Application of exergy analysis in the environmental assessment of concrete structures

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ABSTRACT: Exergy analysis is a thermodynamic technique based on sound scientific and engineering principles: the first and second laws of thermodynamics, and provides a means of assessing and evaluating the impact of materials and processes on the environment. For materials, exergy is defined as the amount of work needed to produce the resource from common materials in the environment. A material generally has physical and chemical exergy components that are measured relative to the environment. This study demonstrates the applicability of exergy analysis in accounting for resource consumption of products. The exergies of raw materials and energy for concrete are computed from the cradle- to-factory gate phase. The results show that cement (CEM I) has the highest exergy value at 79.5% of the total exergy required for the production of 1m³ of concrete. This is followed by coarse aggregates (16.5%), fine aggregates from crushed rock (3.5%) and water (0.5%). In conclusion, exergy is found to be a suitable metric for resource consumption as it provides a common set of units to evaluate material and energy flows.

1 INTRODUCTION

1.1 Thermodynamic methods for evaluating resource consumption

The first and second laws of thermodynamics form a basis for conducting material and energy resource flows. Thermodynamic methods of evaluating resource consumption include mass and energy flows, life cycle assessment (LCA) (ISO 14040, 2006; ISO 14044, 2006), exergy analysis (Wall, 1977) and emergy analysis (Odum, 1996). The key differences between these methods are in the metrics they use to measure environmental impacts, in particular resource consumption.

1.2 Energy Analysis

Energy analysis is based on the first law of thermodynamics (FLT) (law of conservation of energy/mass) which states that mass can neither be created nor destroyed. In the construction industry energy analysis has been found appropriate in calculating the energy flows of materials e.g. cement and steel (Hammond and Jones, 2008) and, in selecting efficient heating, ventilating and air conditioning (HVAC) appliances in buildings (Holness, 2008). Energy (measured in MJ) can be applied as an indirect indicator of the volume of materials consumed (Keoleian & Spitzley, 2006). The higher the production of materials, the more energy is used. Energy as a metric for resource consumption is usually preferred due to the relative ease with which energy data are available. However, energy provides weak reflections of the environmental impacts of non-fuel materials e.g. mineral resources, metallic ores and renewable resources (such as water) and corresponding impacts on land use due to quarrying of materials. An energy analysis per se
does not account for consumption of non-energy resources such as water, hence other complimentary indicators are required to be applied if all the resources are to be accounted for. A material flow analysis (resource flow analysis) (Griffiths et al., 2003) is applied as a complimentary measure to cover impacts due to consumption of non-fuel resources.

1.3 Resource Consumption Metrics in Life Cycle Assessment

Both energy and material flow analysis are precedents of the LCA which considers waste impacts in addition to material and energy flows of a process. LCA applies two impact indicators for material flows: abiotic depletion potential (ADP) and surplus energy (SE) (Guinée et al., 2002). ADP is the ratio of present use of resources (specifically with energy and metallic minerals) to its reserve (Van Oers et al., 2000). However, it is difficult to know the stock size of the reserve. Further, the indicator assumes substitutability when aggregating all kinds of resources, be they fossil fuels or minerals.

Surplus energy is defined as the energy needed to extract a resource now compared to extracting the resource at some point in the future (Guinée et al., 2002). The drawback lies in estimating future conditions.

Strictly speaking, resource accounting indicators based on FLT i.e. energy balances are also not suitable indicators for resource consumption as according to the FLT, energy and matter are never destroyed but only transformed. Thus, the expressions “energy/material consumption”, should be considered redundant since resources are simply transformed from one form to another and not depleted (Wall, 1977). What is consumed and eventually depletes is the resource quality, quantified using an exergy analysis.

1.4 Exergy Analysis

The use of exergy analysis can potentially overcome the problems of accounting for non-fuel resources and the application of subjective weighting techniques when aggregating indicators in LCA. The term “exergy” was introduced in the 1950’s by Rant (1956) to represent the change in quality of resources (materials and energy) due to conversions from one form to another. Exergy consumption, represented by Equation 1 (Guoy-Stodola’s theorem) reflects the minimum amount of theoretical work needed to produce the resource from common materials in the environment or reversely, the maximum amount of work that can be extracted from a resource relative to its environment (Ayres, 1998; Bösch et al., 2007; Sciubba & Wall, 2007; Çengel & Boles, 2011).

\[ W_{lost} = E_x = T^0S_{gen} \]  

where: 

- \( W_{lost} \) - Work lost during a production process [J];
- \( E_x \) - Exergy of the product [J];
- \( T^0 \) - Temperature of surroundings (K);
- \( S_{gen} \) - Entropy generated according to the second law of thermodynamics [J/K].

