binder content of 4.15%, thus less virgin bitumen is needed in the asphalt mixture, helping to reduce embodied carbon

RAP will be included in any mixture containing 20mm and/or 14mm stone to see what affect this has on the total embodied carbon content. After discussions with Gordon Hynd at Barr it has been decided that the RAP content used in their future coating plant will be up to 30%. This sensitivity analysis will also look at smaller stone sizes of 10mm and 6mm RAP. By undertaking the sensitivity analysis with a larger range of stone sizes, a greater understanding of how RAP affects overall EC content can be achieved. Moisture content of RAP at Killoch is on average around 6%, however asPECT does not let the uses alter this value (it is set at 5%), therefore 5% moisture content will be used as in the previous virgin calculations. *Table 16* below summarises the two studies taking place.

| **Sensitivity Study** | **RAP Replacement Stone Sizes Used** | **RAP %** |
|---|---|---|
| 1 | 14mm, 20mm | Up to 30% |
| 2 | 6mm, 10mm, 14mm, 20mm | Up to 30% |

*Table 16 – Summary of RAP Sensitivity Study*

As the RAP has not yet undergone processing at Killoch, no energy usage data is currently available. For this, an assumption will have to be made in determining the EC content of RAP. 3.0 $kgCO_2e/t$ will be applied. This figure has been taken from the asPECT guidance documents *(TRL, 2011)*. Currently no data on fuel required to process RAP and RAP quantities produced exists at Barr, meaning that calculating the EC content of RAP would become very difficult. Another problem is the Barr cannot estimate the amount of RAP they will be able to acquire, as it is dependent on the amount of roads being resurfaced at that time. Also, as only screening will take place to process the RAP, it cannot be estimated the split that will occur between the quantities of different sized materials.

In the *'Materials'* editor, a new profile will be created called *RAP*. By doing this, only the percentage of RAP used will need to be known, which is dependent on the amount of constituent materials used in each asphalt mix. The above method being applied will reduce errors and minimise uncertainties, helping to achieve a realistic and accurate RAP saving figure. *Figure 13* shows the creation of the *RAP* material profile. As stated previously, a possible bug in asPECT prevents it from correctly calculating *RAP Savings.* This means that the calculations will be carried out manually using *Excel*. The *Virgin Mix* figure is taken from asPECT and input into an *Excel* spread sheet, thus calculating the correct value of *RAP Saving.* The manual calculations used are shown below.

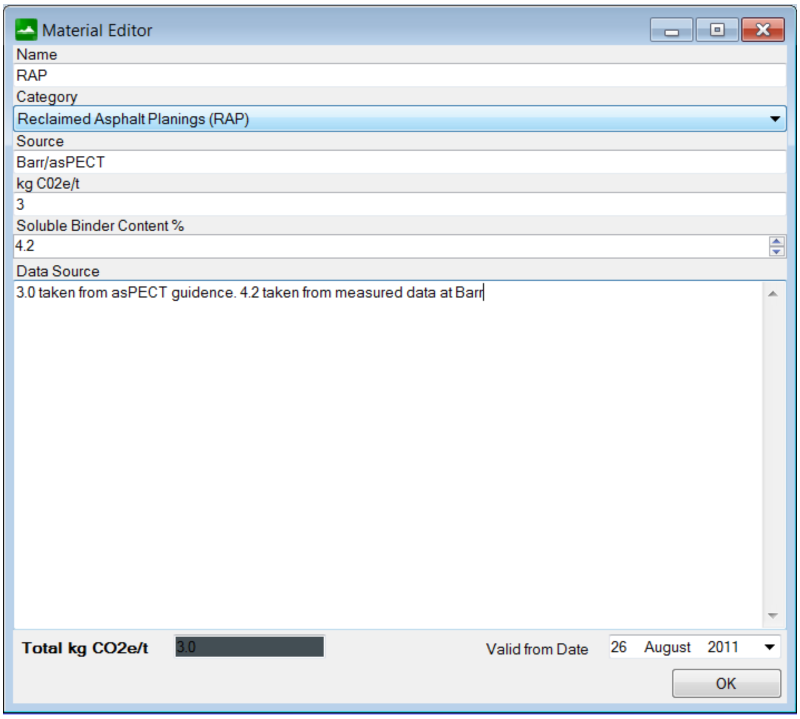



*Figure 13 – RAP Profile In Materials*

asPECT uses a 60:40 approach for recycled content. *Equation 2* below is used by asPECT to calculate the recyclability of asphalt.

$$CO_2e\ (Asphalt\ Mixture) = \big((0.6\ x\ mixCO_2e) + (0.4\ x\ futCO_2e)\big)][kgCO_2\ e)/t]$$

*Transport Research Laboratory, 2011.*

*Where;*

*$mixCO_2e$ = Embodied carbon of current mix constituents, taking into account recycled content*

$$futCO_2 = Virgin\ Mix\ CO_2e - \Big(R\ x\ \big((b_m\ x\ 190) + \big((100\% - b_m)x\ 4.3\ x\ 1.05\big) - futproRAP\big)\Big)\ kgCO_2e/t$$

*R = Recoverability Rate*

*Virgin Mix $CO_2e$ =$mixCO_2$ – (proRAP x %RAP) + %RAP (Aggmix x 1.05 x (100% -$b_r$) + (Bitmix x $b_r$))*

*proRAP = Embodied $CO_2$ of RAP (Taken from asPECT)*

*$b_r$ = Soluable Binder Content of RAP*

*$b_m$ = Virgin Binder Content*

*futproRAP = Future $CO_2e$ content of RAP / tonne (Set At 4 $kgCO_2e/t$ by asPECT)*

*Aggmix = Virgin Aggregate Embodied $CO_2$ Value*

*Recoverability rate R reflects the total loss of mass over the lifetime of asphalt in wearing, extraction and subsequent processing to enable its further use. R is fixed at 95% in asPECT. 1.05 reflects the loss due to moisture.*

Shown below is a manual example of *Equation 2* to calculate the recyclability of Mix 1.

<u>Mix 1 - AC *20 Dense DBM Bin 40/60 Rec*</u>

*RAP – 21.9% (1777.2 tonnes, Soluble Binder Content = 4.2%) proRAP= 3kg$CO_2$e/t*

*10mm Virgin – 11.4% (925.1 tonnes)*

*6mm Virgin – 21.9% (1777.2 tonnes)*

*Sand – 7.6% (616.7 tonnes)*

*Dust – 33.3% (2702.3 tonnes)*

*Bitumen – 3.9% (286.0 tonnes) (4.8 - (4.2 x 6.6% x 30%) = 3.5)*

<u>*Mix $CO_2$ (kg$CO_2$e/tonne)*</u>

*((RAP x E.C [kg$CO_2$e/t]) + (Aggregate x (1+5%) [kg]) x E.C [kg$CO_2$e/t]) + ((Sand) x (1+5%) [kg]) x E.C [kg$CO_2$e/t]) + ((Bitumen [kg]) x E.C [kg$CO_2$e/t])*

*(Transport Research Laboratory, 2011)*

*((1744.7 x 3) + (5404.6 [kg] x (1+5%) [kg] x 3.9 [kg$CO_2$e/t]) + (616.7 [kg] x (1+5%) [kg]) x 3.9 [kg$CO_2$e/t]) + ((316.5 [kg]) x 190 [kg$CO_2$e/t])*

*= 90,076.5/8115kg*

*= **11.10 kg$CO_2$e/t***

<u>*Virgin Mix CO2 (kg$CO_2$/tonne)*</u>

*Virgin Mix $CO_2$ = Mix $CO_2$ – (proRAP x %RAP) + %RAP x ((Aggmix x 1.05 x (100% - $b_r$)) + (Bitmix x $b_r$)*

*11.10 – (3 x 21.9%) + 21.9% x (3.9 x 1.05 x (1 – 4.20%)) + (190 x 4.20%))*

*= **12.99 kg$CO_2$e/t***

<u>*Future $CO_2$ (kg$CO_2$/tonne)*</u>

*fut$CO_2$e = Virgin Mix$CO_2$e – (95% x ((Virgin Bitumen% x E.C) + (100% - Virgin Bitumen % x Virgin Aggregate E.C x 1 + 5%) – 4)) kg$CO_2$e/t*

*fut$CO_2$e = 13.00 – (95% x ((3.9% x 190) + ((100% - 3.9 %) x 4.3 x (1 + 5%)) – 4)) kg$CO_2$e/t*

*= 13.00 – 5.8*

*= **7.20 kg$CO_2$e/t***

Mix 1 - AC *20 Dense DBM Bin 40/60 Rec – Cont.*

*RAP Saving kgCO$_2$e/tonne*

*$CO_2$ Asphalt Mixture = ((0.6 x 11.10) + (0.4 x 5.8)) kgCO$_2$e/t*

*= **8.89 kgCO$_2$e/t***

## *3.7 Data Validation*

To validate that the data supplied by Barr is accurate and correct, independent monitoring has taken place. The data selected for this validation process are the gas oil and electrical consumption of the coating plant. The reason why these two factors have been selected is due to the large contribution they have to the overall EC content of asphalt. Although they are many other streams of data, time constraints and technical feasibility has meant they all cannot be monitored and validated in this investigation. Focussing on two major EC areas should be sufficient enough to provide validation on the same data stream provided by Barr. Also, as all data in this investigation has been provided by Barr from monitored results, the possibility of data not meeting verification from independent monitoring is unlikely. Monitoring took place at the Killoch site on Thursday 25$^{th}$ August 2011.

Gas Oil

From data provided by Barr, average gas oil consumption for each tonne of asphalt produced from the coating plant in August 2010 was **8.70 litres/tonne**. For the independently monitored data, two reading were taken 52 minutes apart. The readings were taken from a PIUSI K40 flow meter located on the burner itself. Readings and subsequent validation is provided below.

*First Reading (11.55am) – 292,597 L*

*Second Reading (12.47pm) – 293,098 L*

*Gas Oil Usage in 52 Minutes = 501 L*

*Coating Plant Production Rate = 70 t/h = 1.166 t/minute*

*Tonnage Produced In 52 Minutes = 1.166 x 52 = 60.66 tonnes*

*Litres Of Gas Oil Consumption to Provide 1 Tonne of Asphalt = 501 / 60.66*

*= **8.26 litres/tonne***

From independent monitoring of gas oil consumption in the coating plant, it can be confirmed that the data provided by Barr is accurate and correct. The 5% variation in values can be attributed to both experimental error and wetter environmental conditions associated with August 2010. Wetter conditions increase moisture in the aggregate resulting in a greater amount of fuel needed to dry them.

Electricity

From data provided by Barr, average electricity consumption for each tonne of asphalt produced from the coating plant in August 2010 was calculated to be **1.94 kWh/tonne.** The calculations used to reach this figure are shown below.

*Bitumen Tanks Consumption*

*kWh Consumed In 16 Hours Each Working Day*

*= 186.67 kWh (Provided by Barr)*

*No Of Working Days in August – 31*

*Total kWh Consumed*

*= 186.67 x 31 = 5787.7 kWh*

*Coating Plant Consumption While NOT in Operation*

*kWh Consumed In Weekend Days/Holidays – 280 (Provided by Barr)*

*No Of Weekend Days/Holidays in August – 9*

*Total kWh Consumed*

*= (280 x 9) + 2787.7 = 8307.7 kWh*

*Total Electricity Consumption at Killoch Submeter*

*= 27,210 kWh (Provided by Barr)*

*Electricity Consumption by Coating Plant Only*

*= 27,210 – 8307.7 = 18,902.3 kWh*

*Electricity Consumed From Plant Idling*

*= 18,902.3 x 0.2 = 3780 kWh (Estimated 20% Idling)*

*Therefore, Electricity Consumption by Coating Plant When Operating*

*= 18,902.3 – 3780 = 15,122.3*

*Total Asphalt Tonnage in August – 7791 tonnes (Provided by Barr)*

*kWh/tonne = 15,122.3 / 7791 =* ***1.94 kWh/tonne***

Power is still required to heat the bitumen tanks and provide security lighting while the plant is not producing. By quantifying both values when in use and not in use the total power consumption can be calculated.

During constant production, different asphalt mixes are produced. The plant is kept at idle power, usually for 15 – 20 minute intervals before the next mix starts production. Another option for the plant operator would be shut the plant down; however, it is not economically viable for this to occur. Greater fuel consumption also occurs due to shut down/start up power. By idling the plant, only minimal power and fuel is required. Through discussion with the Killoch coating plant manager, it is estimated that during continuous production, the plant is idling around 20% of the time. This figure has been applied to calculate the electricity usage required to keep the plant idling and is subtracted from the final electricity value. This occurs as no asphalt is being produced while idling so it cannot be included in the final kWh/tonne asphalt produced figure.

For the independently monitored data, two readings were taken 49 minutes apart. The readings were taken from the coating plant sub meter. Readings and subsequent validation is provided below.

First Reading – 448,014.0 kWh

Second Reading – 448,110.0 kWh

Electricity Usage in 49 Minutes – 96 kWh

Electricity Usage is 60 Minutes = 117.65 kWh

*Coating Plant Production Rate = 70 t/h*

*kWh Consumption to Provide 1 Tonne of Asphalt = 117.65 / 70*

*=* ***1.68 kWh/t***

The electrical value calculated is 13.4% less than the value provided through Barr's data measurements. This variation is due to many factors, some of which would be very difficult to take in to account such as motion detector lighting, space heaters and kitchen appliances (located within the plant control room). A significantly greater in depth look at sub metering within the coating plant over a year would need to be undertaken to quantify and eliminate these values from the 1.94

kWh/tonne value calculated. By taking these factors in to consideration, the final value should decrease slightly; therefore confirming that Barr's measured data is verified by the independent value calculated above.

