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LIMITATIONS OF LIFE CYCLE ASSESSMENT OF GREEN CONCRETES - A STATE-OF-THE-ART REVIEW

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Abstract.
There have been numerous researches focusing on the alternatives to conventional concrete regarding environmental benefits and trade-offs. For this purpose, nowadays, the Life Cycle Assessment (LCA) is widely used. Until now, LCA results of conventional and green concretes have shown some limitations, and this paper focuses on addressing them. Firstly, the researches have been mostly based on a small number of concretes, which can limit the possibility to quantify the range of emissions for different set of assumptions. The second one is regarding the appropriate selection of functional unit where a divergence between different researches is visible. Moreover, it has been recognised that the criteria involved in the investigation of transportation might lead to the variation of results. Also, inventory allocation has to be assessed in detail to reach adequate distribution of the environmental impact of the concrete during its life cycle phases. Finally, CO_2 uptake of the concretes throughout the life cycle should be considered and applied adequately to have representative results of overall CO_2 emissions. It is expected that the differences will depend on construction practices among the countries where the researches are executed. Also, the results will surely vary between different system definitions when LCA is applied.

Keywords: CO_2 uptake, environmental impact, functional unit, green concrete, inventory allocation, life cycle assessment.

1. Introduction

Sustainable development has got numerous definitions, Parkin recognised around 200. This reflects the complexity of the concept and its interpretation as well as possible ways of achieving it. However, it is for sure that it should include economic, environmental, and social dimensions. [1] On the other hand, it has been acknowledged that the structures become sustainable when at least one whole life cycle is assessed and both environmentally beneficial manufacturing processes and deconstruction concepts incorporate the development of circular economy solutions. These solutions are usually based on recycling and reuse of construction and demolition waste (CDW). [2]

Although the construction industry is one of the most significant for the economy, it carries the burden of one of the most harmful to the environment. The contribution of it to the gross domestic product (GDP) is about 9%, and it is providing 18 million direct jobs through around 3 million enterprises in the European Union (EU). On the other hand, the negative effects of the industry are numerous, including dust and gas emissions, land depletion and deterioration, energy and non-renewable natural resources consumption, noise pollution and CDW generation. [3] The construction industry is accountable for the consumption of 50% of natural raw materials, 40% of the energy produced and the generation of 50% of global waste. [4] In countries of Organisation for Economic Co-operation and Development (OECD) and EU buildings contribute to about 30% of total primary energy consumption and more than 30% of greenhouse gas (GHG) emissions. [5] Kofoworal and Ghewaala investigated a typical concrete office building in Thailand based on life cycle energy (LCE) analysis and concluded that operation phase contributes 81.3% to the building's LCE profile. While the manufacturing of the materials was responsible for 16.8% where steel accounted for 42% and concrete for 35% of the initial embodied energy, respectively. The construction, demolition and maintenance phases values were equal to 0.6%, 0.4% and 0.8%, respectively. However, it was recognised that recycling of building materials can contribute about 9% to energy savings. [6] Consequently, sustainable construction has been a focus of research for many decades. In that sense focusing on designing, building, and occupying more sustainable structures would benefit all three beforementioned dimensions of sustainable development. Regarding the environmental aspect of sustainable development, it would lead to improvement in air and water quality, reduction in energy and water consumption, as well as in waste disposal. On the other hand, economic benefits would incorporate a decrease in operating and maintenance costs and an increase in revenue due to sale price or rental. Finally, in a social sense, the enhancement of the occupants' comfort and health, reduction in absenteeism, turnover rate and liabilities would be included. [7]