Raw resources have high exergy values until processed or transformed at which time their exergy is lost as entropy. Thus, exergy is a measure of the usefulness of resources to the society and is based on the application of the second law of thermodynamics (SLT). For any particular process, exergy can be found in different forms: mechanical, physical and/or chemical component (Szargut, 1988). The mechanical component includes potential, kinetic and electric exergy. Physical component includes temperature and pressure exergy. Chemical exergy includes chemical reactions during processing and use of the product. A material generally has only the physical and chemical exergy components whereas waste emissions can have all three exergies. In order to calculate the total exergy of a process or material, all its exergy
components have to be determined separately. This study demonstrates the computation of chemical and physical exergies of raw materials for concrete production from the cradle-to-factory gate phase. This covers activities related to quarrying of raw materials and their subsequent processing.

Exergy is evaluated with respect to a reference environment which could be the atmosphere, the oceans or earth’s crust, and is defined at a standard temperature \( T_0 \) of 25°C (298.15K) and pressure \( P_0 \) of 1 atmosphere (101.325 kPa) (Szargut et al., 1988; Çengel & Boles, 2011). The most stable compound that occurs in the reference environment is selected as a reference species in exergy computations, for example \( O_2 \) for O and \( SiO_2 \) for Si. Chemical exergies of different compounds are documented in Szargut (1989), Finnveden & Ostlund (1997) and Rivero & Garfias (2006).

Although the basis of the exergy concept (SLT) was established as early as the 1800’s, it is only since the 1960’s that the concept has gained interest and has been applied in assessing the thermal performance of industrial systems e.g. power plants, industrial manufacturing processes such as steel (Michaelis et al., 1998), and cement (Koroneos et al., 2005). Recently, exergy has been proposed as an indicator for assessing the environmental effects associated with emissions and resource depletion in Dincer & Rosen (2007) and Ao et al. (2008). Subsequently, exergy analysis has been applied in construction studies mainly to evaluate the thermal efficiency of buildings (Shukuya & Hammache, 2002; Shukuya, 2009) and in assessing the environmental impact of manufacturing paving material (Berthiaume & Bourchard, 1999).

The objective of this paper is to demonstrate the application of exergy analysis in analyzing the environmental impact (resource consumption) of concrete. The „cradle-to-factory gate’ environmental impact of basic material components used in the production of concrete is evaluated.

1.5 Summary

The construction industry is in dire need of a comprehensive metric that can be used to select low resource (energy and materials) intensive materials for construction. Current resource accounting indicators are based on the first law of thermodynamics (FLT) i.e. energy balances and abiotic depletion potential (ADP) and surplus energy (SE) both in LCA. These metrics have been found to be unsuitable for their purpose as according to the FLT energy and matter are never destroyed but only transformed. Further, LCA applies subjective weighting techniques when aggregating the two indicators (i.e. ADP and SE) in LCA and energy analysis does not account for non-fuel materials. This study proposes the use of exergy as a suitable metric for resource consumption. A material generally has physical and chemical exergy components that are measured relative to the environment. This study looks at the chemical exergies of raw materials required for concrete production. The study relies on published data of chemical exergies of materials documented in Szargut et al. (1989) and Finnveden & Ostlund (1997).

2 Exergy Analysis

2.1 Study Boundary

The life-cycle of a concrete structure/element consists of four main phases: (i) the material production which involves raw material acquisition (e.g. limestone) and processing of materials (e.g. cement). This first phase also includes transportation of raw materials from the quarry to processing plants and within the plants; (ii) the construction phase includes all processes in the placement of materials on site. It includes impacts from construction equipment and the health effects on the construction workers and surrounding community (e.g. effect of noise, dust); (iii) use phase includes all interactions the structure may have with the environment and society e.g. CO\(_2\) absorption, thermal exchange (iv) demolition phase includes all the end-of-life strategies.
on the structure after demolition e.g. recycling/reuse of waste materials or their disposal to landfill sites.
The paper considers the „cradle-to-factory gate” phase of concrete which includes raw materials acquisition and their production processes.

2.2 Exergy analysis

2.2.1 Introduction

This section exemplifies the calculation of exergy of raw materials for concrete. Material requirements for the production of 1 m$^3$ of concrete (30MPa) are summarized in Table 1.

Table 1. Summary of material requirements for a 30MPa concrete beam

<table>
<thead>
<tr>
<th>Material requirements</th>
<th>Quantity (per m$^3$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Portland cement</td>
<td>336 kg</td>
</tr>
<tr>
<td>Sand</td>
<td>855 kg</td>
</tr>
<tr>
<td>Aggregates (19mm)</td>
<td>1,040 kg</td>
</tr>
<tr>
<td>Water content</td>
<td>185 kg</td>
</tr>
<tr>
<td>w/b ratio</td>
<td>0.55</td>
</tr>
<tr>
<td>28-day strength (MPa)</td>
<td>30</td>
</tr>
</tbody>
</table>

Amounts and type of materials required to make 1 m$^3$ of concrete are necessary for calculating the exergy of materials and energy used in the production process.

2.2.2 Exergy of materials and energy

Chemical exergy refers to the work necessary to produce one mol of an element in its standard state from the environment in a reversible way, heat being exchanged in the process only with the environment at standard temperature ($T^0$) (Szargut, 1988).

A chemical exergy analysis of materials is carried out in the following steps:

(i) Raw material flows for production of 1m$^3$ of concrete are quantified.