# 4 Results & Discussion

## 4.1 asPECT

The total embodied carbon content of each mix is shown below in *Table 17*, as calculated by asPECT.

| Mixture Name | Virgin Mix kg CO2e/t | RAP Saving kg CO2e/t | Transport kg CO2e/t | Heating kg CO2e/t | Non Heating kgCO2e/t | Total kgCO2e/t |
|---|---|---|---|---|---|---|
| AC 20 DENSE DBM BIN 40/60 REC | 12.99 | 1.6 | 60.7 | 33.88 | 6.85 | 112.8 |
| AC 32 DENSE DBM BASE XX/YY | 11.87 | 1.2 | 58.49 | 33.88 | 6.85 | 109.9 |
| AC 32 DENSE DBM BIN XX/YY | 13.17 | 1.7 | 62.84 | 33.88 | 6.85 | 115.1 |
| AC 32 DENSE HDM BIN 40/60 DES | 13.97 | 2.0 | 57.15 | 33.88 | 6.85 | 109.8 |
| AC 20 DENSE HBM BIN 40/60 REC | 13.95 | 2.0 | 63.27 | 33.88 | 6.85 | 115.9 |
| AC 14 OPEN SURF XX/YY | 13.36 | 1.8 | 55.73 | 33.88 | 6.85 | 108.1 |
| AC 10 OPEN SURF XX/YY | 14.3 | 2.1 | 58.84 | 33.88 | 6.85 | 111.7 |
| AC 14 CLOSED SURF XX/YY | 14.11 | 2.1 | 62.78 | 33.88 | 6.85 | 115.6 |
| AC 10 CLOSED SURF XX/YY | 14.3 | 2.1 | 63.48 | 33.88 | 6.85 | 116.4 |
| AC 6 DENSE SURF XX/YY | 16.15 | 2.9 | 65.06 | 33.88 | 6.85 | 119.1 |
| AC 6 MED SURF XX/YY | 14.66 | 2.3 | 60.08 | 33.88 | 6.85 | 113.2 |
| 14mm BARTEX/TORPAVE HT THIN SURF | 15.6 | 2.7 | 62.15 | 33.88 | 6.85 | 115.8 |
| 10mm BARTEX/TORPAVE HT THIN SURF | 15.92 | 2.8 | 63.38 | 33.88 | 6.85 | 117.2 |
| 10mm BARTEX/TORPAVE MT THIN SURF | 16.12 | 2.9 | 88.52 | 33.88 | 6.85 | 142.5 |
| AC 14 CLOSE BARPAVE SURF XX/YY | 15.16 | 2.5 | 61.35 | 33.88 | 6.85 | 114.8 |
| AC 10 CLOSE BARPAVE SURF XX/YY | 15.39 | 2.6 | 62.04 | 33.88 | 6.85 | 115.6 |
| AC 6 CLOSE BARPAVE SURF XX/YY | 16.7 | 3.1 | 66.92 | 33.88 | 6.85 | 121.2 |
| HRA 50/10 BASE/BIN/REG 40/60 | 15.98 | 2.8 | 81.95 | 33.88 | 6.85 | 135.8 |
| HRA 15/10 F SURF XX/YY/ REC | 23.25 | 5.7 | 128.76 | 33.88 | 6.85 | 187.0 |
| HRA 30/10 F SURF XX/YY REC | 20.19 | 4.5 | 111.64 | 33.88 | 6.85 | 168.1 |
| HRA 30/14 F SURF 40/60 REC | 20.74 | 4.7 | 112.24 | 33.88 | 6.85 | 169.0 |
| HRA 30/14 F SURF 40/60 DES | 19.78 | 4.3 | 109.3 | 33.88 | 6.85 | 165.5 |
| HRA 35/14 F SURF 40/60 DES | 18.81 | 3.9 | 104.05 | 33.88 | 6.85 | 159.6 |
| HRA 55/10 F SURF 40/60 DES | 16.16 | 2.9 | 83.16 | 33.88 | 6.85 | 137.2 |
| HRA 45/10 F SURF 40/60 PROP DES | 17.26 | 3.3 | 96.47 | 33.88 | 6.85 | 151.1 |

| | | | | | | |
|---|---|---|---|---|---|---|
| HRA 45/14 F SURF 40/60 PROP DES | 17.24 | 3.3 | 96.47 | 33.88 | 6.85 | 151.1 |
| AC 14 EME2 BASE/BIN 15/25 DES | 14.17 | 2.1 | 57.44 | 33.88 | 6.85 | 110.3 |
| 15% 0/6 HRA SURFACE COURSE | 23.25 | 5.7 | 128.76 | 33.88 | 6.85 | 187.0 |
| | | | | | | |
| **Average** | **16.23** | **2.91** | **77.97** | **33.88** | **6.85** | **132.0** |

*Table 17 – Total Embodied Carbon Content for Virgin Mixes*

The embodied carbon content of the mixes differs significantly. A difference of 79 kgCO2e/t occurs between *AC 14 OPEN SURF XX/YY* and *HRA 15/10 F SURF XX/YY/ REC.* This difference is mainly due to *HRA 15/10 F SURF XX/YY/ REC* having high filler and bitumen contents (10.0% and 8.8% respectively). Both of these materials have higher embodied carbon contents. *AC 14 OPEN SURF XX/YY* does not contain any filler and has lower bitumen content, resulting in both lower constituent embodied energy and lower transportation embodied energy. *Table 18* shows the percentage make up and embodied carbon makeup of the two mixes and *Figure 14 & 15* below highlight the breakdown of total embodied carbon for these mixes.

| Constituent Material | Percent | Embodied Carbon Content ($kgCO_2e/t$) |
|---|---|---|
| | ***AC 14 OPEN SURF XX/YY*** | |
| Bitumen | 5 | 190 |
| 10mm Stone | 37.1 | 3.9 |
| 6mm stone | 38.0 | 3.9 |
| Dust | 19.9 | 3.9 |
| | ***HRA 15/10 F SURF XX/YY/ REC*** | |
| Bitumen | 8.8 | 190 |
| 6mm Stone | 15.5 | 3.9 |
| Dust | 13.7 | 3.9 |
| Sand | 52.0 | 3.9 |
| Limestone Filler | 10.0 | 32 |

*Table 18 – Constituent Material Information*

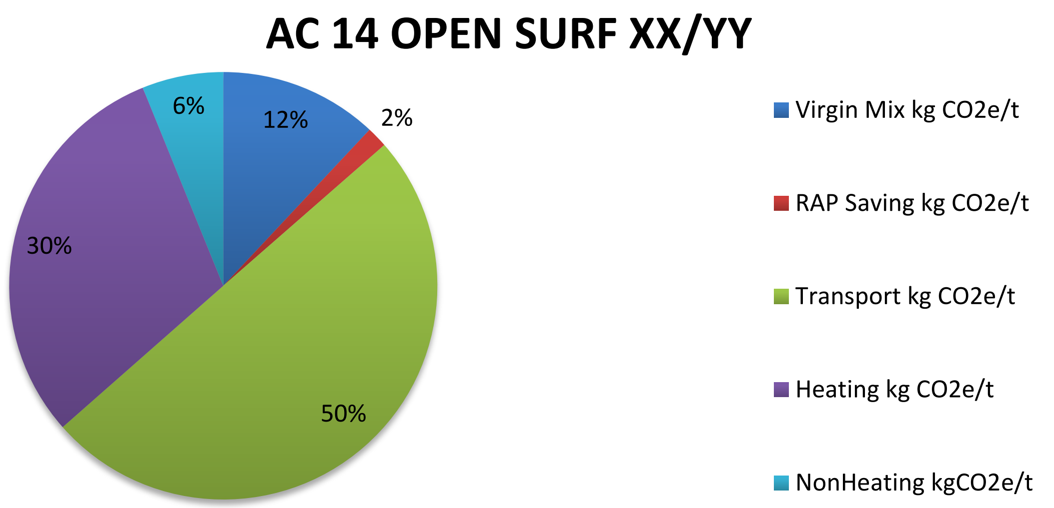



*Figure 14 – Breakdown for Mix AC 14 OPEN SURF XX/YY*

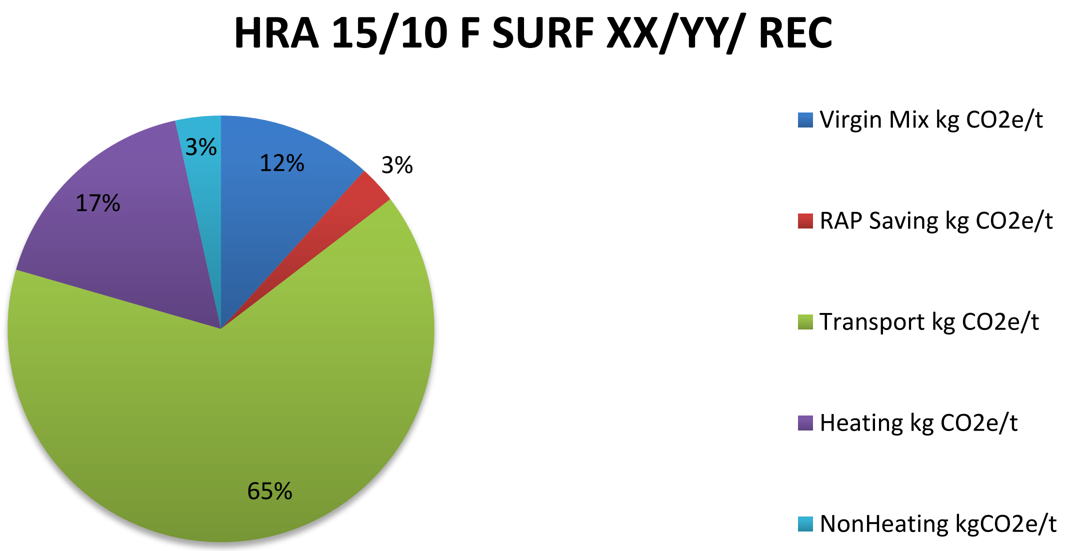



*Figure 15 – Breakdown for Mix Mix HRA 15/10 F SURF XX/YY/ REC*

It can be seen that the transportation contributes significantly to the breakdown of data above. The second mix has a high ration of bitumen and filler (8.8% and 10%), both of which have significantly higher embodied carbon content compared to aggregate. Also, transportation emissions are far greater with these two materials due to their delivery distances. The second mix however does have a lower embodied carbon content from non-heating. This is due to lower amounts of constituent aggregate such as stone and dust, (both of which require greater energy to be processed) (29.2%) when compared to the first mixture (95%).

*Figure 16* below shows a breakdown of the average results for the embodied carbon of the virgin mixes.

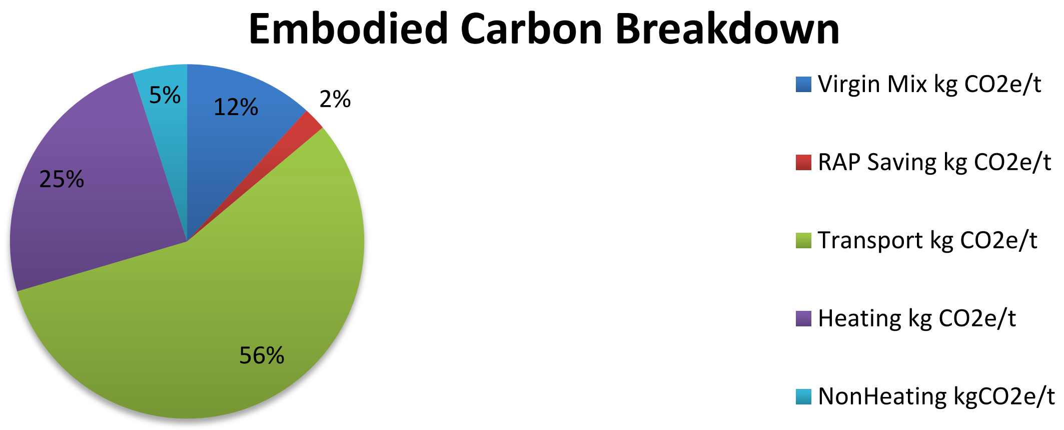



*Figure 16 – Average EC Breakdown for Virgin Results*

Transportation of material accounts for over 50% of the total average embodied carbon of the mixes. One reason why the value for transportation is so high is due to the aggregate production and the asphalt production not being on the same site. Once aggregate has been processed, it needs to be transported from Sorn to Killoch. The lower the embodied carbon a material has (Sorn Aggregate - 3.9 kgCO2e/t) the greater the percentage of carbon associated with transportation. On the contrary, the carbon associated with the transportation of high embodied products such as steel is usually a small percentage of total embodied carbon of that product.

Heating contributes to nearly 1/3 of the total embodied carbon; this is due to the energy intensive process used to manufacture the asphalt. Making energy reductions in heating stage of Hot Mix Asphalt production process is limited; burners are already very efficient in the usage of fuel and are easily controllable. As stated earlier, a certain temperature needs to be maintained for asphalt to be produced, if this temperature is not maintained the degradation in the performance of asphalt can occur. This means large volumes of fuel are required, even with an efficient burner. Factors that also increase fuel usage are ambient temperature, weather and moisture content of the aggregate (although shelters can be erected to keep aggregate dry, this is not always possible due to space restrictions on site and aggregate drying times during busy periods). Analysing these factors to see how they affect fuel usage could prove beneficial; due to time restraints however this will not be undertaken.

To validate the EC content of asphalt calculated in this investigation, it will be compared to other UK results.

As stated earlier, the average EC content of UK aggregate is 4.3 $kgCO_2e/t$. EC content of the case study aggregate was calculated to be 3.9 $kgCO_2e/t$. As it can be seen these figures are very close, with only a 10% difference. *Tarmac* are another large UK producer of asphalt, one study carried out by them quantified the EC content of *their* asphalt mix *AC 6 DENSE SURF 160/220* to be 45.46 $kgCO_2e/t$. This figure is significantly lower than the calculated value for Barr's *AC 6 DENSE SURF XX/YY* of 114.93 $kgCO_2e/t$. *Tarmacs* figure however does not include EC arising from quarrying, site works, aggregate processing and constituent material transportation. By omitting these sources of EC from this total value, the EC content of asphalt decreases to 36.76 $kgCO_2e/t$ of *AC 6 DENSE SURF XX/YY* produced. Thus verifying that the calculation method and data used is accurate and correct giving realistic results.

