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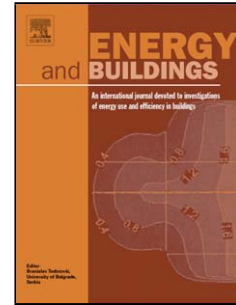
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THE ASSESSMENT OF EMBODIED ENERGY IN TYPICAL REINFORCED CONCRETE BUILDING STRUCTURES IN IRELAND

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Abstract:

This paper demonstrates that by understanding how energy is consumed in the manufacturing of reinforced concrete, designers can significantly reduce the overall embodied energy of structures. Embodied energy of products can vary from country to country. Therefore, to accurately estimate the embodied energy of reinforced concrete structures, data specific to the country where they are being constructed must be used. This paper presents the assessment of embodied energy in typical RC building structures in Ireland.

The most common methods used to calculate EE are evaluated in this paper and the most suitable method was applied to reinforced concrete. The EE of a typical 30MPa concrete mix in Ireland is calculated to be 1.08 MJ/kg. Notably cement is credited with 68% of the total EE. The major contributors of energy consumption are identified, which should aid to minimise energy consumption and optimise efficiency.

A case study is presented which compares the EE of a typical reinforced concrete structure in Ireland using two concrete mix designs. The first uses Ordinary Portland Cement, while the second uses GGBS replacing half of the cement content. As expected, the EE of the GGBS mix is significantly lower (30%) than that of its counterpart.

Keywords: Embodied Energy, Sustainability, Structural Design, Concrete.

1. INTRODUCTION

1.1 Energy consumed by buildings

The energy consumed by buildings accounted for 47% of the UK's total CO₂ emissions [1]. Of this total energy consumed 90% accounted for the operation of these buildings (for example, lighting, heating, cooling, and so on). The rest is made up of what is known as embodied energy; this represents the energy used to make up the building fabric. The development of new technologies – materials, devices and systems – is helping to reduce the energy consumed in the operation of buildings. This is been driven by both legislation and the public's greater understanding of the necessity to reduce our consumption of energy. The EU Directive on Energy Performance of Buildings (Directive 2002/91/EC of 16 December 2002) [2] came into force in member states in January 2006, so that the EU could ensure new buildings would use less energy. The Directive requires that governments, designers and clients take action to reduce the amount of energy consumed in the operation of buildings. It is expected that a new directive will follow requiring the amount of energy stored in all products, including building structures, to be evaluated and reduced. It is envisaged that this will encourage prospective building owners to reduce their environmental impact by consciously choosing a building with low embodied energy. In fact, the World Wildlife Fund's Living Planet Report [3] states that our global footprint now exceeds the world's capacity to regenerate by about 30%. Designing buildings with lower embodied energy can reduce consumption of natural resources and can also reduce the cost of constructing the building.

Having the quantity of embodied energy (EE) in the structure clearly visible to the designer during the design process should make the designer conscience of the impact their decisions in the design are having on the embodied energy in the structure. It may, for example, deter designers from over-specifying the grade of concrete required or encourage designers to consider using alternative binders to cement.

However, this must be incorporated into a software tool/environment that considers other important aspect of the building, including cost, structural zone, buildability, thermal mass, service distribution, future flexibility, foundations and programme. By considering all of these elements together in a holistic approach, the designer can chose the best option for their structure. While the energy performance of a

building can be improved at any stage in its life cycle, decisions made during the design phase are usually the most cost effective.

1.2 Energy Analysis

Sustainable development and the sustainability credentials of construction materials are gaining increasing importance as the environmental impact of the construction industry becomes apparent. One of the most effective means of alleviating this impact is through the reduction of the amount of energy consumed in all aspects of human development. The current era of high energy prices has encouraged all industries to reduce energy consumption as the financial implications of wastage are severe. On the other hand, Kyoto Protocol [4], which is ratified by 183 parties, is an international legally binding agreement to reduce green house gas emissions. Embodied Energy contributes to carbon emissions as fuel releases carbon during combustion.

The first step in reducing the energy usage of a process is energy analysis. Energy analysis highlights individual factors that are responsible for the bulk of the energy consumption relating to a product or process. The quantification of these requires accurate and reliable methods. This is the motivation behind the extensive research that has been completed in the area (for example, [5]-[10]). Many factors must be considered, one of these being embodied energy, EE. EE is the energy consumed over the duration of a product's life cycle [10]. It may be expressed as megaJoules (*MJ*) or gigaJoules (*GJ*) per unit weight (*kg* or tonne) or area (square metre). The embodied energy of an entire building, or a building material or product in a building, comprises of indirect and direct energy. Indirect energy is used to create the inputs of goods and services to the main process, whereas direct energy is the energy used for the main process (Fig. 1). The accuracy and extent of an embodied energy analysis is dependent on which of the three main methods is chosen: process analysis, input–output (I–O) analysis or hybrid analysis [6].

There is data available on the subject of embodied energy from the 1970s onwards. For example, Bullard et al [5] produced a table of the energy intensity of a 368 sector economy for the USA. More recently, Hammond and Jones [10] published an Inventory of Carbon and Energy (ICE), which is a database containing embodied energy (EE) and embodied carbon (EC) values for almost 200 different common

building materials. This has been made freely available to the public and industry. The data for this inventory was extracted from peer reviewed literature on the basis of a defined methodology and criteria [10]. It is considered that the strict criteria used in the selection of source material for the creation of the ICE serves to significantly increase its accuracy and relevancy.

EE can be referred to in two forms: initial EE and recurring EE [11]. Initial EE is that concerned with the acquisition, transportation and processing of raw materials to create a product. Recurring EE, on the other hand, relates to the energy consumed in the maintenance, and associated activities, of a product during its lifetime. It is considered that recurring energy is negligible for concrete as it is a durable material that does not typically require maintenance.