In the case of the construction industry, it has been recognised that sustainable development should be based on a decrease of raw materials, energy and amount of CDW being landfilled. [8] There are significant economic, environmental and social impacts of CDW landfilling. It can reduce the value of the land stock in the area, it can result in the contamination of soil and groundwater due to CDW's composition and finally put public health at risk. [9] Recycling has been recognised as a good practice that includes the reduction of landfilled CDW and the consumption of both energy and raw materials. As a result, recycled aggregate (RA) has been investigated and more widely used in the construction industry. [8] However, all possible alternatives to the conventional concrete should be investigated regarding environmental benefits and trade-offs. For this purpose, nowadays extensively used Life Cycle Assessment (LCA) is applied. [10] Although until now many methods have been developed focusing on the evaluation of the environmental impact (EI), LCA is the most widely used mainly because of its effectiveness to calculate the potential effects that a product, process or service has or may have on the environment during its whole life cycle. [3]

2. Green concrete

By definition, green concrete is concrete which uses waste material as at least one of its components, or its production process does not lead to environmental destruction, or it has high performance and life cycle sustainability. [11] In the EU one-third of total waste generated is CDW, making it the largest waste stream. [12] CDW may be resulting from construction activities, natural hazards, demolition or rehabilitation works. Furthermore, the most substantial amount is corresponding to demolition and rehabilitation works. Around 40 to 50% of CDW is made of concrete, asphalt and brick. [9] The most widely used building material in the construction industry is concrete. [13] Moreover, it is the second most utilized material after water. In 2009 on a global level, it is estimated that between 13 to 21 billion tons of concrete are produced annually. [4] Only in EU in 2018 total concrete produced was about 320 million cubic meters. [14] Moreover, concrete plants globally consume 1 billion tonnes of water, 1.5 billion tonnes of cement and 10 billion tonnes of aggregate annually. [9] These numbers are expected to rise in the future as the production of concrete is expected to increase due to the rise in population and urbanisation. By the increase in the production of the concrete, consumption of natural aggregate (NA) as concrete's largest constituent raises accordingly as well. In the countries of EU annual production of aggregate is equal to three billion tons. [13] Out of this value, about 45% is used in concrete. [3] Hence, the challenge of the availability of NA's sources has been present, which resulted in the placing of the taxes on the use of NA in the case of many European countries. [13]

The recycling rate of CDW in EU is on average 83%. [15] There is a significant difference regarding this value among countries since some of the countries have established this practice for years and others have still a very low rate. [16] Worldwide countries have adopted the strategy of management of CDW expressed by "3R" (reduction, recycling and reuse). Moreover, the EU proposed that the best practice would be for preventing the production of waste. Possible solutions to the reduction of CDW production are improving materials which are energy and environmentally efficient, usage of high-performance materials (resulting in the reduction of the amount of material used) and enhancing the durability of buildings (resulting in the increase of the life span of the raw material used). [2] On the other hand, the percentage corresponding to the CDW compared to the total utilisation of aggregate differs between countries, but there is no case where it can completely replace the use of NAs. [16] CDW is recognised as one of the most significant solid waste streams and recycling of it into useful components of concrete is seen as an important part of sustainable development. However, there has been extensive research on the inclusion of different types of industrial waste into green concretes either as an aggregate or a binder. The precondition to the usage of such materials is their environmental acceptability and technical adequacy. [10] Recycling of CDW can have benefits in reducing the amounts of it disposed to landfills and the preservation of natural resources. This potential can be enhanced if the RA is not just applied to lower quality products but also as a component of structural concrete. Even though the research has been extensive in the area of RA, its usage for higher quality products has not been widely recognised. Due to some national practices, RA is used for granular base or sub-base applications, embankment construction and earth construction works. [13] Moreover, in the researches made, it was shown that NA could be successfully substituted by RAs in producing concrete that fulfils the requirements for structural use. On the other hand, the application for structural purposes has been recognised as feasible in the both commercial and technical sense. [17]

Waste recycling has been largely developed for about three decades now. As a result of this activity, many regulations have been established. As an example, The EU directive defines some conditions that waste must fulfil to be considered as a by-product. These conditions are:

- Further usage of the object or substance is definite;
- The object or a substance is generated as an integral part of a production process;