## *4.2 Sensitivity Analysis*

### *4.21 Transportation Distance*

Transportation contributes significantly to the total embodied carbon of asphalt. By varying the delivery distances of the constituent materials, it can be seen to what affect different distances have on the final EC of the product. *Table 19* below shows the results of all 6 sensitivity studies. Results for the individual asphalt mixes can be found in *Appendix A, Table A.2, A.3, A.4, A.5, A.6* & *A.7.*

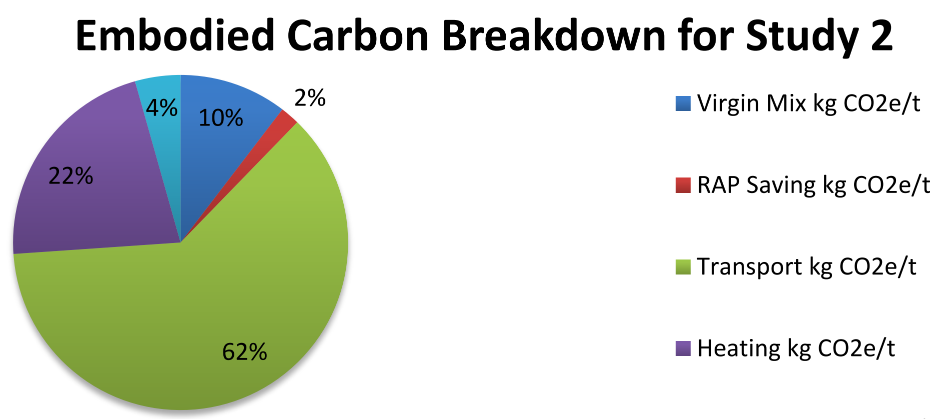
| | Constituent Materials Investigated | Original Outbound Distance (km) | New Outbound Distance (km) | Average Transport Embodied Carbon ($kgCO_2e/t$) | Total Average Embodied Carbon ($kgCO_2e/t$) | Percentage Change From Original Total EC Value |
|---|---|---|---|---|---|---|
| Original | - | 10 | - | 77.97 | 132.00 | 0% |
| Study 1 | Aggregate, Dust | 10 | 0 | 57.24 | 113.70 | -14% |
| Study 2 | Aggregate, Dust | 10 | 20 | 94.78 | 150.30 | +14% |
| Study 3 | Bitumen | 288 | 100 | 50.77 | 106.50 | -19% |
| Study 4 | Bitumen | 288 | 500 | 98.39 | 154.10 | +17% |

| | | | | | | |
|---|---|---|---|---|---|---|
| Study 5 | Aggregate, Dust, Bitumen | 10 / 288 | 0 /100 | 32.00 | 88.20 | -33% |
| Study 6 | Aggregate, Dust Bitumen | 10 / 288 | 20 /500 | 123.78 | 179.10 | +36% |

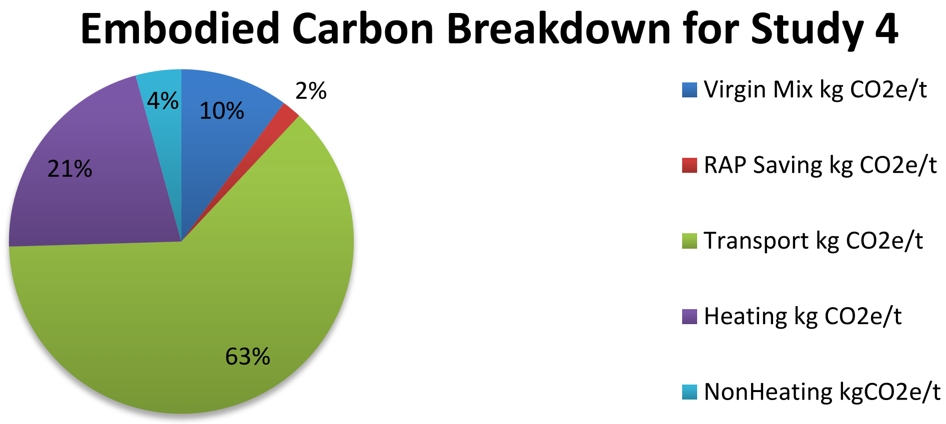
*Table 19 – Transportation Distance Results*

The above results show the significant change in total embodied carbon when transportation distance is varied. In *Study 1*, a 14% decrease occurs resulting in a substantially lower average embodied carbon of all the mixes. By having quarrying, aggregate processing and asphalt production all on one site will lower the embodied carbon of asphalt. *Study 2* shows the opposite results when compared to *Study 1* which is as expected, with the average total embodied carbon of asphalt increasing by 14%. *Study 3*, *4, 5* and *6* show the same pattern, an increase in transportation distance equates to an increase in total average embodied carbon and vice versa.

Although *Study 2* and *Study 4* have similar reductions in total average EC content, *Study 4* has a transportation distance 25 times greater than *Study 2*. This is due both to much more aggregate being transported when compared to bitumen and also the aggregate having a lower embodied carbon content, resulting in transportation gaining a heavier weighting in *Study* 2. This is highlighted in Figures *17 & 18* below.




*Figures 17 – Breakdown of Study 2*




*Figures 18 – Breakdown of Study 4*

*Figure 19* summarises the findings of the transportation sensitivity analysis.

*Study 5* and *Study 6* combine the two materials minimum delivery distances together and their maximum delivery distances together to create a best case and worst case scenario. The purpose of these two studies is to highlight to the reader the difference transportation can make to the EC content of any product, not just asphalt. A difference of 52% is achieved between the two values; annually, this could the potential to save this 4,919 tonnes of embodied carbon from asphalt production a year.

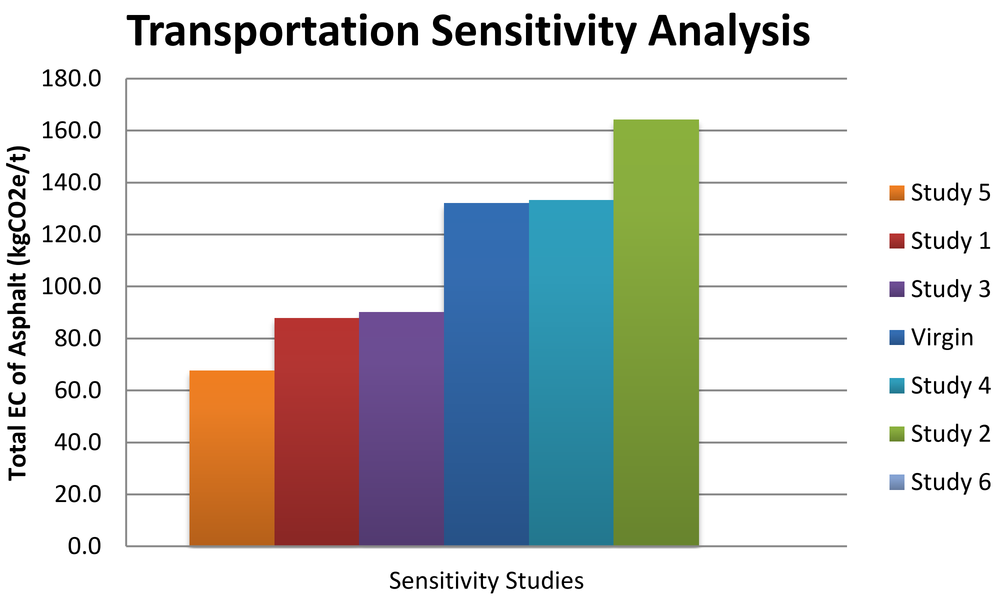



*Figure 19 – Summary of Transportation Study*

By having quarrying, aggregate production and asphalt production on the same site, transportation of materials between sites can be eliminated. For example, by moving Killoch operations to Sorn, and sourcing bitumen from a closer location, an average reduction in total EC content of 36% could be achieved.

## *4.22 Bitumen EC Content*

As expected, the total EC content of asphalt increases as the EC value for bitumen increases. *Table 20* below shows the findings to the study. Results for the individual asphalt mixes can be found in *Appendix A, Table A.8* & *Table A.9.*

| **Sensitivity Study** | **EC Content of Bitumen ($kgCO_2e/t$)** | **EC Content of Asphalt ($kgCO_2e/t$)** | **Percentage Change From Original Value** |
|---|---|---|---|
| Original | 190 | 132.00 | - |
| 1 | 430 | 142.92 | 8.3% |
| 2 | 490 | 146.55 | 14.5% |
| 3 | 590 | 150.16 | 14.8% |

*Table 20 – EC Content of Bitumen Results*

These results highlight that the EC content of the final product relies heavily on where the data for the constituent materials originates from. In this case, a 14.8% difference occurs in the final EC content value of asphalt. As stated earlier, the second source of data comes from the Inventory of Carbon and Energy, published by the University of Bath. In this publication they could only advise on a range of values from 430 $kgCO_2e/t$ to 590 $kgCO_2e/t$. asPECT's value was set at 190 $kgCO_2e/t$. It is still unsure why there is such a variation in values, however, when this does occur a study like the one shown above should be undertaken. Once results have been confirmed, the user can decide on which value to proceed with. A 14.8% variation in results could be carried through to the final EC content; this practice however is uncommon, with the majority of studies just using one value. Still, by quantifying the uncertainty that comes with a constitute material provides clarity and transparency to both the user and the reader. *Figure 20* below summarises the finding of this study.

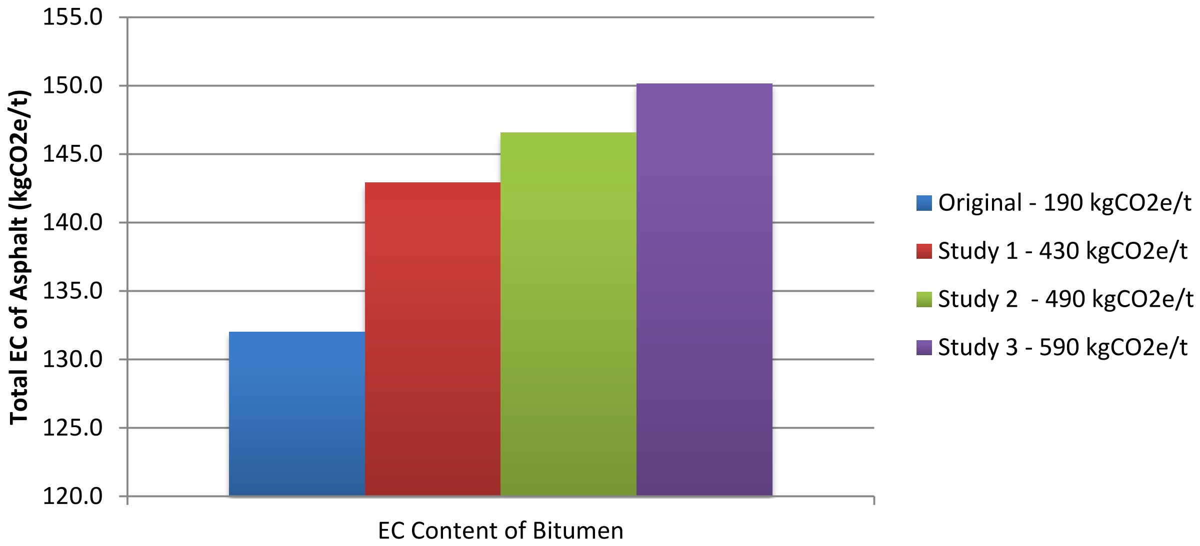



*Figure 20 – Summary of EC Content of Bitumen Study*

## *4.23 RAP Content*

The RAP sensitivity studies focussed on the use of up to 30% RAP, initially with 14mm and 20mm stone, then with 6mm, 10mm, 14mm and 20mm stone. When Barr start using RAP in the future, they plan on using only 14mm and 20mm stone, however by undertaking the second study it can be seen what affect it has on the total EC content of asphalt. During the first analysis, it was not possible to use 30% RAP in every mix, this figure was dependant on the amount of 14mm and 20mm constitute material in each mix. As the second study also included the use of smaller stone, the 30% limit could be achieved the majority of the time, increasing RAP quantity and hence decreasing the EC content of asphalt. *Table 21* below summarises the findings obtained. Results for the individual mixes can be found in *Appendix A, Table A.11* & *A.12*.

| **Study** | **RAP Replacement Stone Sizes Used** | **RAP %** | **RAP Savings Achieved ($kgCO_2e/t$)** | **EC Content of Asphalt ($kgCO_2e/t$)** | **Percentage Change From Original Value** |
|---|---|---|---|---|---|
| Original | - | - | 2.91 | 132.00 | 0 |
| 1 | 14mm, 20mm | Up to 30% | 7.55 | 124.68 | -5.5% |
| 2 | 6mm, 10mm, 14mm, 20mm | Up to 30% | 15.87 | 113.34 | -14.0% |

*Table 21 - RAP EC Content Results*

It can be seen from these results that by the addition of RAP material to virgin asphalt mix the EC content of asphalt decreases by up to 14%. As described above, both studies have a RAP content of up to 30%. However, not all asphalt mixes are capable of achieving the desired 30% content. Virgin asphalt still achieves a RAP saving due to its future recycling properties. Mix 1 *AC 20 DENSE DBM BIN 40/60 REC* constitute material make up for both studies is shown below in *Table 22*.

| **Constitute Material** | **Percentage Make up** | | |
|---|---|---|---|
| | **Virgin** | **Study 1** | **Study 2** |
| RAP | - | 21.9 | 30.0 |
| 14mm | 21.9 | - | - |
| 10mm | 11.4 | 11.4 | 3.3 |
| 6mm | 21 | 21.9 | 22.3 |
| Dust | 33.3 | 33.3 | 33.3 |
| Sand | 7.6 | 7.6 | 7.6 |
| Bitumen | 4.8 | 3.9 | 3.5 |

*Table 22 – Asphalt Constitute Make Up for Each Study*

From the above table it can be seen how the constituent material vary depending on the RAP content used. Study 2 has the maximum 30% RAP content, while Study 1 only has 21.9% RAP content due to only 14mm and 20mm stone being used. Once smaller sizes of stones are used, the RAP content increases and the EC content of asphalt decreases as expected. 6mm stone use increases due to the fact that a left over percentage is needed to be allocated. This left over percentage arises from the smaller bitumen content. As RAP contains bitumen, less virgin bitumen is needed. This means that a material is needed to replace the difference such as 6mm stone. As only a small amount is being substituted, the characteristics of the final product are unaffected.

