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COMPARATIVE LIFE CYCLE ASSESSMENT OF DIFFERENT RECYCLED CONCRETE AGGREGATES

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ABSTRACT
Concrete is recognized as the second most consumed materials in the whole world. Therefore, applying circular solutions to concrete, like recycling or reusing can guarantee a considerable benefits in terms of environmental impacts. In this paper, a comparative life cycle assessment is done for different recipes of recycled concrete aggregates in comparison to a recipe of virgin concrete aggregate, which are used in a case study called "Musterbude". The recycling rate of aggregates used in the recipes are 45%, 60%, and 100% and they are supplied from different resources. For environmental impacts calculation, each recipe is defined as a scenario and their impacts are compared to each. The life cycle assessment results show that, despite low performance in water depletion indicator, the recipes with 100% recycled aggregates shows the best performance from environmental point of view.

1. INTRODUCTION

In the past few years, the member countries of the European Union have made several efforts to move from an economical system described as a linear economy, based on a "produce-use-dispose" model, to a circular economy, focused on the reuse and recycling of waste. Although it could provide several advantages from both an environmental, economic and even social point of view, there are still a lot of barriers to the implementation of this type of economy.

The European Directive 2008/98/EC established a target for reuse, recycling, and other types of material recovery of inert waste up to 70% by weight, and the present paper focused on one of the most voluminous waste flows generated from the EU: concrete and demolition waste. There are different solutions that would allow recycling it, but presently the most commonly used is backfilling, which is a form of down cycling.

Although the construction industry plays an essential role in a country's economic growth, it is also responsible for activities and processes that generate high volumes of waste, which are constantly on the rise with little effort to minimize them. Indeed, the natural environment is constantly being polluted by the activities of the construction industry and the built environment as a whole. Likewise, finite natural resources that are used as raw materials for construction are increasingly being depleted due to continuous extraction (Ogunmakinde et al., 2022).

Construction activities are classified as input and output, with the former being resources that are channeled into a construction project and the latter being products generated from the project. It can be argued that all phases and activities of construction generate waste. The volume of waste generated from each phase and/or activity may vary. However, there is a need to ensure that as much waste as possible is minimized. Construction waste minimization is meant to reduce waste by determining its causes, reducing it from the source and applying ameliorating techniques (Ogunmakinde et al., 2022).

Recycling of demolished concrete and using them as recycled aggregates in concrete production can be considered as a promising solution that can guarantee a considerable decrease in environmental impacts like natural resource use, because 70-80% of concrete is made of aggregates (Alexander & Mindess, 2005). Recycling of concrete aggregates means reduction in excavation of virgin aggregates which results in natural resource preservation. On the other hand, extraction and manufacturing of concrete aggregates is responsible for 7% of total global energy, which can be saved by recycling of concrete (Hossain et al., 2016).

For this reason, research in the field of the construction industry is now focusing on the possibility to use recycled aggregates for generating new concrete, but it is necessary to assess the actual sustainability of this option, especially in comparison to producing from virgin aggregates. In

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order to reach this goal, there are several instruments that could be used, including the Life Cycle Assessment (LCA), a scientific approach that allows taking into account all the aspects of creating a product and evaluating the environmental impact associated with it (ISO 14040:2006). According to ISO 14040, LCA can model, quantify and analyze the environmental impacts of a product over its entire life cycle. ISO 14044 defined a step-by-step environmental assessment methodology to secure the reliable results for further interpretation of environmental footprint of products or services (ISO 14040:2006). In "Methodology" section, each step of LCA will be defined based on ISO 14040 and ISO 14044.

2. CASE STUDY - MUSTERBUDE

Musterbude is a small cabin built in Hamburg, Germany, using seven different recipes of recycled concrete and one recipe of standard concrete, in order to test their different technical and environmental qualities not only on a laboratory scale, but also in a scenario closer to reality.

This showcase is part of the CIRCuIT project, which aims to identify how circular construction approaches can be scaled and replicated across Europe to build more sustainably and promote the transition to a circular economy for the built environment, by delivering a series of demonstrations, case studies, events and other dissemination activities (CIRCuIT). CIRCuIT is led by university and industry partners with an interest in construction and the environment from Copenhagen, Hamburg, the Helsinki region and Greater London. Hamburg partners involved in CIRCuIT and consequently Musterbude project are Otto Dörner Kies und Deponien GmbH & Co.KG, the EGGERS Tiefbau GmbH Group, the Technical University of Hamburg, the Free and Hanseatic City of Hamburg, e-hoch-3 eco impact experts GmbH & Co.KG and OTTO WULFF Bauunternehmung, a family-run company that works in the field of constructions (Figure 1).

It was possible to conduct a life cycle assessment in order to describe the environmental impact of recycled concrete under different recipes because the OTTO WULFF Bauunternehmung GmbH in collaboration with EGGERS Tiefbau GmbH, and Otto Dörner Kies und Deponien GmbH & Co.KG, provided the data of the recipes used to obtain the different concrete mixture.