- The object or substance is usable excluding any further processing other than usual industrial practice;
- Further usage is legitimate meaning that it fulfils all necessary environmental, health and product requirements for that specific use and would not cause overall negative environmental or human health effects. [18]

Moreover, the design and process of recycling should take into account the saving of raw materials and energy and decreasing the potential of environmental pollution. Consequently, recycling and reuse of CDW offer an important opportunity for sustainable development in the construction industry. [2]

3. Life cycle assessment

Back in the late 1960s and early 1970s, environmental issues were addressed extensively, such as resource and energy efficiency, pollution, and solid waste. During that period, studies on EI of consumer products also started which were mainly based on simple principles to be able to compare two products. As a result of this soon enough, it was recognised that the biggest EI is not connected to the products' use but rather to its production, transportation, or disposal. While these studies were evolving, there was a need for standardisation of the assessment tool, which would be widely applied. Finally, the International Organization for Standardization (ISO) published ISO 14040 (2006) and ISO 14044 (2006) standards. Based on these standards, the methodology consists of four main steps which are the definition of a goal and scope, the inventory analysis, the impact assessment and the interpretation [3].

LCA is a methodology used for evaluation of the environmental burden of the processes, products or services throughout their life cycle. [13] In the case of green concretes, LCA can be a useful tool for generating indicators regarding EI in source separation, waste treatment and recycling technologies. However, it was recognised that aggregates' recycling differs between developing and developed countries in terms of production and transportation methods. Moreover, resources availability can vary among countries. For example, in the case of China, the shortage of resources has become a serious issue currently, and the possibility of alternatives to conventional concrete is of significant importance. Furthermore, source locations are mainly on a longer distance from urban areas which then puts a greater environmental burden on conventional concrete [8]. On the other hand, many European countries have been employing regulations to answer to the decreasing availability of the NA resources such as placing taxes on the use [13]. As well as focusing on recovery of CDW by implementing the Waste Framework Directive 2008/98/EC aiming at 70% recycling rate by 2020 [12].

3.1. Quantity of concretes

One of the limitations that have been acknowledged considering the LCA of conventional and green concretes is that the researches are based on a small number of concretes. The range varies mainly between 3 to 18 mix designs. [4] Moreover, the researchers mainly focused on the certain green solution of concretes, generally considering recycled concrete aggregate substitution to NAs. It has been concluded that overall there are five types of green concrete on which the researches have been focused:

1. Recycled aggregate concrete (RAC) for which as aggregates, RAs generated from CDW are used;
2. Blended cement concrete in Ordinary Portland Cement (OPC) in the binder is replaced with a variety of supplementary cementitious materials;
3. Alkali activated concrete where no OPC is used but materials which are rich in alumina and/or reactive silica;
4. High performance concrete which is considered as a concrete of improved mechanical and durability properties compared to one generated using OPC;
5. Bio-concrete which is produced mainly using various bacteria. [19]

These five types of concrete can have a beneficial behaviour in EI sense compared to traditional concrete.

Furthermore, most of the researchers have used the conventional mixture design method in case of RAC, which is based on replacing a certain percentage of NA with RA based on equivalent volume or mass [20]. In advance, it has been noticed that the amount of cement is increased in RAC mixes to achieve those properties of natural aggregate concrete (NAC) [21]. Eventually, this could lead to more CO_2 emissions. This is why researchers worked on developing some alternative mix design methods that could lead to improved performance of RACs and better and fairer comparison to NAC. The alternative to the classical approach of mixture design in the case of the RAC, equivalent volume mortar method (EMV) has been proposed. This method is based on the fact that RAC is two-phase material including NA and mortar, so it seeks to use the same amount of total mortar volume in mixtures of both NAC and RAC [22]. Other than mixture design methods, the development of the different mixing methods mainly based on the sequential mixing approach in order to improve properties of RAC have been introduced [23]. Furthermore, there have been just a few researches regarding the effect of mixing methods on LCA of RAC, which can lead to possible better performance of green concretes on both material and LCA level.