As described earlier, the amount of fuel used to produce asphalt with RAP is greater when compared to the amount used to produce virgin asphalt. Unfortunately the data needed to quantify this increased fuel usage was unobtainable. *Figures 21, 22 & 23* below show the breakdown of EC of asphalt of *AC 20 DENSE DBM BIN 40/60 REC* for both studies.

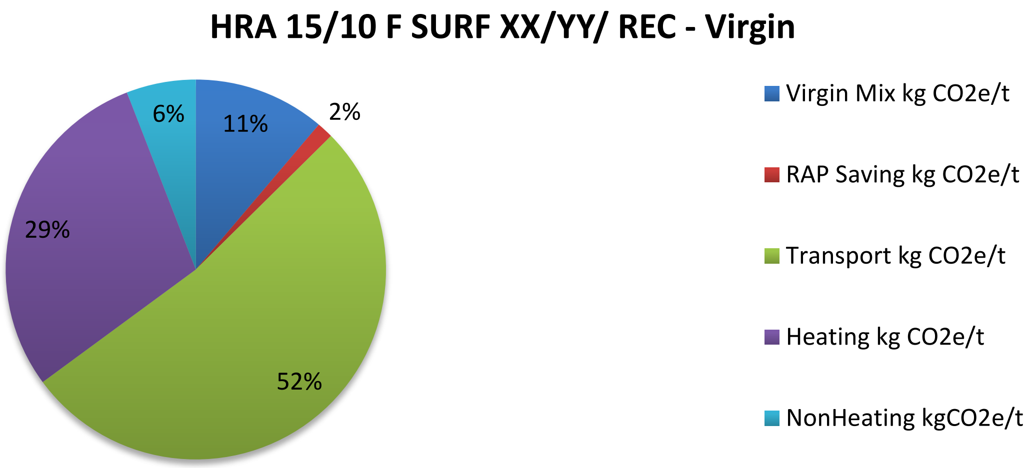



*Figure 21 – Breakdown of EC Content for Virgin AC 20 DENSE DBM BIN 40/60 REC (Mix 1)*

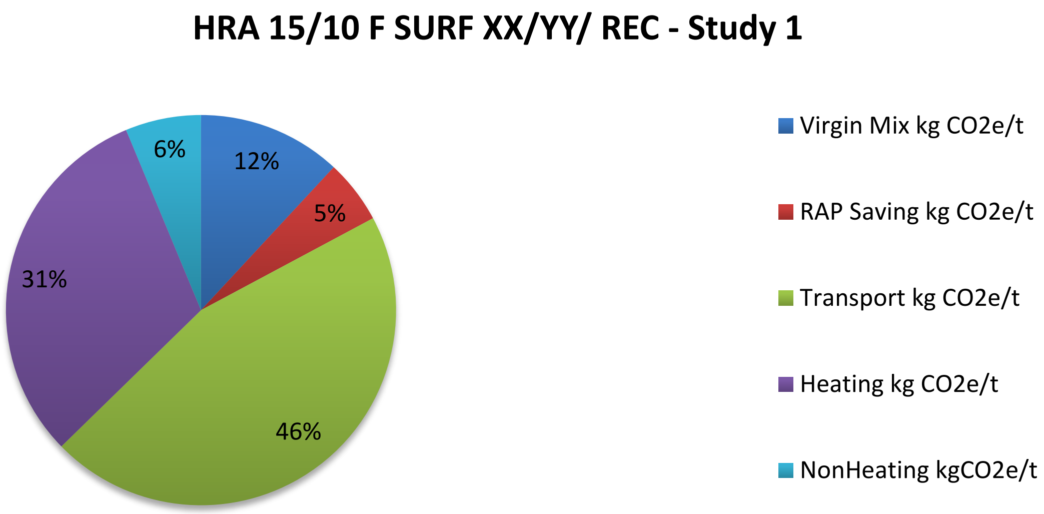



*Figure 22 – Breakdown of EC Content for Study 1 AC 20 DENSE DBM BIN 40/60 REC (Mix 1)*

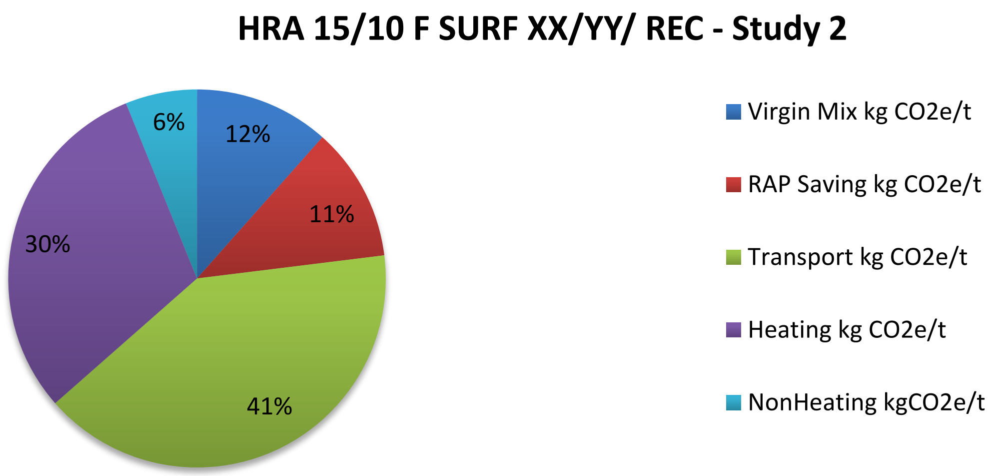



*Figure 23 – Breakdown of EC Content for Study 1 AC 20 DENSE DBM BIN 40/60 REC (Mix 1)*

These figures show that as EC saved from the use of RAP increases, EC associated with transportation decreases. This can be attributed to the fact that less virgin aggregate and virgin bitumen is delivered to site, thus reducing transportation. By using asphalt with RAP content, both material and transportation EC content savings can be achieved. *Study 1* achieves a transportation saving of 6%, while *Study 2* achieves a transportation saving of 11%. This saving is equivalent to a reduction of 84 and 116 truckloads a year respectively of aggregate transportation between Sorn and Killoch. Although RAP is also transported to site, the boundaries associated with this investigation means that it is not included. RAP values of greater than 50% can be achieved in today's asphalt manufacturing process, producing an even greater EC saving. However Barr have no intention of using RAP values above 30% due to both economic reasons and the ability to acquire larger quantities of RAP (30% +). For these reasons it has been decided that that increasing quantity of RAP above 30% will not be further investigated.

# 5 Conclusion

The aim of this study was to quantify the EC content of asphalt using case study data and understand the affect RAP had on this value, both of which have been achieved. Currently, little is known about the EC associated with asphalt, mainly due to a lack of legal and environmental drivers associated with the asphalt industry which has been described in the literature review.

asPECT was used to calculate the associated EC values of each asphalt mix. The makes use of many different data streams including blasting material used, overburden removal, constituent transportation etc. to undertake an in depth analysis. This method provides far greater accuracy in the calculated results. Many other free EC software programmes do not require nearly as much input data, over simplifying the calculation process which in turn only produces rough results. asPECT does has limitation, including the inability to vary the moisture content of input aggregate and RAP. This is essential as it is directly related to fuel consumption, resulting in a different EC content value produced. By being able to input different moisture content values would result in a greater accuracy and realism of results. Also, asPECT does not allow the user to vary the EC content of bitumen, as it is set at 190 $kgCO_2e/t$. This figure lacks transparency resulting in the user being unsure in the pre-set value. Although bitumen content can be changed, it requires the creation of a new material profile which is time consuming. Letting the user vary the bitumen content would give the software and user far greater flexibility and ease of use. During the investigation, a possible bug was discovered in asPECT resulting in the RAP calculations being incorrect. An Excel spread sheet had to be created in order to calculate the EC savings associated with the use of RAP. This was time consuming and gave the user doubts in software's ability to provide an accurate answer.

Monitored data provided by the case study varied. Certain streams had daily monitored data such as fuel consumption of site vehicles, while other data streams were taken from advice given by experienced site managers such as coating plant idling times and asphalt production rates. A greater amount of monitored data from the coating plant including sub metering for the electric bitumen heaters, control room, security lighting would be useful. Although the data used in this investigation is sufficient, a greater understanding of energy usage could occur with certain sub meters in place; this would also make data validation easier by allowing elimination of non-coating plant electrical consumption. Greater amounts of monitored data on the fuel usage of the coating plant would also have been beneficial including hourly ambient temperatures during production cross referenced with the mix being produced at that time and its moisture content. This would help provide more accurate fuel consumption rates depending on the time of year asphalt is produced. Currently, asPECT only requires yearly data which is sufficient enough to calculate a yearly average EC content for asphalt. A monthly EC content however would provide a greater insight in to fuel usage depending on season/ time of year, giving greater accuracy to calculations resulting in monthly EC content values. For a LCA, it is extremely important to have access to and use as much measured data as possible, reducing the possibility of estimation errors and creating a more substantial solid methodology on which to conduct the investigation. In reality this is not always possible due to both economic and logistical factors.

From the results obtained though the investigation, it can be seen that the embodied carbon content of asphalt can vary significantly and is dependent on a number of factors including the EC content of its constituent materials, the transportation involved in delivering these constituent materials to site and the quantity of RAP used in the asphalt mix. Surprisingly, EC arising from transportation of constituent materials significantly affects the final value. *Figure 24* summarises all the findings of this investigation from the case study data.

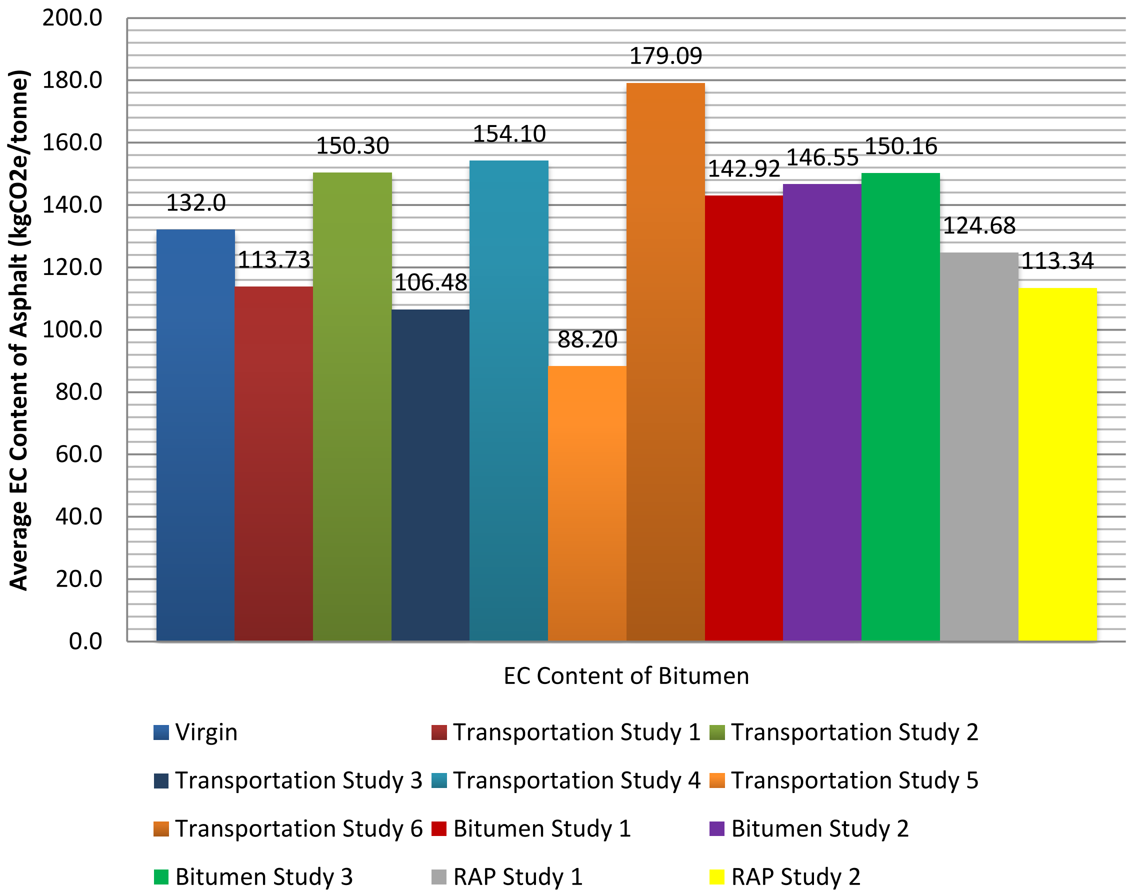



*Figure 24 – Summary of all studies undertaken.*

By eliminating the need to transport the aggregate from quarry to asphalt production plant (Transportation Study 1, Sorn to Killoch – 10km) reduces the average EC of asphalt by 14%. By minimising the delivery distance of bitumen the average EC content decreases even further resulting in a 19% reduction (Transportation Study 3 – 100km). Increasing transportation distances has an adverse effect on the average EC content. The EC content of asphalt can increase by up to 11% depending on what EC content value for bitumen is used (Bitumen Study 3 – 150.2 kg$CO_2$e/t).