3. METHODOLOGY

Based on the framework provided by the ISO 14040 and ISO 14044 standards, it is possible to report the information gathered during a Life Cycle Assessment study, presenting the results obtained in an organic form and making it possible for different audiences to understand how the study was conducted. Goal definition, scope definition, inventory analysis, impact assessment, and interpretation are presented in the following sections.

3.1 Goal and Scope Definition

The OTTO WULFF Company, as part of the CIRCuIT project, commissioned the study and it was performed at the Technical University of Hamburg, with the use of OpenLCA, a free software purposely created to conduct Life Cycle Assessments, with the support of sophisticated information databases.

The database used in this study is Ecoinvent, version 3.7.1, which has sufficient information to perform LCA in the construction field. It is a Swiss database that contains approximately 12,500 processes organized under different themes like transport, energy, material production, agriculture, etc. All processes are available as unit- and system-processes, all of which are documented in detail (Bjørn et al., 2018).

The present study aims at establishing the environmental impact of seven different recipes of concrete (indicated as R1, R3, R4, R5, R6, R7, R8), containing recycled aggregates from demolition waste, in comparison to a reference

FIGURE 1: Musterbude.

concrete (RB), produced in accordance with the standard mixture of materials and only using virgin resources (Table 1).

The purpose of the study is to support research in the field of circular economy applied to the construction industry.

The study did not apply the standard "cradle-to-grave" approach of LCA, but it was limited to the final production of the concrete, without considering the impacts determined by the use and disposal at the end-of-life. Therefore, the study can be defined as a "cradle-to-gate" study and this approach was chosen due to the lack of information about the use and disposal phases, as the "Musterbude" was only recently constructed.

The chosen functional unit for this study is 1m^3 of concrete produced, however it should be mentioned that the stress resistance of the different recipes resulted to be extremely variable, making them fit for different use, and none of them showed physical characteristics actually comparable to those of the reference concrete.

The entire study was conducted after defining the foreground system (Figure 2).

The study is performed in Attributional LCI modelling, whose overall aim is to represent a product system in isolation from the rest of the Technosphere or economy. In fact, the main purpose of the study was to identify the best mixture in a set of options, not to consider how the environmental impact will change in accordance with variations in the technology or in the market demand.

As for the geographical boundaries, it was taken in consideration that the entire study was located in Germany, so, where possible, the providers for the different inputs and outputs processes were associated to Germany itself. However, when the information were not present for this country, they were associated to average European values, always provided by the Ecoinvent v3.7.1 database. At the same time, also the temporal settings needed to be established. The construction of the Musterbude took place between April and June 2022, so all the technologies considered were referred to this period. Moreover, as the study does not take in consideration the environmental impact associated to the use and disposal phases, possible future technological development was not taken into consideration.

3.2 Inventory Analysis

The data collected for the comparison between the recipes were relative to the quantity and type of material used in each of them, including the standard one, and they have been provided directly from the OTTO WULFF company, while all the information relative to the energy, emissions and heat used or wasted, were collected from the Ecoinvent v3.7.1 database.

The information relative to the distance covered by the trucks for the material transport, were calculated by Google Maps, based on the information about where the different activities were taking place. Transportation activity is modelled by the pre-defined flow "transport, freight, lorry >32 metric ton, EURO6" in Ecoinvent v3.7.1 database.

TABLE 1: Concrete Recipes (OTTO WULFF).

Parameter	R1	R3	R4	R5	R6	R7	R8	RB	Unit
Recycled Aggregates	299.8	400.1	296.4	233.4	607.1	606.9	233.4	0	dm^3
Virgin sand	625	715	300	661	0	0	661	787	kg
Virgin Gravel	346	0	650	484	0	0	484	1180	kg
Total Water	240	274	258	231	332	343	243	170	kg
Cement	300	300	300	300	300	300	300	300	kg
Fly Ash	60	60	60	60	60	60	60	60	kg

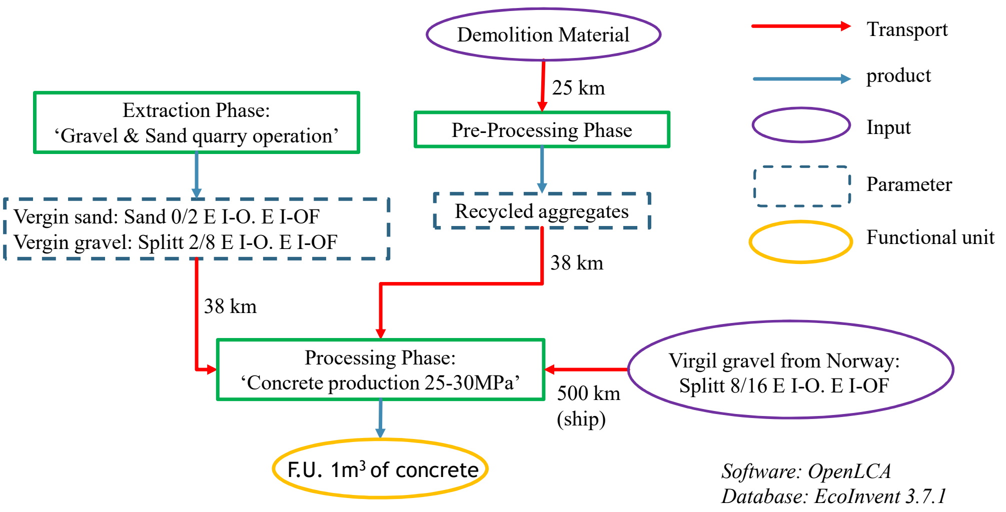

FIGURE 2: Foreground system LCA.