The choice of system boundary is important in the estimation of embodied energy. Three common boundaries include: cradle to gate, cradle to site and cradle to grave [9]. Cradle to gate accounts for all the EE of a product until it leaves the factory gate. Cradle to site takes into consideration the EE of a product until its arrival on site. For materials with a high EE and high density, there should be very little difference between the cradle to gate and cradle to site values. However, when using this type of system boundary the user is encouraged to consider transportation on a case by case basis. The addition of EE from transport will be more substantial for low energy intensity materials such as aggregate and sand. The third system boundary, cradle to grave, encompasses the energy usage of a product over its lifetime. In the case of reinforced concrete, to perform a cradle to grave analysis would involve consideration of the demolition of the structure at the end of its life.

Kennedy [12] has performed a highly detailed Process Analysis to assess the EE in materials required for road construction. Data pertaining to the energy usage by various vehicle types on a number of road types is produced in tabular form and is used as part of this study to calculate the energy consumed during the transport of concrete and reinforcement.

For the purpose of this study, the energy consumption of the construction industry in Ireland is considered. In particular, the EE in concrete, a material which is used extensively worldwide, is

investigated. EE analysis enables informed decision making in relation to the processing methods used and the products purchased in the manufacture and supply of concrete.

2. EMBODIED ENERGY ANALYSIS

There have been many methods developed for assessing EE. The accuracy and completeness of an analysis depends on the method used, as demonstrated, for example, by Crawford [7]. The first methods used to assess EE were Process methods. I-O analysis, which was originally developed in 1941 by Leontief as a means to measure the flow of goods and services through the economy, was later modified by Herendeen and Bullard [13] into an energy analysis tool. Each of the aforementioned methods have major limitations and for these reasons, both are considered to provide an inaccurate estimation of the embodied energy, EE of a product. Thus, these two methods have been combined in different ways to form two other techniques making use of the strengths of each. For example, Bullard et al [5] developed a Process Based Hybrid Analysis method. Later, Treloar [6] developed an Input-Output Based Hybrid Analysis. The advantages and disadvantages of each method are discussed in Table 1.

2.1 Process Analysis

Process Analysis focuses on one particular product or service. It is most suited to products or processes that have a very high direct energy component, such as cement. Acquaye et al [8] define the direct energy intensity of a product as the energy used directly during the processes of its manufacture, whilst the indirect component is the sum of all the other non-energy contributions.

A list of all the goods and services that are required directly to produce the particular product must be obtained for this type of analysis. The list consists of direct energy, such as fuel and electricity, that is easily quantified, and non-energy inputs which require significant effort to quantify. Each non-energy input is further analysed to break it down into its constituent processes. These will again contain direct energy and non-energy processes. This loop can continue indefinitely so a system boundary must be established, as shown in Figure 1.

Generally, the boundary is drawn when it is considered that any additional inputs will be negligible [5]. This truncation can greatly affect the results obtained as there is no way of knowing if an upstream process is contributing a large amount of EE to the target product. This system incompleteness is the main reason why this method is not considered accurate [5], [6].

Previous research by Treloar [6] has proven that even the most extensive process based inventories do not achieve a sufficient level of system completeness. In the second and subsequent stages of Process Analysis only the most significant contributions are analysed. The inputs which are considered negligible and those that are outside the system boundary are referred to as truncated. The total EE is obtained by summing all the constituent values. Detailed data pertaining to the production of the target product is required to perform a process analysis. Assessment of indirect components also requires detailed information but not as extensive as that required for the main processes. This information may be obtained from the manufacturers, trade associations and from any available relevant research. Ideally it would be possible to express the energy intensity in GJ/unit output. However, this data is rarely available.

In summary, the benefit of this analysis is apparent within energy intensive industries such as cement production. The major contributing inputs to these industries can be identified and efforts can be made to reduce their impact. The major disadvantage of this method is the incompleteness resulting from the truncation of processes.

2.2 Input – Output Analysis

National average statistics that model the financial flows of goods and services between sectors of the economy, referred to as I–O data, can be used to fill the gaps that are caused by system boundary incompleteness. However, the level of segregation of the economy varies from country to country. For example, the Australian Bureau of Statistics has segregated the Australian economy into 109 sectors [15], while the US Bureau of Economic Analysis has divided the US economy into 443 individual sectors for Benchmark years [16]. In Ireland, the Central Statistics Office collects data for a 53 sector economy [17].

Similar products and services are aggregated into unique sectors regardless of the different processes used in their manufacture or the different methods used to provide the service. If a product or service accounts for a large part of a sector's output or if it is typical of the sector's output then the National I-O tables will provide relevant and useful information. However, due to the level of aggregation of the Irish economy, the data available can only be considered very relevant to a minority of products and services. Ideally, each product would be the output of an individual sector and consequently would have a unique energy coefficient. If the target product's proportion within its economic sector is known then an assessment can be made of the relevancy of the available data.

Herendeen and Bullard [13] adapted the Input-Output method from an economic research tool to an energy flow research tool. This is based on the first law of thermodynamics: energy can neither be created nor destroyed, it can only be changed from one form to another. The statistics provided by National I-O tables is combined with energy use data to create an energy model. The National I-O tables [17] provide sufficient data relating to the flow of energy from sector to sector, while Sustainable Energy Ireland, SEI, provide data on energy costs of the main fuels used in Ireland for several years [18].

Let A be the table of direct requirement coefficients as published in the National I-O tables. For Ireland, this is a 53×53 matrix [17]. The direct energy intensity for a particular sector is obtained by multiplying the direct requirement coefficient of that sector for each energy type by the average energy tariff and summing the results.