The use of RAP does decrease the EC content of asphalt, however not significantly. Only a 5.5% reduction occurs when Barr's proposed RAP usage is implemented (RAP Study 1) which is 30% RAP rate using 14mm and 20mm stone. By including 6mm and 10mm stone at the same 30% RAP rate a 14% reduction occurs (RAP Study 2 in average EC content when compared to the virgin asphalt mixes currently being produced on the Killoch site. Using RAP in asphalt production not only saves EC but also reduces virgin material use helping to conserve resources, which is always an important ecological matter that is only gaining more prominence year on year. When both RAP usage and minimised case study transportation were combined, a 36% saving in EC content of asphalt occurred.

Although the results obtained are from the case study, general observations can still be made which are not case study specific. Minimising constituent material transportation including aggregates and bitumen will significantly reduce EC content of asphalt; this is due to both these materials having relatively low embodied carbon content, meaning that transportation is carbon intensive. Although EC associated with the coating plant will be site specific, in all cases it very likely to be the largest contributor to the final EC content of asphalt. As explained above, coating plants are currently very efficient, any reduction in energy use in a coating plant would be difficult and not make a major difference. With this in mind, the easiest and most effective way to reduce the EC content of asphalt is to minimise transportation and maximise the use of RAP.

Over a year, Barr could save 391 t$CO_2$e when using RAP 1 sensitivity study. 2,457 t$CO_2$e could be saved annually if Barr minimised their material transportation and maximised their RAP usage. When the April 2010 – March 2013 purchasing price of £12/tonne is applied to both savings, £4692 and £29,484 could be made saved respectively. These savings would result in less carbon credits needing to be purchased and improved performance on the CRC league tables. Both economic and environmental performance would be increased, saving money, promoting business and ultimately help in aiding the reduction of the company's carbon footprint.

## *Future Work*

There are many possible lines of future work to follow regarding this study. A more in depth look at the energy intensive asphalt production process would be beneficial. By quantifying the increase in fuel consumption associated with the application of RAP would provide the reader with an understanding of the negative effects of its use. Also by investigation of how factors including ambient temperature and moisture content of both virgin aggregate and RAP will affect fuel consumption in the burner would be also be highly beneficial. A tool could be created to predict fuel consumption; $CO_2$ output and EC content when the relevant factor is applied (e.g. RAP content, moisture content and ambient temperature). This would help give even greater accuracy in predicting fuel consumption, helping not to save only fuel and money but also reduce carbon emissions even further for the respective company.

Other possible lines of work could include extending this study and calculating the EC content of asphalt from cradle to grave. By understanding the EC involved in the transportation of asphalt, the laying of asphalt on the road, repairs throughout its lifetime, its eventual uptake off the roads and its transportation from site to asphalt plant to be processed into RAP, thus creating a full EC cycle for asphalt. The *Projects* section of asPECT could be utilised for this investigation.

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## *Appendix A*

| | Fuel Usage (Litres) | | | | |
|---|---|---|---|---|---|
| | Monday | Tuesday | Wednesday | Thursday | Friday |
| **04-Jan** | | | | | |
| **11-Jan** | 87 | 67 | 71 | | 7 |
| **18-Jan** | 59 | 51 | 60 | 80 | |
| **25-Jan** | 68 | 71 | | 97 | |
| **01-Feb** | 90 | 77 | | | |
| **08-Feb** | | | | | |
| **15-Feb** | | | | | |
| **22-Feb** | | | | | |
| **01-Mar** | | | | | |
| **08-Mar** | | | | | |
| **15-Mar** | | | | 136 | |
| **22-Mar** | | | | | 89 |
| **29-Mar** | 125 | 120 | | | |
| **05-Apr** | | 117 | | 160 | |
| **12-Apr** | 78 | | 161 | 98 | 105 |
| **19-Apr** | 83 | 92 | 45 | 105 | 98 |
| **26-Apr** | 100 | 56 | | | 100 |
| **03-May** | | 91 | 59 | 104 | |
| **10-May** | | 105 | | 192 | 62 |
| **17-May** | 84 | | | 110 | 105 |
| **24-May** | 84 | 98 | 82 | 107 | 112 |
| **31-May** | 101 | 118 | 112 | 110 | 127 |
| **07-Jun** | 92 | 123 | | 174 | 81 |
| **14-Jun** | 90 | | 63 | 100 | |
| Average | **95.42** | | | | |

*Table A.1 – Findlay 394 Daily Fuel Consumption at Sorn Stone Productions*

Fuel usage was zero certain days as the screener was not operational on these days. Screening only occurs when aggregate is needing to be processed.

| Mixture Name | Virgin Mix kg CO2e/t | RAP Saving kg CO2e/t | Transport kg CO2e/t | Heating kg CO2e/t | Non Heating kgCO2e/t | Total kgCO2e/t |
|---|---|---|---|---|---|---|
| **AC 20 DENSE DBM BIN 40/60 REC** | 12.99 | 1.6 | 39.13 | 33.88 | 6.85 | 91.2 |
| **AC 32 DENSE DBM BASE XX/YY** | 11.87 | 1.2 | 37.23 | 33.88 | 6.85 | 88.7 |
| **AC 32 DENSE DBM BIN XX/YY** | 13.17 | 1.7 | 41.76 | 33.88 | 6.85 | 94.0 |
| **AC 32 DENSE HDM BIN 40/60 DES** | 13.97 | 2.0 | 34.44 | 33.88 | 6.85 | 87.1 |
| **AC 20 DENSE HBM BIN 40/60 REC** | 13.95 | 2.0 | 42.41 | 33.88 | 6.85 | 95.1 |
| **AC 14 OPEN SURF XX/YY** | 13.36 | 1.8 | 32.33 | 33.88 | 6.85 | 84.7 |
| **AC 10 OPEN SURF XX/YY** | 14.3 | 2.1 | 35.56 | 33.88 | 6.85 | 88.4 |
| **AC 14 CLOSED SURF XX/YY** | 14.11 | 2.1 | 40.86 | 33.88 | 6.85 | 93.6 |
| **AC 10 CLOSED SURF XX/YY** | 14.3 | 2.1 | 41.61 | 33.88 | 6.85 | 94.5 |
| **AC 6 DENSE SURF XX/YY** | 16.15 | 2.9 | 42.03 | 33.88 | 6.85 | 96.0 |
| **AC 6 MED SURF XX/YY** | 14.66 | 2.3 | 36.86 | 33.88 | 6.85 | 90.0 |
| **14mm BARTEX/TORPAVE HT THIN SURF** | 15.6 | 2.7 | 40.03 | 33.88 | 6.85 | 93.7 |
| **10mm BARTEX/TORPAVE HT THIN SURF** | 15.92 | 2.8 | 41.11 | 33.88 | 6.85 | 95.0 |
| **10mm BARTEX/TORPAVE MT THIN SURF** | 16.12 | 2.9 | 73.69 | 33.88 | 6.85 | 127.7 |
| **AC 14 CLOSE BARPAVE SURF XX/YY** | 15.16 | 2.5 | 38.57 | 33.88 | 6.85 | 92.0 |
| **AC 10 CLOSE BARPAVE SURF XX/YY** | 15.39 | 2.6 | 39.31 | 33.88 | 6.85 | 92.9 |
| **AC 6 CLOSE BARPAVE SURF XX/YY** | 16.7 | 3.1 | 43.97 | 33.88 | 6.85 | 98.3 |
| **HRA 50/10 BASE/BIN/REG 40/60** | 15.98 | 2.8 | 64.19 | 33.88 | 6.85 | 118.1 |
| **HRA 15/10 F SURF XX/YY/ REC** | 23.25 | 5.7 | 121.56 | 33.88 | 6.85 | 179.8 |
| **HRA 30/10 F SURF XX/YY REC** | 20.19 | 4.5 | 100.95 | 33.88 | 6.85 | 157.4 |
| **HRA 30/14 F SURF 40/60 REC** | 20.74 | 4.7 | 101.79 | 33.88 | 6.85 | 158.5 |
| **HRA 30/14 F SURF 40/60 DES** | 19.78 | 4.3 | 98.78 | 33.88 | 6.85 | 155.0 |
| **HRA 35/14 F SURF 40/60 DES** | 18.81 | 3.9 | 92.57 | 33.88 | 6.85 | 148.2 |
| **HRA 55/10 F SURF 40/60 DES** | 16.16 | 2.9 | 66.91 | 33.88 | 6.85 | 120.9 |
| **HRA 45/10 F SURF 40/60 PROP DES** | 17.26 | 3.3 | 83.44 | 33.88 | 6.85 | 138.1 |
| **HRA 45/14 F SURF 40/60 PROP DES** | 17.24 | 3.3 | 83.44 | 33.88 | 6.85 | 138.1 |
| **AC 14 EME2 BASE/BIN 15/25 DES** | 14.17 | 2.1 | 35.03 | 33.88 | 6.85 | 87.8 |
| **15% 0/6 HRA SURFACE COURSE** | 23.25 | 5.7 | 121.56 | 33.88 | 6.85 | 179.8 |
| | | | | | | |
| **AVERAGE** | 16.23 | 2.91 | 59.68 | 33.88 | 6.85 | 113.7 |

*Table A.2 – Transport Study 1*

| Mixture Name | Virgin Mix kg CO2e/t | RAP Saving kg CO2e/t | Transport kg CO2e/t | Heating kg CO2e/t | Non Heating kgCO2e/t | Total kgCO2e/t |
|---|---|---|---|---|---|---|
| **AC 20 DENSE DBM BIN 40/60 REC** | 12.99 | 1.6 | 82.27 | 33.88 | 6.85 | 134.4 |
| **AC 32 DENSE DBM BASE XX/YY** | 11.87 | 1.2 | 79.75 | 33.88 | 6.85 | 131.2 |
| **AC 32 DENSE DBM BIN XX/YY** | 13.17 | 1.7 | 83.93 | 33.88 | 6.85 | 136.1 |
| **AC 32 DENSE HDM BIN 40/60 DES** | 13.97 | 2.0 | 79.86 | 33.88 | 6.85 | 132.6 |
| **AC 20 DENSE HBM BIN 40/60 REC** | 13.95 | 2.0 | 84.13 | 33.88 | 6.85 | 136.8 |
| **AC 14 OPEN SURF XX/YY** | 13.36 | 1.8 | 79.13 | 33.88 | 6.85 | 131.5 |
| **AC 10 OPEN SURF XX/YY** | 14.3 | 2.1 | 82.11 | 33.88 | 6.85 | 135.0 |
| **AC 14 CLOSED SURF XX/YY** | 14.11 | 2.1 | 84.7 | 33.88 | 6.85 | 137.5 |
| **AC 10 CLOSED SURF XX/YY** | 14.3 | 2.1 | 85.35 | 33.88 | 6.85 | 138.2 |
| **AC 6 DENSE SURF XX/YY** | 16.15 | 2.9 | 88.09 | 33.88 | 6.85 | 142.1 |
| **AC 6 MED SURF XX/YY** | 14.66 | 2.3 | 83.31 | 33.88 | 6.85 | 136.4 |
| **14mm BARTEX/TORPAVE HT THIN SURF** | 15.6 | 2.7 | 84.26 | 33.88 | 6.85 | 137.9 |
| **10mm BARTEX/TORPAVE HT THIN SURF** | 15.92 | 2.8 | 85.64 | 33.88 | 6.85 | 139.5 |
| **10mm BARTEX/TORPAVE MT THIN SURF** | 16.12 | 2.9 | 103.34 | 33.88 | 6.85 | 157.3 |
| **AC 14 CLOSE BARPAVE SURF XX/YY** | 15.16 | 2.5 | 84.13 | 33.88 | 6.85 | 137.5 |
| **AC 10 CLOSE BARPAVE SURF XX/YY** | 15.39 | 2.6 | 84.78 | 33.88 | 6.85 | 138.3 |
| **AC 6 CLOSE BARPAVE SURF XX/YY** | 16.7 | 3.1 | 89.88 | 33.88 | 6.85 | 144.2 |
| **HRA 50/10 BASE/BIN/REG 40/60** | 15.98 | 2.8 | 99.71 | 33.88 | 6.85 | 153.6 |
| **HRA 15/10 F SURF XX/YY/ REC** | 23.25 | 5.7 | 135.95 | 33.88 | 6.85 | 194.2 |
| **HRA 30/10 F SURF XX/YY REC** | 20.19 | 4.5 | 122.33 | 33.88 | 6.85 | 178.8 |
| **HRA 30/14 F SURF 40/60 REC** | 20.74 | 4.7 | 122.68 | 33.88 | 6.85 | 179.4 |
| **HRA 30/14 F SURF 40/60 DES** | 19.78 | 4.3 | 119.82 | 33.88 | 6.85 | 176.0 |
| **HRA 35/14 F SURF 40/60 DES** | 18.81 | 3.9 | 115.53 | 33.88 | 6.85 | 171.1 |
| **HRA 55/10 F SURF 40/60 DES** | 16.16 | 2.9 | 99.42 | 33.88 | 6.85 | 153.4 |
| **HRA 45/10 F SURF 40/60 PROP DES** | 17.26 | 3.3 | 109.5 | 33.88 | 6.85 | 164.2 |
| **HRA 45/14 F SURF 40/60 PROP DES** | 17.24 | 3.3 | 109.5 | 33.88 | 6.85 | 164.2 |
| **AC 14 EME2 BASE/BIN 15/25 DES** | 14.17 | 2.1 | 79.85 | 33.88 | 6.85 | 132.7 |
| **15% 0/6 HRA SURFACE COURSE** | 23.25 | 5.7 | 135.95 | 33.88 | 6.85 | 194.2 |
| | | | | | | |
| **AVERAGE** | 16.23 | 2.91 | 96.25 | 33.88 | 6.85 | 150.3 |