3.2. Functional unit

Another limitation, the functional unit (FU) is used as a key factor influencing LCA. FU is a quantified performance of a product system for use as a reference unit. [24] As the definition implies, it is an important factor for comparison of LCA results for investigating alternative solutions for a certain product. That applies to the production of concrete also. So, many researchers based their LCA of green concretes on the functional units (FUs). However, the selection of FUs differs, including volume of concrete, combining two or more variables such as volume and strength; volume, strength, durability; and strength reliability. The biggest disadvantage of having different FUs in the conducted researchers is that these results can not be compared. [25] By many researchers volume of concrete as a FU was found as not reliable since it does not take into concern that for 1 m3 NAC and RAC compressive strength results are not equivalent. On the other hand, FU per strength, which combines both volume and strength, neglects the durability properties of the concrete. [26] However, it has been recognised that FU has to incorporate the workability, strength and durability/service life differences between investigated concretes. [3]

3.3. Transportation

Non-renewable energy consumption and global warming potential (GWP) as EI in the case of concrete significantly depend on the transportation scenarios. [27] Ding, Xia and Tam showed in their study based on data in China that aside from cement proportion, transportation is the top contributor to the CO_2 emissions and energy consumption for both conventional and RAC. In the conducted sensitivity analysis, it was concluded that longer delivery distances for NA lead to the possibility of decreasing EI of RAC. So, by increasing the replacement ratio of NA by RA, there is a possibility of reducing the negative EI of concrete. [8] On the other hand, Marinković et al. based their LCA in Serbia, and the results showed that the total EI of conventional and RAC depend on the NA and RA transport distances and types. Since the EI of the aggregate and cement production phase gave slightly disadvantageous results for RAC compared to conventional concrete in their research, the transportation phase was recognised as a possible source for reducing the EI of RAC. [13] Knoeri, Sanye-Mengual and Althaus examined RAC mixtures according to laws, standards, and construction practices in Switzerland. They concluded that the additional transportation distances more than 15 km result in higher EI for RAC than conventional concrete. Based on the present market mixtures in Switzerland, the beneficial results can be expected for RAC compared to conventional one if supplementary cement and transportation are kept limited. [28]

3.4. Inventory allocation

Life Cycle Inventory (LCI) corresponds to the collection of data, all inputs and outputs of the considered life cycle phases. [9] In green concretes, the research should adequately address inventory allocation for the recycled and/or reused products. For RA, this allocation is important to be suitably distributed between waste management and material production. [4] In general, for the inventory analysis for LCA information can be collected from industries involved usually by questionnaires, publicly available annual environmental reports (ERs), and environmental product declarations (EPDs), LCA related journals and LCA databases (e.g. Ecoinvent, GaBi). The most precise data can be obtained from questionaries. However, generally all the data can not be collected this way, so alternative beforementioned sources are also used. [3] When it comes to waste recycling, the main issue of the LCA is the allocation process. In the present practice to the waste production, no environmental burdens are assigned, if we disregard waste disposal, because it is not generated on purpose. But when we consider waste as a by-product, it has been recognised that some allocation coefficient has to be applied. However, there is no consensus on the correct allocation procedure in this case in the previous researchers. So, it rather relies on the choice of the researcher, and since it can have an important effect on the results, it is one of the most debatable issues in LCA of green concretes. According to the abovementioned ISO standards when there is a possibility of several allocation procedures, it is recommended to conduct a sensitivity analysis demonstrating the impact of different choices. [18]