The matrix of total requirement coefficients, $(I-A)^{-1}$, where A is the matrix of direct requirement coefficients and I is the identity matrix, can be obtained by the power series expansion $(I-A)^{-1} = I + A + A^2 + A^3 + A^4 + \dots$ [5]. This power series expansion derives almost identical results to the Leontief inverse matrix, except the energy intensity of each upstream stage can be identified and analysed prior to aggregation [6]. Total energy intensity is obtained by multiplying the total requirement coefficients by the average energy tariff for that sector and summing the results.

The National I-O tables account for a multi-fuel Irish economy and this analysis can be repeated for each type of energy facilitating the calculation of the total primary energy intensity of a product. Peat is

accounted for in the sector referred to as 'other mining and quarrying products'. Oil and petroleum products are aggregated in the 'petroleum and other manufacturing products' sector, whilst electricity and gas form their own sector. Due to the inherent assumption that the product in question is a typical output of its economic sector, this method is flawed. For example, a wide range of products such as plaster and lime are accounted for in the sector 'other mining and quarrying products'. Acquaye et al [8] have calculated disaggregation constants for the energy producing sectors of the Irish economy. The disaggregation constant for an energy sector is the proportion of total output from that sector accounted for by energy. Disaggregation constants reduce the level of error resulting from aggregation of the I-O analysis.

Primary energy factors for Ireland have also been calculated by Acquaye et al [8]. These factors take into account the EE of the energy supply sectors. For example, there are significant losses involved in the generation and transmission of electricity. The direct requirement coefficients for the energy sectors are eliminated from the matrix of direct requirement coefficients as the primary energy factors account for all energy inputs into the energy sectors.

The data required for this analysis is very complex and an immense human effort is required to collate these tables and to analyse the data, even in the case of the highly aggregated Irish model. This data is only collected for certain years and thus the analysis can only be completed for these years. The other data required for this analysis must be modified to make it relevant to the I-O data. The most recent I-O tables available for Ireland relate to 2005 and were published in March 2009 [17]. Though this publication does not contain the matrix of direct requirement coefficients necessary to perform an I-O analysis, the matrix of total requirement coefficients is published. From this the matrix of direct requirement coefficients can be obtained, if and only if, this matrix is invertible, otherwise a non-unique solution will be obtained. The matrix of total requirement coefficients for 2005 is invertible and thus the matrix of direct requirement coefficients was obtained.

Price indices are published by the CSO [19] which can be used to achieve conformity with the data from the National I-O tables. The cost of every good and service does not fluctuate uniformly and thus the

price indices only provide an estimate. There are indices published specifically for energy cost fluctuations and thus these are highly accurate.

Due to the limitations of this method, if it is not used correctly, with proper knowledge and understanding, and if the data is not of high quality, the results will prove to be very inaccurate. Using Input-Output (I-O) analysis, Keane and Kelly [20] calculated the direct and total embodied energy for concrete in Ireland to be 0.156MJ/kg and 0.298MJ/kg, respectively. Consequently, the indirect EE of concrete is found to be 49% of the direct EE. A Process Analysis does not account for a major proportion of the indirect EE. This example illustrates how significant the indirect energy intensity can be. Due to the inherent problems with process analysis and I-O analysis, hybrid methods of embodied energy analysis have been developed in an attempt to minimise the limitations and errors of these traditional methods. Hybrid methods combine process data and I-O data in a variety of formats (for example, [5], [6], [8], [21]). In this paper, a hybrid method will be used to estimate the EE of concrete.

2.3 Process Based Hybrid Analysis

Bullard et al [5] describes a method for combining I-O data and Process data referred to as Hybrid Analysis. In theory, both I-O analysis and Process Analysis require identical inputs and provide identical results [5]. In practice, in Ireland the complete set of I-O data is only available at the aggregated level of 53 sectors [17]. Thus, I-O results only give the average energy intensity of a sector's output. For example, sector 45 accounts for all construction in Ireland. The results from I-O analysis for a house and a pipeline of the same cost will have the same EE as they are both in sector 45. The analysis of atypical products within a sector can be completed using Process Analysis, if all the inputs are traced sufficiently far back. The errors associated with truncation can be replaced by a smaller aggregation error associated with energy costing the higher order indirect inputs [5].

To perform a process based hybrid analysis the following steps are completed [5]:

□ The direct energy used and the materials required are identified. Some of the materials may be typical products of economic sectors. In this case, the total energy intensity value as calculated using I-O analysis can be used.

□ Materials and other inputs not easily classified in economic sectors, must be further analysed necessitating that all their inputs must be energy costed using either I-O analysis or further Process Analysis, depending on whether they are typical outputs of economic sectors or not.

This form of Process Based Hybrid analysis is most suited to analysing large atypical products such as an entire building. An entire building is analysed by breaking it down into each of its components and energy costing them. This method requires the identification of the energy paths for which process data is available. An energy path comprises a flow of a good or service and an associated amount of energy consumption [6]. The energy intensity of a material, estimated using the process based hybrid method, is given by [22]:

$$EI_M = PEI_M + (EI_n - TEI_M) \times \epsilon_M \quad (1)$$

where EI_M is the hybrid energy intensity of the basic material, PEI_M is the material process based hybrid energy intensity, TEI_n is the total energy intensity of I-O sector n , representing the basic material, TEI_M is the total energy intensity of I-O path representing the basic material, and ϵ_M is the total price of the basic material.

According to Crawford and Treloar [22], hybrid methods based on process data suffer from the same inherent limitations as process analysis. The I-O system completeness is only applied to the components of the model upstream from the process analysis data. Acquaye et al [8] used four case studies (the construction of a bridge, a three bedroom terraced house, a three bedroom semi-detached house and a four bedroom detached house) to show that the large error associated with the aggregation of the Irish economy into 53 sectors can be greatly reduced through the use of data from several censuses by the CSO on the construction industry. The construction sector is further segregated into five detailed sectors by

using the information contained in the censuses. This combination of statistical analysis results in an enhanced assessment of the EE of each of the case studies [8].