*Table A.3 – Transport Study 2*

| Mixture Name | Virgin Mix kg CO2e/t | RAP Saving kg CO2e/t | Transport kg CO2e/t | Heating kg CO2e/t | Non Heating kgCO2e/t | Total kgCO2e/t |
|---|---|---|---|---|---|---|
| **AC 20 DENSE DBM BIN 40/60 REC** | 13.0 | 1.6 | 40.4 | 33.9 | 6.9 | 92.5 |
| **AC 32 DENSE DBM BASE XX/YY** | 11.9 | 1.2 | 40.8 | 33.9 | 6.9 | 92.2 |
| **AC 32 DENSE DBM BIN XX/YY** | 13.2 | 1.7 | 42.2 | 33.9 | 6.9 | 94.4 |
| **AC 32 DENSE HDM BIN 40/60 DES** | 14.0 | 2.0 | 36.5 | 33.9 | 6.9 | 89.2 |
| **AC 20 DENSE HBM BIN 40/60 REC** | 14.0 | 2.0 | 42.6 | 33.9 | 6.9 | 95.3 |
| **AC 14 OPEN SURF XX/YY** | 13.4 | 1.8 | 34.6 | 33.9 | 6.9 | 86.9 |
| **AC 10 OPEN SURF XX/YY** | 14.3 | 2.1 | 35.6 | 33.9 | 6.9 | 88.5 |
| **AC 14 CLOSED SURF XX/YY** | 14.1 | 2.1 | 40.0 | 33.9 | 6.9 | 92.8 |
| **AC 10 CLOSED SURF XX/YY** | 14.3 | 2.1 | 40.3 | 33.9 | 6.9 | 93.2 |
| **AC 6 DENSE SURF XX/YY** | 16.2 | 2.9 | 37.6 | 33.9 | 6.9 | 91.6 |
| **AC 6 MED SURF XX/YY** | 14.7 | 2.3 | 36.0 | 33.9 | 6.9 | 89.1 |
| **14mm BARTEX/TORPAVE HT THIN SURF** | 15.6 | 2.7 | 38.9 | 33.9 | 6.9 | 92.6 |
| **10mm BARTEX/TORPAVE HT THIN SURF** | 15.9 | 2.8 | 38.9 | 33.9 | 6.9 | 92.8 |
| **10mm bARTEX/TORPAVE MT THIN SURF** | 16.1 | 2.9 | 63.6 | 33.9 | 6.9 | 117.6 |
| **AC 14 CLOSE BARPAVE SURF XX/YY** | 15.2 | 2.5 | 37.3 | 33.9 | 6.9 | 90.7 |
| **AC 10 CLOSE BARPAVE SURF XX/YY** | 15.4 | 2.6 | 37.6 | 33.9 | 6.9 | 91.1 |
| **AC 6 CLOSE BARPAVE SURF XX/YY** | 16.7 | 3.1 | 38.2 | 33.9 | 6.9 | 92.5 |
| **HRA 50/10 BASE/BIN/REG 40/60** | 16.0 | 2.8 | 54.9 | 33.9 | 6.9 | 108.8 |
| **HRA 15/10 F SURF XX/YY/ REC** | 23.3 | 5.7 | 91.6 | 33.9 | 6.9 | 149.9 |
| **HRA 30/10 F SURF XX/YY REC** | 20.2 | 4.5 | 79.1 | 33.9 | 6.9 | 135.6 |
| **HRA 30/14 F SURF 40/60 REC** | 20.7 | 4.7 | 79.7 | 33.9 | 6.9 | 136.5 |
| **HRA 30/14 F SURF 40/60 DES** | 19.8 | 4.3 | 78.9 | 33.9 | 6.9 | 135.1 |
| **HRA 35/14 F SURF 40/60 DES** | 18.8 | 3.9 | 75.4 | 33.9 | 6.9 | 130.9 |
| **HRA 55/10 F SURF 40/60 DES** | 16.2 | 2.9 | 58.7 | 33.9 | 6.9 | 112.7 |
| **HRA 45/10 F SURF 40/60 PROP DES** | 17.3 | 3.3 | 69.9 | 33.9 | 6.9 | 124.5 |
| **HRA 45/14 F SURF 40/60 PROP DES** | 17.2 | 3.3 | 69.9 | 33.9 | 6.9 | 124.5 |
| **AC 14 EME2 BASE/BIN 15/25 DES** | 14.2 | 2.1 | 37.2 | 33.9 | 6.9 | 90.0 |
| **15% 0/6 HRA SURFACE COURSE** | 23.3 | 5.7 | 91.6 | 33.9 | 6.9 | 149.9 |
| | | | | | | |
| **AVERAGE** | 16.2 | 2.9 | 52.4 | 33.9 | 6.9 | 106.5 |

*Table A.4 – Transport Study 3*

| Mixture Name | Virgin Mix kg CO2e/t | RAP Saving kg CO2e/t | Transport kg CO2e/t | Heating kg CO2e/t | Non Heating kgCO2e/t | Total kgCO2e/t |
|---|---|---|---|---|---|---|
| **AC 20 DENSE DBM BIN 40/60 REC** | 13.0 | 1.6 | 80.4 | 33.9 | 6.9 | 132.5 |
| **AC 32 DENSE DBM BASE XX/YY** | 11.9 | 1.2 | 74.6 | 33.9 | 6.9 | 126.0 |
| **AC 32 DENSE DBM BIN XX/YY** | 13.2 | 1.7 | 82.3 | 33.9 | 6.9 | 134.5 |
| **AC 32 DENSE HDM BIN 40/60 DES** | 14.0 | 2.0 | 80.5 | 33.9 | 6.9 | 133.2 |
| **AC 20 DENSE HBM BIN 40/60 REC** | 14.0 | 2.0 | 83.5 | 33.9 | 6.9 | 136.2 |
| **AC 14 OPEN SURF XX/YY** | 13.4 | 1.8 | 79.5 | 33.9 | 6.9 | 131.9 |
| **AC 10 OPEN SURF XX/YY** | 14.3 | 2.1 | 85.0 | 33.9 | 6.9 | 137.9 |
| **AC 14 CLOSED SURF XX/YY** | 14.1 | 2.1 | 86.2 | 33.9 | 6.9 | 139.0 |
| **AC 10 CLOSED SURF XX/YY** | 14.3 | 2.1 | 87.3 | 33.9 | 6.9 | 140.2 |
| **AC 6 DENSE SURF XX/YY** | 16.2 | 2.9 | 96.0 | 33.9 | 6.9 | 150.0 |
| **AC 6 MED SURF XX/YY** | 14.7 | 2.3 | 87.2 | 33.9 | 6.9 | 140.3 |
| **14mm BARTEX/TORPAVE HT THIN SURF** | 15.6 | 2.7 | 88.3 | 33.9 | 6.9 | 142.0 |
| **10mm BARTEX/TORPAVE HT THIN SURF** | 15.9 | 2.8 | 91.0 | 33.9 | 6.9 | 144.8 |
| **10mm bARTEX/TORPAVE MT THIN SURF** | 16.1 | 2.9 | 104.3 | 33.9 | 6.9 | 158.3 |
| **AC 14 CLOSE BARPAVE SURF XX/YY** | 15.2 | 2.5 | 88.5 | 33.9 | 6.9 | 141.9 |
| **AC 10 CLOSE BARPAVE SURF XX/YY** | 15.4 | 2.6 | 89.7 | 33.9 | 6.9 | 143.2 |
| **AC 6 CLOSE BARPAVE SURF XX/YY** | 16.7 | 3.1 | 99.3 | 33.9 | 6.9 | 153.6 |
| **HRA 50/10 BASE/BIN/REG 40/60** | 16.0 | 2.8 | 103.6 | 33.9 | 6.9 | 157.5 |
| **HRA 15/10 F SURF XX/YY/ REC** | 23.3 | 5.7 | 149.4 | 33.9 | 6.9 | 207.7 |
| **HRA 30/10 F SURF XX/YY REC** | 20.2 | 4.5 | 131.0 | 33.9 | 6.9 | 187.4 |
| **HRA 30/14 F SURF 40/60 REC** | 20.7 | 4.7 | 132.0 | 33.9 | 6.9 | 188.7 |
| **HRA 30/14 F SURF 40/60 DES** | 19.8 | 4.3 | 126.5 | 33.9 | 6.9 | 182.7 |
| **HRA 35/14 F SURF 40/60 DES** | 18.8 | 3.9 | 120.5 | 33.9 | 6.9 | 176.1 |
| **HRA 55/10 F SURF 40/60 DES** | 16.2 | 2.9 | 101.1 | 33.9 | 6.9 | 155.1 |
| **HRA 45/10 F SURF 40/60 PROP DES** | 17.3 | 3.3 | 111.9 | 33.9 | 6.9 | 166.6 |
| **HRA 45/14 F SURF 40/60 PROP DES** | 17.2 | 3.3 | 111.9 | 33.9 | 6.9 | 166.6 |
| **AC 14 EME2 BASE/BIN 15/25 DES** | 14.2 | 2.1 | 80.3 | 33.9 | 6.9 | 133.1 |
| **15% 0/6 HRA SURFACE COURSE** | 23.3 | 5.7 | 149.4 | 33.9 | 6.9 | 207.7 |
| | | | | | | |
| **AVERAGE** | 16.2 | 2.9 | 100.0 | 33.9 | 6.9 | 154.1 |

*Table A.5– Transport Study 4*

| Mixture Name | Virgin Mix kg CO2e/t | RAP Saving kg CO2e/t | Transport kg CO2e/t | Heating kg CO2e/t | Non Heating kgCO2e/t | Total kgCO2e/t |
|---|---|---|---|---|---|---|
| **AC 20 DENSE DBM BIN 40/60 REC** | 13.0 | 1.6 | 18.9 | 33.9 | 6.9 | 71.0 |
| **AC 32 DENSE DBM BASE XX/YY** | 11.9 | 1.2 | 19.5 | 33.9 | 6.9 | 70.9 |
| **AC 32 DENSE DBM BIN XX/YY** | 13.2 | 1.7 | 21.1 | 33.9 | 6.9 | 73.3 |
| **AC 32 DENSE HDM BIN 40/60 DES** | 14.0 | 2.0 | 13.8 | 33.9 | 6.9 | 66.5 |
| **AC 20 DENSE HBM BIN 40/60 REC** | 14.0 | 2.0 | 21.7 | 33.9 | 6.9 | 74.4 |
| **AC 14 OPEN SURF XX/YY** | 13.4 | 1.8 | 11.2 | 33.9 | 6.9 | 63.6 |
| **AC 10 OPEN SURF XX/YY** | 14.3 | 2.1 | 12.4 | 33.9 | 6.9 | 65.2 |
| **AC 14 CLOSED SURF XX/YY** | 14.1 | 2.1 | 18.1 | 33.9 | 6.9 | 70.8 |
| **AC 10 CLOSED SURF XX/YY** | 14.3 | 2.1 | 18.4 | 33.9 | 6.9 | 71.3 |
| **AC 6 DENSE SURF XX/YY** | 16.2 | 2.9 | 14.6 | 33.9 | 6.9 | 68.6 |
| **AC 6 MED SURF XX/YY** | 14.7 | 2.3 | 12.8 | 33.9 | 6.9 | 65.9 |
| **14mm BARTEX/TORPAVE HT THIN SURF** | 15.6 | 2.7 | 16.8 | 33.9 | 6.9 | 70.5 |
| **10mm BARTEX/TORPAVE HT THIN SURF** | 15.9 | 2.8 | 16.6 | 33.9 | 6.9 | 70.5 |
| **10mm BARTEX/TORPAVE MT THIN SURF** | 16.1 | 2.9 | 48.8 | 33.9 | 6.9 | 102.8 |
| **AC 14 CLOSE BARPAVE SURF XX/YY** | 15.2 | 2.5 | 14.5 | 33.9 | 6.9 | 67.9 |
| **AC 10 CLOSE BARPAVE SURF XX/YY** | 15.4 | 2.6 | 14.8 | 33.9 | 6.9 | 68.4 |
| **AC 6 CLOSE BARPAVE SURF XX/YY** | 16.7 | 3.1 | 15.3 | 33.9 | 6.9 | 69.6 |
| **HRA 50/10 BASE/BIN/REG 40/60** | 16.0 | 2.8 | 37.2 | 33.9 | 6.9 | 91.1 |
| **HRA 15/10 F SURF XX/YY/ REC** | 23.3 | 5.7 | 84.4 | 33.9 | 6.9 | 142.7 |
| **HRA 30/10 F SURF XX/YY REC** | 20.2 | 4.5 | 68.5 | 33.9 | 6.9 | 124.9 |
| **HRA 30/14 F SURF 40/60 REC** | 20.7 | 4.7 | 69.3 | 33.9 | 6.9 | 126.0 |
| **HRA 30/14 F SURF 40/60 DES** | 19.8 | 4.3 | 68.4 | 33.9 | 6.9 | 124.6 |
| **HRA 35/14 F SURF 40/60 DES** | 18.8 | 3.9 | 63.9 | 33.9 | 6.9 | 119.5 |
| **HRA 55/10 F SURF 40/60 DES** | 16.2 | 2.9 | 42.4 | 33.9 | 6.9 | 96.4 |
| **HRA 45/10 F SURF 40/60 PROP DES** | 17.3 | 3.3 | 56.9 | 33.9 | 6.9 | 111.5 |
| **HRA 45/14 F SURF 40/60 PROP DES** | 17.2 | 3.3 | 56.9 | 33.9 | 6.9 | 111.5 |
| **AC 14 EME2 BASE/BIN 15/25 DES** | 14.2 | 2.1 | 14.8 | 33.9 | 6.9 | 67.6 |
| **15% 0/6 HRA SURFACE COURSE** | 23.3 | 5.7 | 84.4 | 33.9 | 6.9 | 142.7 |
| | | | | | | |
| **AVERAGE** | 16.2 | 2.9 | 34.1 | 33.9 | 6.9 | 88.2 |