(ii) The chemical exergy value of each raw material ($E_{chem}^x$ in MJ) is then computed using Equation 2 (Wall, 1977):

$$E_{chem}^x = \left[ G_f^0 + RT^0 n \ln(c) \right]$$

where: $G_f^0$ - Standard Gibbs energy of formation; $R$ - 8.314 Jmol$^{-1}$k$^{-1}$; $T^0$ - 298.15 K; $c$ - concentration of the material [J]; $n$ - number of moles and; $c$ - molar concentration of the element/compound in the environment.

Information on Gibbs energy of formation and the standard chemical exergies of elements forming the materials is documented in Atkins (2001), Szargut, (1989) and Finnveden & Ostlund (1997).

Determining exergy of a fuel($E_{fuel}^x$) involves calculating the maximum amount of work obtainable form the fuel. $E_{fuel}^x$ is in fact, energy multiplied by a quality factor as shown in Equation 3 (Szargut, 1988). Exergy is in essence a compliment of the energy method.
\[ E_{x}^{\text{Fuel}} = \left( 1 - \frac{T_o}{T_p} \right) Q_p \]  

where: \( Q_p \) - Energy from the heat source in [MJ], \( T_p \) constant temperature of the heat source and \( T_o \) is the reference temperature of the environment taken as 298.15K.

The total exergies of raw materials and fuels required in the „cradle-to-factory” phase of concrete are summarized in Table 2.

Table 2. Inventory of standard exergies of elements and compounds in the raw materials

<table>
<thead>
<tr>
<th>Resources</th>
<th>Exergy content</th>
<th>Total exergy content</th>
<th>Exergy for 1m³ of concrete</th>
<th>Percentage of total exergy</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Exergy</td>
<td>Exergy</td>
<td>Mass per m³</td>
<td>Exergy of concrete (MJ/t)</td>
</tr>
<tr>
<td></td>
<td>(MJ/t)</td>
<td>(MJ/t)</td>
<td>(t)</td>
<td>(MJ)</td>
</tr>
<tr>
<td>Portland cement</td>
<td>Materials</td>
<td>1,434</td>
<td>5,089</td>
<td>1,709.9</td>
</tr>
<tr>
<td></td>
<td>Energy</td>
<td>3,655</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fine aggregates (Sand)</td>
<td>Materials</td>
<td>31.6</td>
<td>87.41</td>
<td>0.855</td>
</tr>
<tr>
<td></td>
<td>Energy</td>
<td>55.81</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Coarse aggregates (Granite)</td>
<td>Materials</td>
<td>286.6</td>
<td>342.41</td>
<td>1.040</td>
</tr>
<tr>
<td></td>
<td>Energy</td>
<td>55.81</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Water content</td>
<td>Materials</td>
<td>50</td>
<td>60</td>
<td>0.185</td>
</tr>
<tr>
<td></td>
<td>Energy</td>
<td>10</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total exergy of raw materials and energy necessary to produce 1m³ of concrete (MJ/m³)</td>
<td></td>
<td></td>
<td></td>
<td>2 151.85</td>
</tr>
</tbody>
</table>

The total exergy of the raw materials used in the production of 1 m³ of concrete was computed as 2 151.85 MJ. This means that it takes at least 2 152 MJ of work to produce 1 m³ of concrete from components that are thermodynamically stable on earth (in this case all raw materials and energy for cement production, aggregates and water).

Cement is credited for the highest consumption of raw materials at 79.5 % of the total exergy, followed by coarse aggregates (16.5 %), fine aggregates from crushed rock (3.47 %) and water (0.5 %).

The knowledge of chemical exergies of raw materials value can enable the following:

1. Comparison of resource consumption of different materials in the same units. The measures are also made relative to the earth’s environment and are thus linked to sustainability.

2. The exergy analysis gives not only the mass of raw materials (i.e. quantity) but also their quality expressed as exergy content and is therefore an improved measure compared to traditional mass balances.

3. A further applicability of exergy is its ability to account for both fuel and non-fuel resources using one set of units (MJ). This avoids subjective weights setting in the evaluation of resource consumption.

However, there are questions on the quality of data used in the analysis. The exergy values, adopted from Szargut (1988) are derived for a particular reference environment (\( T^o \) of 25°C and pressure \( P^o \) of 1 atmosphere). The values also relate to a certain composition of rock. However, these values may change depending on geographical locations and a petrologic examination is
required for determining the composition of ores or rock in a particular region. Uncertainties due to variations in measurement errors and use of out-of-date data need to be included.

The study covers the exergy of the raw materials and energy for the „cradle-to-factory gate“ phase of concrete. In order to compute the total exergy of concrete there is need to make further computations on the „gate-to-grave“ phase.

2.2.3 Conclusions

The study shows the application of thermodynamic principles in assessing resource utilization. The exergies of raw materials and energy used in the „cradle-to-factory gate“ of concrete were computed. The results showed that cement (CEM I) has the highest exergy value at 79.5 % of the total exergy, followed by coarse aggregates (16.5 %), fine aggregates from crushed rock (3.5%) and water (0.5%).

2.2.4 References