2.4 Input-Output Based Hybrid Analysis

The I-O Based Hybrid analysis further increases the completeness of the Process Based Hybrid method. It involves the complete disaggregation of the Leontief matrix of total requirement coefficients. The matrix of total requirement coefficients $(I-A)^{-1}$ is computed using the power series approximation $(I-A)^{-1} = I + A^2 + A^3 + A^4 + A^5 + \dots$, where A is the matrix of total requirement coefficients and I is the identity matrix. When two $N \times N$ matrices are multiplied, each value in the resulting matrix is the sum of N individual products. Each one of these products is a potentially significant energy path. As there are three energy sectors in the Irish economy and 53 sectors in total, the total amount of potential energy paths at stage one is $3 \times 53 = 159$. Each of these 159 energy paths have 5 possible inputs meaning that there are 159×5 potential energy paths at Stage 2. Therefore, the total amount of potential energy paths for all upstream stages is $3(53) + 3(53)^2 + 3(53)^3 + \dots + 3(53)^n$. The matrix of total requirement coefficients is calculated up to stage nine for this paper. Hence, there are millions of potential energy paths to be analysed.

To eliminate negligible paths a threshold value is used. The total energy intensity of a path is compared to the threshold value. The total energy intensity of a path is the sum of all the energy intensities further upstream of it. If the total energy intensity is below the threshold value then all upstream energy paths may be eliminated. This greatly reduces the number of upstream paths. An algorithm was developed by Treloar [6] which systematically checks each energy path, eliminating negligible ones. It runs a sensitivity analysis to check which I-O coefficients have significant direct and indirect effects. This algorithm is highly suited to programming and Figure 2 shows an example of a flow diagram for this algorithm.

Theoretically, the figure obtained from this method is more accurate than both the process value and the I-O value and the Process Based Hybrid method [6]. Crawford and Treloar [22] analysed an office building using each energy analysis method and found vast differences between the values obtained from each of the methods.

3. EMBODIED ENERGY IN REINFORCED CONCRETE

3.1 Introduction

Concrete is the most utilised substance in the world after water. In order to study the embodied energy (EE) in reinforced concrete it is necessary to have a comprehensive knowledge of the processes involved in its manufacture and of the production of its component materials. Concrete is divided into its constituent parts of aggregate, binders, water, admixtures and reinforcement. The path of contributing direct EE in concrete is illustrated in Figure 3.

Kennedy [12] performs a detailed process analysis on cement and aggregate using Irish data. These process values are used in the calculation of a Process Based Hybrid energy intensity for concrete.

3.2 Binders

Ordinary Portland Cement (OPC) is the most common binder used in concrete and can typically contribute to well over 50% of the embodied energy in concrete. Ordinary Portland Cement (OPC) is manufactured by combing, blending, heating and grinding together calcareous material, such as limestone or chalk, and argillaceous materials, limestone and shale that contain alumina or silica minerals [24]. The energy consumed in cement manufacturing process varies depending on process used [25], but is largely due to the high temperature at which limestone, clay and sand are heated in order to form clinker. Some industries put the cement industry total as high as 7% of total global anthropogenic CO₂ emissions [26].

However, with new technologies the cement industry is reducing its CO₂ emissions. For example, the Australian cement sector reduced its reportable CO₂ emission per tonne of cement produced by 20% between 1990 and 2007 [27]. Any further cuts are limited to the extent of which cement extenders can be used to still produce a material with the right stress and strength properties [26]. Van Puyvelde [26] believes that further reductions beyond that will require either a move away from a calcination process (i.e. not using a carbonate as a raw material) or to adopt the use of carbon capture and storage (CCS) for the cement industry. Since the move away from using carbonates unlikely, CCS is the only option available to the cement sector for deep cuts from cement production.

Gartner [28] carried out analysis that showed that the most promising low-CO₂ alternative cementing systems appear to be those that make use of large amounts of either natural or artificial pozzolans or those that effectively stabilise hydrated calcium sulfates (e.g., as ettringite).

One of the three most common recycled materials used as a binder is ground granulated blast furnace slag, GGBS; the others being silica fume and pulverised fuel ash [29]. GGBS contains lime, silica and alumina; the same minerals that cement contains except in differing proportions. However, GGBS has only slight cementitious properties and in conventional concrete, is used in combination with OPC whose alkalinity provides the catalyst to activate the cementitious properties of the GGBS. For this reason up to 85% of cement can be GGBS in place of Portland cement in concrete design mixes. Replacement levels vary, but are typically of the order of 40 - 50% [24]. GGBS is a by-product of the steel industry.

As will be seen from the case study, the use of this recycled material reduces the overall EE, and thus the embodied CO₂, of concrete. Furthermore, other studies have shown that greenhouse gas emissions are reduced by 40% using a replacement of 50% of cement with GGBS [30]. Concrete mixes containing GGBS yield a high ultimate strength and produce a lower heat of hydration [24]. This makes it ideal for thick sections where the temperature gradient resulting from the heat of hydration from Ordinary Portland Cement induces excessive thermal stresses. These thermal stresses may cause microcracking which exposes the concrete to external attack. However, a disadvantage is that as the GGBS content is increased, rate of early strength is reduced. This may be of concern to contractors when constructing concrete frames, as it may delay the time required for curing before striking of formwork can take place.

3.3 Aggregate

Aggregate constitutes up to 80% of a unit of concrete and serves to add strength to the overall composite. Sources of aggregate are: quarrying of sand, gravel and stone, and the recycling of concrete.

Natural aggregates originally formed part of a larger mass of rock. They are fragmented either naturally, by weathering and abrasion, or artificially. Quarries process stone by different methods. One common method is to remove the rock by drilling boreholes and inserting gelignite which is detonated, which

dislodges large volumes of rock. This aggregate material is crushed and screened before being loaded and conveyed to bins for storage. A typical aggregate is limestone. Its EE estimated using the process based hybrid method based on Irish data is $0.124MJ/kg$, as given in Table 4.