*Table A.6 – Transport Study 5*

| Mixture Name | Virgin Mix kg CO2e/t | RAP Saving kg CO2e/t | Transport kg CO2e/t | Heating kg CO2e/t | NonHeating kgCO2e/t | Total kgCO2e/t |
|---|---|---|---|---|---|---|
| **AC 20 DENSE DBM BIN 40/60 REC** | 13.0 | 1.6 | 105.1 | 33.9 | 6.9 | 157.2 |
| **AC 32 DENSE DBM BASE XX/YY** | 11.9 | 1.2 | 99.7 | 33.9 | 6.9 | 151.2 |
| **AC 32 DENSE DBM BIN XX/YY** | 13.2 | 1.7 | 107.3 | 33.9 | 6.9 | 159.5 |
| **AC 32 DENSE HDM BIN 40/60 DES** | 14.0 | 2.0 | 103.2 | 33.9 | 6.9 | 155.9 |
| **AC 20 DENSE HBM BIN 40/60 REC** | 14.0 | 2.0 | 107.5 | 33.9 | 6.9 | 160.1 |
| **AC 14 OPEN SURF XX/YY** | 13.4 | 1.8 | 102.9 | 33.9 | 6.9 | 155.3 |
| **AC 10 OPEN SURF XX/YY** | 14.3 | 2.1 | 108.3 | 33.9 | 6.9 | 161.2 |
| **AC 14 CLOSED SURF XX/YY** | 14.1 | 2.1 | 110.4 | 33.9 | 6.9 | 163.2 |
| **AC 10 CLOSED SURF XX/YY** | 14.3 | 2.1 | 111.5 | 33.9 | 6.9 | 164.4 |
| **AC 6 DENSE SURF XX/YY** | 16.2 | 2.9 | 119.0 | 33.9 | 6.9 | 173.0 |
| **AC 6 MED SURF XX/YY** | 14.7 | 2.3 | 110.4 | 33.9 | 6.9 | 163.5 |
| **14mm BARTEX/TORPAVE HT THIN SURF** | 15.6 | 2.7 | 110.4 | 33.9 | 6.9 | 164.1 |
| **10mm BARTEX/TORPAVE HT THIN SURF** | 15.9 | 2.8 | 113.3 | 33.9 | 6.9 | 167.1 |
| **10mm BARTEX/TORPAVE MT THIN SURF** | 16.1 | 2.9 | 131.4 | 33.9 | 6.9 | 185.4 |
| **AC 14 CLOSE BARPAVE SURF XX/YY** | 15.2 | 2.5 | 111.3 | 33.9 | 6.9 | 164.7 |
| **AC 10 CLOSE BARPAVE SURF XX/YY** | 15.4 | 2.6 | 112.4 | 33.9 | 6.9 | 165.9 |
| **AC 6 CLOSE BARPAVE SURF XX/YY** | 16.7 | 3.1 | 122.3 | 33.9 | 6.9 | 176.6 |
| **HRA 50/10 BASE/BIN/REG 40/60** | 16.0 | 2.8 | 130.2 | 33.9 | 6.9 | 184.1 |
| **HRA 15/10 F SURF XX/YY/ REC** | 23.3 | 5.7 | 177.8 | 33.9 | 6.9 | 236.1 |
| **HRA 30/10 F SURF XX/YY REC** | 20.2 | 4.5 | 159.0 | 33.9 | 6.9 | 215.4 |
| **HRA 30/14 F SURF 40/60 REC** | 20.7 | 4.7 | 159.3 | 33.9 | 6.9 | 216.1 |
| **HRA 30/14 F SURF 40/60 DES** | 19.8 | 4.3 | 154.1 | 33.9 | 6.9 | 210.3 |
| **HRA 35/14 F SURF 40/60 DES** | 18.8 | 3.9 | 147.9 | 33.9 | 6.9 | 203.5 |
| **HRA 55/10 F SURF 40/60 DES** | 16.2 | 2.9 | 127.0 | 33.9 | 6.9 | 181.0 |
| **HRA 45/10 F SURF 40/60 PROP DES** | 17.3 | 3.3 | 139.5 | 33.9 | 6.9 | 194.2 |
| **HRA 45/14 F SURF 40/60 PROP DES** | 17.2 | 3.3 | 139.5 | 33.9 | 6.9 | 194.1 |
| **AC 14 EME2 BASE/BIN 15/25 DES** | 14.2 | 2.1 | 102.7 | 33.9 | 6.9 | 155.5 |
| **15% 0/6 HRA SURFACE COURSE** | 23.3 | 5.7 | 177.8 | 33.9 | 6.9 | 236.1 |
| | | | | | | |
| **AVERAGE** | 16.2 | 2.9 | 125.0 | 33.9 | 6.9 | 179.1 |

*Table A.7 – Transport Study 6*

| Mixture Name | Virgin Mix kg CO2e/t | RAP Saving kg CO2e/t | Transport kg CO2e/t | Heating kg CO2e/t | Non Heating kgCO2e/t | Total kgCO2e/t |
|---|---|---|---|---|---|---|
| **AC 20 DENSE DBM BIN 40/60 REC** | 24.51 | 5.22 | 60.70 | 33.88 | 6.85 | 120.72 |
| **AC 32 DENSE DBM BASE XX/YY** | 21.95 | 4.59 | 58.49 | 33.88 | 6.85 | 116.58 |
| **AC 32 DENSE DBM BIN XX/YY** | 24.93 | 5.33 | 62.84 | 33.88 | 6.85 | 123.17 |
| **AC 32 DENSE HDM BIN 40/60 DES** | 25.73 | 5.33 | 57.15 | 33.88 | 6.85 | 118.28 |
| **AC 20 DENSE HBM BIN 40/60 REC** | 25.71 | 5.33 | 63.27 | 33.88 | 6.85 | 124.38 |
| **AC 14 OPEN SURF XX/YY** | 25.36 | 5.43 | 55.73 | 33.88 | 6.85 | 116.39 |
| **AC 10 OPEN SURF XX/YY** | 27.50 | 5.95 | 58.84 | 33.88 | 6.85 | 121.12 |
| **AC 14 CLOSED SURF XX/YY** | 27.07 | 5.85 | 62.78 | 33.88 | 6.85 | 124.73 |
| **AC 10 CLOSED SURF XX/YY** | 27.50 | 5.95 | 63.48 | 33.88 | 6.85 | 125.76 |
| **AC 6 DENSE SURF XX/YY** | 31.75 | 7.00 | 65.06 | 33.88 | 6.85 | 130.54 |
| **AC 6 MED SURF XX/YY** | 28.34 | 6.16 | 60.08 | 33.88 | 6.85 | 122.99 |
| **14mm BARTEX/TORPAVE HT THIN SURF** | 28.80 | 5.95 | 62.15 | 33.88 | 6.85 | 125.73 |
| **10mm BARTEX/TORPAVE HT THIN SURF** | 29.84 | 6.27 | 63.38 | 33.88 | 6.85 | 127.68 |
| **10mm BARTEX/TORPAVE MT THIN SURF** | 30.28 | 6.37 | 88.52 | 33.88 | 6.85 | 153.16 |
| **AC 14 CLOSE BARPAVE SURF XX/YY** | 28.84 | 6.16 | 61.35 | 33.88 | 6.85 | 124.76 |
| **AC 10 CLOSE BARPAVE SURF XX/YY** | 29.31 | 6.27 | 62.04 | 33.88 | 6.85 | 125.81 |
| **AC 6 CLOSE BARPAVE SURF XX/YY** | 33.02 | 7.31 | 66.92 | 33.88 | 6.85 | 133.36 |
| **HRA 50/10 BASE/BIN/REG 40/60** | 31.34 | 6.90 | 81.95 | 33.88 | 6.85 | 147.12 |
| **HRA 15/10 F SURF XX/YY/ REC** | 44.37 | 9.41 | 128.76 | 33.88 | 6.85 | 204.45 |
| **HRA 30/10 F SURF XX/YY REC** | 38.67 | 8.26 | 111.64 | 33.88 | 6.85 | 182.78 |
| **HRA 30/14 F SURF 40/60 REC** | 39.22 | 8.26 | 112.24 | 33.88 | 6.85 | 183.93 |
| **HRA 30/14 F SURF 40/60 DES** | 37.06 | 7.73 | 109.30 | 33.88 | 6.85 | 179.36 |
| **HRA 35/14 F SURF 40/60 DES** | 35.13 | 7.31 | 104.05 | 33.88 | 6.85 | 172.60 |
| **HRA 55/10 F SURF 40/60 DES** | 30.08 | 6.27 | 83.16 | 33.88 | 6.85 | 147.70 |
| **HRA 45/10 F SURF 40/60 PROP DES** | 32.38 | 6.79 | 96.47 | 33.88 | 6.85 | 162.79 |
| **HRA 45/14 F SURF 40/60 PROP DES** | 32.36 | 6.79 | 96.47 | 33.88 | 6.85 | 162.77 |
| **AC 14 EME2 BASE/BIN 15/25 DES** | 25.69 | 5.22 | 57.44 | 33.88 | 6.85 | 118.64 |
| **15% 0/6 HRA SURFACE COURSE** | 44.37 | 9.41 | 128.76 | 33.88 | 6.85 | 204.45 |
| | | | | | | |
| **AVERAGE** | 30.75 | 6.53 | 77.97 | 33.88 | 6.85 | 142.92 |

*Table A.8 – Bitumen Study 1*

| Mixture Name | Virgin Mix kg CO2e/t | RAP Saving kg CO2e/t | Transport kg CO2e/t | Heating kg CO2e/t | Non Heating kgCO2e/t | Total kgCO2e/t |
|---|---|---|---|---|---|---|
| **AC 20 DENSE DBM BIN 40/60 REC** | 27.39 | 5.22 | 60.70 | 33.88 | 6.85 | 123.60 |
| **AC 32 DENSE DBM BASE XX/YY** | 24.47 | 4.59 | 58.49 | 33.88 | 6.85 | 119.10 |
| **AC 32 DENSE DBM BIN XX/YY** | 27.87 | 5.33 | 62.84 | 33.88 | 6.85 | 126.11 |
| **AC 32 DENSE HDM BIN 40/60 DES** | 28.67 | 5.33 | 57.15 | 33.88 | 6.85 | 121.22 |
| **AC 20 DENSE HBM BIN 40/60 REC** | 28.65 | 5.33 | 63.27 | 33.88 | 6.85 | 127.32 |
| **AC 14 OPEN SURF XX/YY** | 28.36 | 5.43 | 55.73 | 33.88 | 6.85 | 119.39 |
| **AC 10 OPEN SURF XX/YY** | 30.80 | 5.95 | 58.84 | 33.88 | 6.85 | 124.42 |
| **AC 14 CLOSED SURF XX/YY** | 30.31 | 5.85 | 62.78 | 33.88 | 6.85 | 127.97 |
| **AC 10 CLOSED SURF XX/YY** | 30.80 | 5.95 | 63.48 | 33.88 | 6.85 | 129.06 |
| **AC 6 DENSE SURF XX/YY** | 35.65 | 7.00 | 65.06 | 33.88 | 6.85 | 134.44 |
| **AC 6 MED SURF XX/YY** | 31.76 | 6.16 | 60.08 | 33.88 | 6.85 | 126.41 |
| **14mm BARTEX/TORPAVE HT THIN SURF** | 32.10 | 5.95 | 62.15 | 33.88 | 6.85 | 129.03 |
| **10mm BARTEX/TORPAVE HT THIN SURF** | 33.32 | 6.27 | 63.38 | 33.88 | 6.85 | 131.16 |
| **10mm BARTEX/TORPAVE MT THIN SURF** | 33.82 | 6.37 | 88.52 | 33.88 | 6.85 | 156.70 |
| **AC 14 CLOSE BARPAVE SURF XX/YY** | 32.26 | 6.16 | 61.35 | 33.88 | 6.85 | 128.18 |
| **AC 10 CLOSE BARPAVE SURF XX/YY** | 32.79 | 6.27 | 62.04 | 33.88 | 6.85 | 129.29 |
| **AC 6 CLOSE BARPAVE SURF XX/YY** | 37.10 | 7.31 | 66.92 | 33.88 | 6.85 | 137.44 |
| **HRA 50/10 BASE/BIN/REG 40/60** | 35.18 | 6.90 | 81.95 | 33.88 | 6.85 | 150.96 |
| **HRA 15/10 F SURF XX/YY/ REC** | 49.65 | 9.41 | 128.76 | 33.88 | 6.85 | 209.73 |
| **HRA 30/10 F SURF XX/YY REC** | 43.29 | 8.26 | 111.64 | 33.88 | 6.85 | 187.40 |
| **HRA 30/14 F SURF 40/60 REC** | 43.84 | 8.26 | 112.24 | 33.88 | 6.85 | 188.55 |
| **HRA 30/14 F SURF 40/60 DES** | 41.38 | 7.73 | 109.30 | 33.88 | 6.85 | 183.68 |
| **HRA 35/14 F SURF 40/60 DES** | 39.21 | 7.31 | 104.05 | 33.88 | 6.85 | 176.68 |
| **HRA 55/10 F SURF 40/60 DES** | 33.56 | 6.27 | 83.16 | 33.88 | 6.85 | 151.18 |
| **HRA 45/10 F SURF 40/60 PROP DES** | 36.16 | 6.79 | 96.47 | 33.88 | 6.85 | 166.57 |
| **HRA 45/14 F SURF 40/60 PROP DES** | 36.14 | 6.79 | 96.47 | 33.88 | 6.85 | 166.55 |
| **AC 14 EME2 BASE/BIN 15/25 DES** | 28.57 | 5.22 | 57.44 | 33.88 | 6.85 | 121.52 |
| **15% 0/6 HRA SURFACE COURSE** | 49.65 | 9.41 | 128.76 | 33.88 | 6.85 | 209.73 |
| | | | | | | |
| **AVERAGE** | 34.38 | 6.53 | 77.97 | 33.88 | 6.85 | 146.55 |