3.5. CO_2 uptake

To evaluate the portion of GHG that concrete is responsible for, it has been acknowledged that it is needed to adequately cover the net balance of GHG in the use of concrete as a construction material. This implies that CO_2 uptake throughout the whole product life cycle shall also be considered. So, as the emissions are emerging by the concrete production, there is a parallel CO_2 uptake process going on in the already produced concrete. However, when the uptake is considered, there is one corresponding to primary concrete product (i.e. concrete used in the construction of the structures) and the secondary resulting from demolishing and crushing the primary one. This secondary product can be landfilled, used as a road base material or RA in green concretes. [29] If the CO_2 uptake is not considered in the LCA of concrete, it can lead to the overestimation of the emissions. CO_2 is absorbed during the carbonation of the concrete during both the primary and secondary product phase. [4] Collins proposed the formula for the calculation of CO_2 uptake from the atmosphere:

$$\mathrm{CO_2}_{\text{uptake}} = x \cdot \mathrm{c_{OPC}} \cdot \mathrm{CaO} \cdot r \cdot A \cdot M \qquad (1)$$

Where x corresponds to calculated depth of carbonation equation (2), c_{OPC} is amount of OPC in binder and CaO refers to calcium oxide content of

OPC. While r is a fraction of CaO in fully carbonated OPC, A denotes surface area of the exposed concrete and chemical molar proportion of CO_2/CaO is assigned by M. Moreover, carbonation depth can be calculated using the following formula:

$$x = k\sqrt{t} \tag{2}$$

Where k is carbonation rate coefficient which covers the chemical and physical characteristics of the concrete and environment (can be determined experimentally or measured on the structure) and t is exposure time. [30]

From the above-presented equations, it can be concluded that the CO_2 uptake is dependent on the properties of the concrete such as cement content, CO_2 in the atmosphere which relies on the exposure condition and diffusion process between the atmosphere and the concrete effected by the exposed surface. [4] Full carbonation of the concrete, hence, can lead to a substantial reduction in the GWP. However, this complete carbonation does not seem like a realistic outcome, since by researchers 75 % has been concluded as a maximum value. [31] Moreover, just 11 % of theoretical maximum CO_2 uptake has been recognised as possible during the primary production phase. [29] However, when concrete is considered as a part of the CDW, demolishing and crushing results in the smaller particle size henceforth larger exposed surface area. [31] Further investigation has to be conducted regarding the CO_2 uptake for green concretes, especially when RA is an ingredient of it.

4. Conclusions

LCA is the standardised tool for determining EI of a product or process, and it has been the most widely used one for this purpose. Some limitations have been recognised when it comes to its applicability to the evaluation of concrete's performance. This is especially the case when alternative solutions to conventional concrete are assessed. Although the research in this field has been present for some decades now, there are some parts of the LCA of the concrete where consensus between researchers has not been made. Consequently, the large-scale assessment of the EI of concretes, especially green concretes is scarce. In further researches, special attention should be paid to incorporating a larger quantity of investigated concretes. It is essential to investigate different mix design methods, especially since they may offer better performance in both material and LCA sense for green concretes. On the other hand, one of the most critical questions when concretes' LCA is conducted is FU. The variety of FUs used in research leads to the limited possibility of comparing the results of the different studies. This is one of the main issues on which consensus should be made to have a more precise picture about EI of concrete.

As expected, transportation takes a significant portion of the GWP of concrete. Moreover, after the cement production phase, it is the most influential factor. The results showed that by reducing the transportation distance for RA compared to NA beneficial results can be conducted in the case of green concretes. In LCA of any product or process, inventory allocation is a very important phase. It can lead to significantly over- or underestimated results if not adequately conducted. Moreover, in the case of green concretes, special attention has to be paid to the usage of materials as by-products. Finally, to have representative results of GHG emissions of the concrete adequate net balance calculation has to be made. In that sense, CO_2 uptake takes a significant role. It is of great importance to consider both primary and secondary (one emerging after demolishing and crushing of the first one) product's CO_2 uptake. CO_2 is absorbed during the carbonation of concrete as both primary and secondary product. If this net balance is not appropriately calculated, the results lead to overestimating GHG emissions of concrete. To sum up, LCA of alternatives to conventional concretes require more detailed evaluation to have representative results. Further investigations for sure have to be conducted, which will focus on the abovementioned limitations for improving the LCA tool for the evaluation of concrete.

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