In recent years, aggregates from construction, demolition and excavation waste, have been recycled and used as partial replacements for natural aggregates in concrete. According to Collins [31] the jaw crusher is the most common method of reducing concrete to aggregate. It is important to remove contaminants before crushing [31]. Different types of materials are separated, ideally, before collection from the demolition site. On arrival at the recycling plant, the concrete is conveyed through the crushing machine, impurity levels are closely monitored to ensure that the concrete material has consistent strength and durability [31]. The aggregate is sorted by size with larger particles being crushed again as necessary [32]. Aggregates for concrete may require washing to remove dusty material [31].

Unlike deposits of sand, gravel and crushed stone, sources of recyclable aggregate are generally found in urban areas. This implies that production and sourcing cannot be increased with demand as its supply depends on the decay and demolition of structures. Quality and properties of recycled aggregate are highly variable.

In the new Wessex Water Operations centre project in the UK, the proportion of coarse aggregate replaced by recycled concrete aggregate (RCA) was limited to 40% [33]. An additional initial capital cost of using RCA on this project represented approximately 5–6% of the cost of the placed concrete [33]. Kwong [34] verified that recycled concrete aggregate can be used in the production of high strength and high performance concrete, stating that it is economically viable to do so in Queensland Australia.

There are two methods for including recycled material in an EE analysis; the *substitution method* and the *recycled content method*. The substitution method credits recyclability while the recycled content method credits recycling. The distinction between these two methods is crucial to achieving an accurate EE analysis. The recycled content approach takes into account any recycled materials in a product for example; ground granulated blast slag, GGBS, or recycled aggregate in concrete. The use of the substitution method means that the product being analysed will be credited with whatever the likely

percentage of it to be recycled is. An extreme case of this could see the EE of a concrete structure being drastically reduced as it may be recycled as aggregate at the end of its life. Hammond and Jones [10] believe that the recycled content approach better serves to accomplish the motivations behind energy analysis by giving a more realistic approximation of EE and where possible, these values are used.

3.4 Water

Combining water with cement, which contains silicates and aluminates, forms a binder by the process of hydration. Hydration involves many different reactions, often occurring at the same time. As the reactions proceed, the products of the cement hydration process gradually bond together the individual sand and gravel particles, and other components of the concrete, to form a solid mass [24].

Generally, water in concrete consists of that added to the mix and that which is carried by the aggregates. The quality of the water used in the production of concrete is very important. Impure water can cause problems during setting, adversely affect the strength of the concrete and may stain the concrete surface or cause corrosion of reinforcement. In general, potable water is specified as appropriate for use [29]. Often water is recycled many times in these processes by regular pumping and filtering. As a result, water has a relatively low impact on the CO₂ emissions of concrete.

In this study, the EE of water is calculated using I-O analysis. Water is accounted for in the 'water collection and distribution' economic sector. As water supply is the sole activity of this sector, the data is assumed to be accurate and for this reason, a Process Analysis is not required. The local authority provide information pertaining to the price of water in €/m³ charged to commercial customers. Table 2 displays the EE of water determined from this information using I-O analysis.

3.5 Admixtures

Admixtures are chemicals that are added to concrete to give it certain characteristics, which are not obtainable with the regular concrete mix. Admixtures are added in very small amounts during mixing. Because of the nature of their production, it is difficult to quantify energy involved in production of

admixtures. As they account for such a small part of a unit of concrete it is assumed that their contribution is almost negligible.

3.6 Energy analysis of concrete

In the manufacture of concrete, appropriate amounts of dry ingredients are thoroughly blended together. Next, water is added to make a stiff but workable mixture. The Process Based Hybrid method, as described in the previous section, is now applied using Irish data where possible. The application of this method required results from a Process and an Input-Output based analysis. It is first necessary to estimate the embodied energy of each of the constituent materials and add these to the direct energy required during the production of the concrete. Transportation of the ingredients and final product will also be accounted for in the analysis. The process data compiled by Kennedy [12] is considered to be highly accurate and relevant to Ireland and will be used, where appropriate, in this analysis. The application of the Process Based Hybrid Method requires the compilation of tables of the direct and total energy intensity of each of the 53 sectors of the Irish economy. These tables may be used to calculate the EE of any product manufactured in Ireland. With the application of a small amount of process data, the result obtained is thought to be reasonably accurate.

3.6.1 Input-Output Analysis

The Input-Output (I-O) direct and total energy intensities for concrete in Ireland is calculated using the 2005 National Input-Output tables and the price indices as published by the Central Statistics Office, CSO [17] [19]. The primary energy factors, *PEF*, and the disaggregation constants evaluated by Acquaye et al [8] in addition to the pricing information obtained from suppliers are applied in the following calculations.

Firstly, the matrix of direct requirement coefficients is determined from the matrix of total requirement coefficients published by the CSO [17]. Concrete is included in the economic sector “other non-metallic mineral products” [17]. The direct requirement coefficients for this sector were obtained from this table.

The data from Table 3 is used in conjunction with the direct requirement coefficients to assess the direct energy intensity of concrete.

The direct energy intensity of I-O sector n is

$$DEI_n = \sum_{e=1}^E D_{RC} \times C_d \times T_e \times PEF \quad (2)$$

and the total energy intensity of I-O sector n is

$$TEI_n = \sum_{e=1}^E T_{RC} \times C_d \times T_e \times PEF \quad (3)$$

where D_{RC} is the direct requirement coefficients (€/€), T_{RC} is the total requirement coefficients (€/€), C_d is the disaggregation constant (dimensionless), E is the total number of energy supply sectors, e in the I-O table, T_e is the average energy tariff (GJ/€) and PEF is the Primary Energy Factor (dimensionless).