*Table A.9 – Bitumen Study 2*

| Mixture Name | Virgin Mix kg CO2e/t | RAP Saving kg CO2e/t | Transport kg CO2e/t | Heating kg CO2e/t | Non Heating kgCO2e/t | Total kgCO2e/t |
|---|---|---|---|---|---|---|
| **AC 20 DENSE DBM BIN 40/60 REC** | 32.19 | 5.22 | 60.70 | 33.88 | 6.85 | 128.40 |
| **AC 32 DENSE DBM BASE XX/YY** | 28.67 | 4.59 | 58.49 | 33.88 | 6.85 | 123.30 |
| **AC 32 DENSE DBM BIN XX/YY** | 32.77 | 5.33 | 62.84 | 33.88 | 6.85 | 131.01 |
| **AC 32 DENSE HDM BIN 40/60 DES** | 33.57 | 5.33 | 57.15 | 33.88 | 6.85 | 126.12 |
| **AC 20 DENSE HBM BIN 40/60 REC** | 33.55 | 5.33 | 63.27 | 33.88 | 6.85 | 132.22 |
| **AC 14 OPEN SURF XX/YY** | 33.36 | 5.43 | 55.73 | 33.88 | 6.85 | 124.39 |
| **AC 10 OPEN SURF XX/YY** | 36.30 | 5.95 | 58.84 | 33.88 | 6.85 | 129.92 |
| **AC 14 CLOSED SURF XX/YY** | 35.71 | 5.85 | 62.78 | 33.88 | 6.85 | 133.37 |
| **AC 10 CLOSED SURF XX/YY** | 36.30 | 5.95 | 63.48 | 33.88 | 6.85 | 134.56 |
| **AC 6 DENSE SURF XX/YY** | 42.15 | 7.00 | 65.06 | 33.88 | 6.85 | 140.94 |
| **AC 6 MED SURF XX/YY** | 37.46 | 6.16 | 60.08 | 33.88 | 6.85 | 132.11 |
| **14mm BARTEX/TORPAVE HT THIN SURF** | 37.60 | 5.95 | 62.15 | 33.88 | 6.85 | 134.53 |
| **10mm BARTEX/TORPAVE HT THIN SURF** | 39.12 | 6.27 | 63.38 | 33.88 | 6.85 | 136.96 |
| **10mm BARTEX/TORPAVE MT THIN SURF** | 39.72 | 6.37 | 88.52 | 33.88 | 6.85 | 162.60 |
| **AC 14 CLOSE BARPAVE SURF XX/YY** | 37.96 | 6.16 | 61.35 | 33.88 | 6.85 | 133.88 |
| **AC 10 CLOSE BARPAVE SURF XX/YY** | 38.59 | 6.27 | 62.04 | 33.88 | 6.85 | 135.09 |
| **AC 6 CLOSE BARPAVE SURF XX/YY** | 43.90 | 7.31 | 66.92 | 33.88 | 6.85 | 144.24 |
| **HRA 50/10 BASE/BIN/REG 40/60** | 41.58 | 6.90 | 81.95 | 33.88 | 6.85 | 157.36 |
| **HRA 15/10 F SURF XX/YY/ REC** | 58.45 | 9.41 | 128.76 | 33.88 | 6.85 | 218.53 |
| **HRA 30/10 F SURF XX/YY REC** | 50.99 | 8.26 | 111.64 | 33.88 | 6.85 | 195.10 |
| **HRA 30/14 F SURF 40/60 REC** | 51.54 | 8.26 | 112.24 | 33.88 | 6.85 | 196.25 |
| **HRA 30/14 F SURF 40/60 DES** | 48.58 | 7.73 | 109.30 | 33.88 | 6.85 | 190.88 |
| **HRA 35/14 F SURF 40/60 DES** | 46.01 | 7.31 | 104.05 | 33.88 | 6.85 | 183.48 |
| **HRA 55/10 F SURF 40/60 DES** | 39.36 | 6.27 | 83.16 | 33.88 | 6.85 | 156.98 |
| **HRA 45/10 F SURF 40/60 PROP DES** | 42.46 | 6.79 | 96.47 | 33.88 | 6.85 | 172.87 |
| **HRA 45/14 F SURF 40/60 PROP DES** | 42.44 | 6.79 | 96.47 | 33.88 | 6.85 | 172.85 |
| **AC 14 EME2 BASE/BIN 15/25 DES** | 33.37 | 5.22 | 57.44 | 33.88 | 6.85 | 126.32 |
| | | | | | | |
| **AVERAGE** | 39.77 | 6.42 | 76.08 | 33.88 | 6.85 | 150.16 |

*Table A.10 – Bitumen Study 3*

| Mixture Name | Virgin Mix kg CO2e/t | RAP Saving kg CO2e/t | Transport kg CO2e/t | Heating kg CO2e/t | Non Heating kgCO2e/t | Total kgCO2e/t |
|---|---|---|---|---|---|---|
| **AC 20 DENSE DBM BIN 40/60 REC** | 13.01 | 5.43 | 49.68 | 33.88 | 6.85 | 97.99 |
| **AC 32 DENSE DBM BASE XX/YY** | 12.94 | 5.43 | 49.00 | 33.88 | 6.85 | 97.24 |
| **AC 32 DENSE DBM BIN XX/YY** | 12.93 | 5.42 | 49.05 | 33.88 | 6.85 | 97.29 |
| **AC 32 DENSE HDM BIN 40/60 DES** | 13.88 | 5.54 | 41.67 | 33.88 | 6.85 | 90.74 |
| **AC 20 DENSE HBM BIN 40/60 REC** | 13.60 | 5.33 | 51.03 | 33.88 | 6.85 | 100.03 |
| **AC 14 OPEN SURF XX/YY** | 13.36 | 5.43 | 55.73 | 33.88 | 6.85 | 104.39 |
| **AC 10 OPEN SURF XX/YY** | 14.30 | 5.95 | 58.84 | 33.88 | 6.85 | 107.92 |
| **AC 14 CLOSED SURF XX/YY** | 14.11 | 5.85 | 62.78 | 33.88 | 6.85 | 111.77 |
| **AC 10 CLOSED SURF XX/YY** | 14.30 | 5.95 | 63.48 | 33.88 | 6.85 | 112.56 |
| **AC 6 DENSE SURF XX/YY** | 16.15 | 7.00 | 65.06 | 33.88 | 6.85 | 114.94 |
| **AC 6 MED SURF XX/YY** | 14.66 | 6.16 | 60.08 | 33.88 | 6.85 | 109.31 |
| **14mm BARTEX/TORPAVE HT THIN SURF** | 15.50 | 6.17 | 46.67 | 33.88 | 6.85 | 96.73 |
| **10mm BARTEX/TORPAVE HT THIN SURF** | 15.92 | 6.27 | 63.38 | 33.88 | 6.85 | 113.76 |
| **10mm BARTEX/TORPAVE MT THIN SURF** | 16.12 | 6.37 | 88.52 | 33.88 | 6.85 | 139.00 |
| **AC 14 CLOSE BARPAVE SURF XX/YY** | 15.09 | 6.36 | 48.23 | 33.88 | 6.85 | 97.69 |
| **AC 10 CLOSE BARPAVE SURF XX/YY** | 15.39 | 6.27 | 62.04 | 33.88 | 6.85 | 111.89 |
| **AC 6 CLOSE BARPAVE SURF XX/YY** | 16.70 | 7.31 | 66.92 | 33.88 | 6.85 | 117.04 |
| **HRA 50/10 BASE/BIN/REG 40/60** | 15.98 | 6.90 | 81.95 | 33.88 | 6.85 | 131.76 |
| **HRA 15/10 F SURF XX/YY/ REC** | 23.25 | 9.41 | 128.76 | 33.88 | 6.85 | 183.33 |
| **HRA 30/10 F SURF XX/YY REC** | 20.19 | 8.26 | 111.64 | 33.88 | 6.85 | 164.30 |
| **HRA 30/14 F SURF 40/60 REC** | 20.74 | 8.26 | 112.24 | 33.88 | 6.85 | 165.45 |
| **HRA 30/14 F SURF 40/60 DES** | 19.78 | 7.73 | 109.30 | 33.88 | 6.85 | 162.08 |
| **HRA 35/14 F SURF 40/60 DES** | 18.81 | 7.31 | 104.05 | 33.88 | 6.85 | 156.28 |
| **HRA 55/10 F SURF 40/60 DES** | 16.16 | 6.27 | 83.16 | 33.88 | 6.85 | 133.78 |
| **HRA 45/10 F SURF 40/60 PROP DES** | 17.26 | 6.79 | 96.47 | 33.88 | 6.85 | 147.67 |
| **HRA 45/14 F SURF 40/60 PROP DES** | 17.24 | 6.79 | 96.47 | 33.88 | 6.85 | 147.65 |
| **AC 14 EME2 BASE/BIN 15/25 DES** | 14.09 | 5.39 | 45.56 | 33.88 | 6.85 | 94.99 |
| **15% 0/6 HRA SURFACE COURSE** | 23.25 | 9.41 | 128.76 | 33.88 | 6.85 | 183.33 |
| | | | | | | |
| **AVERAGE** | 16.24 | 6.60 | 74.30 | 33.88 | 6.85 | 124.68 |

*Table A.11 – RAP Study 1*

| Mixture Name | Virgin Mix kg CO2e/t | RAP Saving kg CO2e/t | Transport kg CO2e/t | Heating kg CO2e/t | Non Heating kgCO2e/t | Total kgCO2e/t |
|---|---|---|---|---|---|---|
| **AC 20 DENSE DBM BIN 40/60 REC** | 12.92 | 5.46 | 45.20 | 33.88 | 6.85 | 93.39 |
| **AC 32 DENSE DBM BASE XX/YY** | 11.81 | 4.83 | 43.02 | 33.88 | 6.85 | 90.72 |
| **AC 32 DENSE DBM BIN XX/YY** | 13.10 | 5.56 | 47.37 | 33.88 | 6.85 | 95.64 |
| **AC 32 DENSE HDM BIN 40/60 DES** | 13.90 | 5.56 | 41.67 | 33.88 | 6.85 | 90.74 |
| **AC 20 DENSE HBM BIN 40/60 REC** | 13.89 | 5.56 | 47.79 | 33.88 | 6.85 | 96.85 |
| **AC 14 OPEN SURF XX/YY** | 13.29 | 5.67 | 40.25 | 33.88 | 6.85 | 88.61 |
| **AC 10 OPEN SURF XX/YY** | 14.23 | 6.19 | 43.36 | 33.88 | 6.85 | 92.13 |
| **AC 14 CLOSED SURF XX/YY** | 14.03 | 6.08 | 47.30 | 33.88 | 6.85 | 95.97 |
| **AC 10 CLOSED SURF XX/YY** | 14.23 | 6.19 | 48.01 | 33.88 | 6.85 | 96.77 |
| **AC 6 DENSE SURF XX/YY** | 16.06 | 7.23 | 49.58 | 33.88 | 6.85 | 99.14 |
| **AC 6 MED SURF XX/YY** | 14.58 | 6.40 | 44.61 | 33.88 | 6.85 | 93.52 |
| **14mm BARTEX/TORPAVE HT THIN SURF** | 15.53 | 6.19 | 46.67 | 33.88 | 6.85 | 96.74 |
| **10mm BARTEX/TORPAVE HT THIN SURF** | 15.82 | 6.50 | 47.90 | 33.88 | 6.85 | 97.95 |
| **10mm BARTEX/TORPAVE MT THIN SURF** | 16.05 | 6.61 | 73.04 | 33.88 | 6.85 | 123.21 |
| **AC 14 CLOSE BARPAVE SURF XX/YY** | 15.08 | 6.40 | 45.87 | 33.88 | 6.85 | 95.29 |
| **AC 10 CLOSE BARPAVE SURF XX/YY** | 15.30 | 6.50 | 46.57 | 33.88 | 6.85 | 96.09 |
| **AC 6 CLOSE BARPAVE SURF XX/YY** | 16.62 | 7.55 | 51.45 | 33.88 | 6.85 | 101.25 |
| **HRA 50/10 BASE/BIN/REG 40/60** | 15.90 | 7.13 | 66.47 | 33.88 | 6.85 | 115.97 |
| **HRA 15/10 F SURF XX/YY/ REC** | 23.16 | 9.50 | 120.58 | 33.88 | 6.85 | 174.97 |
| **HRA 30/10 F SURF XX/YY REC** | 20.20 | 8.53 | 97.13 | 33.88 | 6.85 | 149.53 |
| **HRA 30/14 F SURF 40/60 REC** | 20.72 | 8.48 | 99.04 | 33.88 | 6.85 | 152.01 |
| **HRA 30/14 F SURF 40/60 DES** | 19.78 | 7.97 | 96.05 | 33.88 | 6.85 | 148.59 |
| **HRA 35/14 F SURF 40/60 DES** | 18.75 | 7.56 | 88.57 | 33.88 | 6.85 | 140.50 |
| **HRA 55/10 F SURF 40/60 DES** | 16.08 | 6.51 | 67.69 | 33.88 | 6.85 | 117.99 |
| **HRA 45/10 F SURF 40/60 PROP DES** | 17.18 | 7.03 | 81.00 | 33.88 | 6.85 | 131.88 |
| **HRA 45/14 F SURF 40/60 PROP DES** | 17.17 | 7.03 | 81.00 | 33.88 | 6.85 | 131.87 |
| **AC 14 EME2 BASE/BIN 15/25 DES** | 14.10 | 5.46 | 41.97 | 33.88 | 6.85 | 91.34 |
| **15% 0/6 HRA SURFACE COURSE** | 23.16 | 9.50 | 120.58 | 33.88 | 6.85 | 174.97 |
| | | | | | | |
| **AVERAGE** | 16.17 | 6.76 | 63.21 | 33.88 | 6.85 | 113.34 |

*Table A.11 – RAP Study.*