The direct energy intensity for concrete is calculated using Equation 2 and the data contained in Table 3 to be 7.42MJ/€. Pricing information obtained for concrete, cement, aggregate and water relates to 2009. These prices are converted to 2005 prices using the price indices published by the CSO, a price deflator of 1.11 is calculated. Assuming the cost of concrete to be €72/m³ in 2009, and the density of concrete to be 2400kg/m³, the associated EE of concrete is evaluated to be 0.201 MJ/kg. The total energy intensity for concrete is calculated to be 11.01MJ/€. Using the same assumptions as above this is converted to relevant units. The resultant total embodied energy, EE of concrete is calculated to be 0.298MJ/kg. Consequently, the indirect EE of concrete is found to be 0.142MJ/kg. This is 49% of the direct EE. A Process Analysis does not account for a major proportion of the indirect EE. The above example illustrates how significant the indirect energy intensity may be.

3.6.2 Process Based Hybrid Analysis

The application of this method required results from a Process and an Input-Output based analysis. The Process Based Hybrid embodied energy of a product is:

$$EE_t = \sum Q_M \times W \times EI_M + DEI_n \times \epsilon_{BP} \quad (4)$$

where EE_t is the total EE through process based hybrid analysis, Q_M is the quantity of the material, W is the wastage multiplier of the material, EI_M is the energy intensity of the material from Eqn 1, DEI_n is the direct energy intensity of I-O sector n from Eqn 2, and ϵ_{BP} is the basic price of the product.

Assuming that the main contractor is responsible for the ordering and pouring of concrete the wastage factors W for concrete and reinforcement are 4.86% and 5.0%, respectively. The EE of concrete using Process Based Hybrid Analysis is calculated as

$$EE_t = Q_{Cem} \times EI_{Cem} + Q_{Agg} \times EI_{Agg} + Q_{H2O} \times EI_{H2O} \times (+W) \times \frac{DEI_{Con} \times \epsilon_{BP09}}{\rho_{Con} \times PD} \quad (4)$$

where Q_{Cem} , Q_{Agg} , Q_{H2O} are the proportions of cement, water and aggregate respectively; EI_{Cem} , EI_{Agg} and EI_{H2O} are the EE of cement, aggregate and water calculated using Eqn 1 respectively; W is the wastage multiplier of the material; DEI_{Con} is the direct energy intensity of concrete calculated using I-O analysis from Eqn 2; ϵ_{BP09} is the cost of concrete in 2009; ρ_{con} is the density of concrete; PD is the price deflator from 2009 to 2005.

Using Equation 4 and mix proportions of 12%, 82% and 6% of cement, aggregate (and sand) and water, respectively, the EE of 30MPa concrete is 1.08MJ/kg. However, this figure does not include transport, reinforcement, pouring of concrete or dismantling at end structure's life. It is a cradle to gate figure as defined by Hammond and Jones [9].

3.7 Transport

A concrete ready mix truck generally carries either $6m^3$ or $8m^3$. Table 5 gives the kerb weight and the fully loaded mass of $6m^3$ and $8m^3$ capacity ready mix truck [36], assuming a density of concrete of $2400kg/m^3$. The kerb weight of a vehicle is the mass of the vehicle at rest with all standard equipment, all necessary consumables, a full tank of fuel, allowing for a 75kg driver while not loaded with cargo (EU Commission Directive 95/48/EC, 1995) [37].

Kennedy [12] calculates the energy usage by various vehicles types for various road types (see Table 6). Due to the very high mass of concrete ready mix trucks the values of energy usage for trucks and trailers in Table 6 are considered appropriate to the outbound journey. Conversely, the value for energy usage of trucks will be used for the return journey as the concrete has been unloaded. In both situations the mean of the five values is deemed applicable. The energy required to transport concrete is $11.04 MJ/km$ for the outbound journey and $8.42 MJ/km$ for the return journey. The majority of concrete batching sites in Ireland have an on site quarry. This is due to the expense of transporting the aggregate from the quarry to the batching plant. All calculations are completed on this assumption.

The total time between the beginning of the mixing of the concrete and the final pouring of the concrete should not exceed 90 minutes [38]. After this the quality of the hardened concrete will be impaired. Orlowski [38] presents two possible rates of pouring, $0.25 m^3/min$ and $0.33 m^3/min$. Taking the mean of these, a $6 m^3$ capacity truck will take 21 minutes to unload. Assuming that the time to mix the concrete is negligible, the truck travels at an average speed of $50 km/h$ and the truck is waiting to unload for 5 minutes, then the maximum distance that concrete may be transported is $53 km$.

In the case of a $6 m^3$ capacity truck travelling the calculated maximum distance of $53 km$ to site and returning empty to the batching plant, the energy consumed is $53 * 11.04 + 53 * 8.42 = 1031 MJ$. As this truck can carry 14400 kg of concrete, this converts to $1031 / 14400 = 0.072 MJ/kg$, representing less than 6% of the Process Based Hybrid Analysis EE value for concrete. Although the transport data does not distinguish between the type of truck or the mass of the truck it is regarded as providing a reasonably accurate indication of the energy consumed during the transportation of concrete. Therefore, the maximum increase in EE of concrete due to transport is 6%, assuming that the ready mix truck is full to capacity. Transport may significantly increase the EE of concrete if partial loads are required.

3.8 Reinforcement

All steel reinforcement manufactured in the United Kingdom is made from 100% recycled scrap metal [39]. Although all reinforcement used in Ireland is sourced in the UK, it is bent and cut in Ireland. Hammond and Jones [9] provide a value for the EE of reinforcement steel. Transport and further

processing of the steel must be accounted for in order to make this figure more accurate. For the purposes of this analysis the energy used to cut and bend the steel is assumed to be negligible considering the high energy use in recycling the steel. Wastage of reinforcement at the bending and cutting facility is, however, not negligible. The standard bar length is 14m. After the bar is cut there are normally sections of bar remaining which are too short to be used. As there is no facility in Ireland to recycle these, they must be returned to the UK for further processing. This analysis will assume that 15% of the steel is returned for further processing.

The value of EE for recycled steel given by Hammond and Jones [9] is 8.8 MJ/kg compared to 36.4 MJ/kg for virgin steel. Assuming that a fully loaded truck can carry 24,000 kg of steel [36] the energy used in transport is $11.044 \text{ MJ} / \text{km} / 24000 = 0.00046 \text{ MJ}/\text{km}/\text{kg}$ steel for the outbound journey and $8.42 \text{ MJ}/\text{km}/24000 = 0.00035 \text{ MJ}/\text{km}/\text{kg}$ steel for the return journey. Assuming a total return journey length of 900km from the steel recycling facility in the UK to site (via the processing facility in Ireland) the energy required to transport the steel is $450\text{km} * 11.044 \text{ MJ} / \text{km} / 24000 \text{ kg} + 450\text{km} * 8.42 \text{ MJ} / \text{km} / 24000 \text{ kg} = 0.365 \text{ MJ} / \text{kg}$. This is 4.1% of the cradle to gate value for recycled steel.

3.9 Summary

The results of the above calculations are summarised in Table 7.

4. CASE STUDY

A 3-storey office block located in Galway city in Ireland will be used as an example calculation of the embodied energy, EE, in a typical reinforced concrete flat slab. The building chosen consists of a 5 x 5 grid with each panel spanning 7m x 5m. For this study, the loadings on all slab panels and the roof are equal and the mass of reinforcement is assumed to be approximately equal in all panels. This assumption is reasonably accurate, as the first internal panel contains less steel than the external panel, but more than the middle internal panel. The batching plant chosen for this case study is a batching plant, which is located 11km from the case study building.

A 40MPa concrete mix is used. A comparison is made using two mix designs. The first contains a binder solely of Ordinary Portland Cement (OPC), while in the second mix design 50% of the OPC is replaced with GGBS. . The resulting EE of the two mixes will be compared to highlight the positive effect its introduction can have in reducing the EE of a concrete structure.

The results of this study are displayed in Table 8. The total EE of the building is calculated by multiplying the total EE per panel by the total number of panels in the building. In this case, for a 3-storey building with 5 x 5 panels at each floor, the total number of panels is 75. The EE value calculated is for the superstructure slab only and does not include the ground floor slab or foundations.

As can be seen from Table 8, cement is by far the greatest contributor to the total EE, even in the 50% GGBS mix. In fact, cement accounts for 60% and 43% of the EE in the mixes with 0% GGBS and 50% GGBS, respectively. Having said that, the EE of the case study building is reduced by 30% through the use of GGBS. The total energy saving achieved through the use of GGBS is 914GJ. Reinforcement is also a major contributor to the total EE, accounting for 15% and 21% of the EE in the mixes with 0% GGBS and 50% GGBS, respectively. The direct energy refers to the energy required to combine the cement, aggregate and water into concrete. As transport contributes relatively little to the total EE of the superstructure, it is assumed that any increase or decrease in the total distance travelled resulting from the use of GGBS is negligible. For the purposes of this calculation the distance that the GGBS is transported is assumed to be equal to the distance that the cement is transported to the batching plant.

In Ireland, 651g of CO_2 was produced for every kWh of electricity produced in the year 2004 [40]. Putting this into perspective, 914GJ of electricity represents 165 tonnes of CO_2 . Consequently, it is apparent that the potential environmental benefits of GGBS are significant. Due to the immense amount of energy consumed by reinforced concrete there is scope for significant energy savings to be achieved.

This case study highlights the large quantities of energy required to construct a reinforced concrete slab. The case study building chosen for this example is a three storey office block in Galway city with superstructure floor area of $2625m^2$. The floor slabs are designed using two concrete mixes of equal strength for comparison, one containing 0% GGBS and the other having a GGBS content of 50%. The

total energy required to construct the floor slabs in this building is 3064GJ and 2150GJ for the 0% and 50% GGBS mixes respectively. An energy saving of 1046GJ is achieved by using 50% GGBS, which equates to 165 tonnes of CO_2 .

5. CONCLUSIONS

Resource depletion and climate change have become topics of major concern, as it becomes more and more apparent to governments and the public alike that human development of the earth is not sustainable at its current rate. Amongst others, the construction industry is striving to achieve the difficult task of reducing the environmental impact resulting from its processes, while still providing a high quality product. Research is ongoing to develop methods of significantly reducing CO_2 emissions. The first step towards achieving this is to measure, monitor and review all energy use to understand energy demands.

This paper investigates the energy consumed in the production of reinforced concrete in Ireland. The process involved in the manufacture of concrete and reinforcement were analysed with the most energy intensive processes being identified. A detailed Process Based hybrid analysis was performed and the EE of a 30MPa concrete mix was found to be 1.08 MJ/kg. A case-study of a 3-storey office block in Galway city showed that by replacing 50% of the cement content with Ground Granulated Blast Slag (GGBS) a 30% reduction in the EE of the slab panels could be achieved. This large energy saving demonstrates the significant environmental benefits that may be achieved through the use of cement replacements.

Although 100% of reinforcement used in Ireland is manufactured from recycled steel, the EE of reinforcement still represents a considerable portion of the total EE of a reinforced concrete slab. EE of concrete could be further reduced by using recycled aggregates, as it was shown in the case study that natural aggregates accounted for up to 9% of the EE of concrete. Currently, recycled aggregates are only used in a small minority of reinforced concrete structures. Savage [33] has shown that recycled aggregates can be successfully used in the production of high strength concrete, even for architecturally finished concrete. Further affirmation of this is given by Kwong [34].

In this study, the Process Based Hybrid Method was used to assess the EE in reinforced concrete in Ireland. However, the Input-Output (I-O) Based Hybrid Method is the most accurate model developed to date. The Input-Output Based Hybrid method can be applied to Irish data. A significant amount of effort would be required to complete this and is beyond the scope of this paper. However, as mentioned previously, the increased completeness obtained through the use of this method is assumed to be negligible when applied to concrete. On the other hand Treloar [6] found this increased completeness to be considerable when applied to the construction industry in Australia. To improve the accuracy of the Input-Output Based Hybrid method for construction products in Ireland, the level of aggregation of the Irish economy needs to be reduced. The current level of aggregation allows for the detailed analysis of only a small minority of products. The availability of this data would enable researchers to perform accurate energy analysis on many products, with the identification of important energy inputs.

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Figure 1: Embodied Energy Analysis System Boundary (after Boustead & Hancock [14])

Figure 2: Algorithm for eliminating negligible paths [23]

Figure 3: Path of contributing embodied energy in concrete

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Table 1: Comparison of the various methods of assessing EE

Table 2: Calculation of the I-O Total Energy Intensity of Water.

Table 3: Primary Energy Factors, Average Energy Tariff, Disaggregation Constants and the Direct and Total Requirement Coefficients for Sector 45: other non-metallic mineral products [8] [17].

Table 4: Calculation of the Process Based Hybrid energy intensity of aggregate and cement

Table 5: Mass of loaded and unloaded ready mix trucks.

Table 6: Energy usage by vehicle type by road type [12].

Table 7: Summary of Embodied Energy and Energy used during transport

Table 8: Embodied energy of RC building in case study

Table 1: Comparison of the various methods of assessing EE

	Relevancy	Completeness	Ease of Application
Process	The results obtained are highly relevant to the product analysed.	Depends upon the level of detailed used in the analysis. Impossible to achieve system completeness.	Requires significant research into the target product.
Input-Output (I-O)	The results are very general, the average of an entire sector. Relevancy of analysis depends on whether a product is a typical output of its economic sector.	Systematically complete.	The most straightforward to apply. However, it requires manipulation of large amounts of data.
Process Based Hybrid	The process component is highly relevant, whilst the I-O component is generalised.	The system completeness is only applied to the components of the model upstream from the process analysis data.	Combined effort of Process and I-O methods.
Input-Output Based Hybrid	The process component is highly relevant, whilst the I-O component is generalised.	Systematically complete.	Requires major manipulation of data achieved by writing a computer programme. Results from a Process-based Hybrid Analysis are also required. Takes an immense effort and expertise.

Table 2: Calculation of the I-O Total Energy Intensity of Water.

Energy Supply Sector	Primary Energy Factor, PEF	Average Energy Tariff, T_e (GJ/€)	Disaggregation Constant, C_d	Total Requirement Coefficient, T_{RC} (€/€)
Peat	1.01	0.377	0.290	0.045
Oil	1.01	0.094	0.700	0.01
Electricity	2.90	0.034	0.755	0.057
Natural Gas	1.03	0.088	0.205	0.057
Renewable Energy	1.00	0.034	0.040	0.057
Total Energy Intensity, TEI (MJ/€)				9.72
Price €/m ³ (2009)				0.93
Price €/m ³ (2005)				0.838
Total Energy Intensity, TEI (MJ/m ³)				8.14

Table 3: Primary Energy Factors, Average Energy Tariff, Disaggregation Constants and the Direct and Total Requirement Coefficients for Sector 45: other non-metallic mineral products [8] [17].

Energy Supply Sector	Primary Energy Factor, PEF	Average Energy Tariff, T_e (GJ/€)	Disaggregation Constant, C_d	Direct Requirement Coefficient, D_{RC} (€/€)	Total Requirement Coefficient, T_{RC} (€/€)
Peat	1.01	0.377	0.290	0.034	0.045
Oil	1.01	0.094	0.700	0.004	0.01
Electricity	2.90	0.034	0.755	0.036	0.057
Natural Gas	1.03	0.088	0.205	0.036	0.057
Renewable Energy	1.00	0.034	0.040	0.036	0.057

Table 4: Calculation of the Process Based Hybrid energy intensity of aggregate and cement

	Aggregate	Cement
PEI_M (MJ/kg)	0.028	5.35
TEI_n (MJ/€)	137.52	11.02
TEI_M (MJ/€)	128.63	1.14
€/kg (2009)	0.012	0.09
€/kg (2005)	0.011	0.081
Embodied Energy, EI_n (MJ/kg)	0.124	6.15

Table 5: Mass of loaded and unloaded ready mix trucks.

Truck Capacity	Kerb weight (kg)	Mass of concrete (kg)	Total mass (kg)
$6m^3$	21515	14400	35915
$8m^3$	22350	19200	41550

Table 6: Energy usage by vehicle type by road type [12].

Route Type	Cars (MJ/10km)	Trucks (MJ/10km)	Trucks & trailers (MJ/10km)
1	18.6	83.3	110.5
2	18.6	83.2	110.4
3	18.6	86.5	111.8
4	18.6	85.5	111.0
5	18.6	82.7	108.5

Table 7: Summary of Embodied Energy and Energy used during transport

	Cement	Aggregate	Water	30MPa Concrete	Reinforcement
Embodied Energy (MJ/kg)	6.15	0.124	0.00814	1.08	8.08
Transport Outbound (MJ/kg/km)				0.000793	0.00046
Transport Return (MJ/kg/km)				0.000585	0.00035

Table 8: Embodied energy of RC building in case study

Embodied Energy (MJ)	0% GGBS	50% GGBS
Reinforcement	6121	6121
Aggregate	2556	2556
Cement	24377	12188
Water	15	15
Transport	428	428
Direct	7358	7358
Total Embodied Energy per panel	40855	28666
Total Embodied Energy	3064125	2139950

Figure1