To compare the environmental impacts of different recipes, seven scenarios are defined:

- Reference Scenario (RB): Production of 1 m^3 of concrete with virgin aggregate (0% recycled aggregates);
- Scenario 1 (R1): Production of 1 m^3 of recycled concrete with 45% recycled aggregate;
- Scenario 2 (R3): Production of 1 m^3 of recycled concrete with 60% recycled aggregate;
- Scenario 3 (R4): Production of 1 m^3 of recycled concrete with 45% recycled aggregate (different supplier);
- Scenario 4 (R5): Production of 1 m^3 of recycled concrete with 35% recycled aggregate (different supplier);
- Scenario 5 R(6): Production of 1 m^3 of recycled concrete with 100% recycled aggregate;
- Scenario 6 (R7): Production of 1 m^3 of recycled concrete with 100% recycled aggregate (different supplier);
- Scenario 7 (R8): Production of 1 m^3 of recycled concrete with 45% recycled aggregate (different supplier).

3.3 Life Cycle Impact Assessment

The impact assessment method used in this LCA is the ReCiPe Midpoint H, which is part of the ReCiPe method, one of the most recent and updated impact assessment methods available to LCA practitioners. It addresses a number of environmental concerns and expresses them through 18 midpoint level categories, which are then weighed and aggregated into a set of three endpoint categories. In this study, it was decided to present the results only at midpoint level (Table 2).

3.4 Interpretation of Results

In this section, the significant issues from the LCA phases that are not considered in the system boundaries are mentioned and their influence on the overall LCA results will be evaluated. The interpretation of results deals with the identification of the significant issues from the other phases of the LCA as well as with the evaluation of their influence on the overall results of the LCA and the completeness and consistency with which they have been handled in the study. Then, the results of the evaluation are used in the formulation of conclusions and recommendations from the study.

The present study was conducted with the information provided by the OTTO WULFF construction company, which was directly responsible for the production of the eight types of concrete. Such information included the composition of each recipe, with a high level of detail in regard to the amount of consumed water, the quantity of cement and fly ashes, and the amount of recycled and virgin aggregates used, also grouped according to their dimensions and origin.

During the production of the recycled aggregates, some information regarding the type of instruments were provided as well, however, there was a lack of information about the amount of energy they used. For this reason, the study was conducted using as inputs some engines that belonged to the same category and had similar technical characteristics, but above everything, the only parameter needed to calculate their impact was the amount of material that they processed. Nonetheless, it is logical to suppose that the production of material with different granulomeres dimensions could determine different amounts of energy consumed by the machines, and, consequently, generate different impacts. Unfortunately, this was impossible to determine, but it is supposed to have little influence on the results, as the impact associated exclusively to the production of the recycled aggregates represents only a small fraction of the total impact described by the LCA.

One more element that should be taken into account is that at the beginning of the LCA it was assumed that the demolition activities were the same in all scenarios, so both in the case of the recycled and the standard concrete; this is far from reality, as, in order to create the recycled aggregates, it is necessary to conduct a selective demolition, which implies the use of different instruments from a standard demolition and takes more time. Generally, a selective demolition has a higher influence on the costs than on the environment and, for this reason, it was decided that the energy used for the demolition in any scenario was the same. Nonetheless, the important effects of demolition technique and treatment equipment of concrete waste on the performance of the recycled aggregates should be emphasized, since they lead to different mechanical properties and durability of recycled aggregates, and influence the energy consumption and environmental emissions in producing them. Hence, the life cycle inventory of 72 recycled aggregate should include its production modes, the effects of demolition techniques, treatment equipment and size of aggregate (Zhang et al., 2019).

In addition, it was assumed that, according to the law in Germany, no waste was generated from both the demolition and all of the other activities, as concrete waste is always used for backfilling. One additional choice was not

TABLE 2: ReCiPe Midpoint H (Ecoinvent 3.7, 2021).

Indicator	Acronym	Unit
Agricultural land occupation	ALOP	m^2a
Climate change	GWP	kg CO_2- Eq
Fossil depletion	FDP	kg oil-Eq
Freshwater ecotoxicity	FETPinf	kg 1,4-DCB-Eq
Freshwater eutrophication	FEP	kg P-Eq
Human toxicity	HTPinf	kg 1,4-DCB-Eq
Ionising radiation	IRP_HE	kg U_{235}- Eq
Marine ecotoxicity	METPinf	kg 1,4-DCB-Eq
Marine eutrophication	MEP	kg N-Eq
Metal depletion	MDP	kg Fe-Eq
Natural land transformation	NLTP	m^2
Ozone depletion	ODPinf	kg CFC-11-Eq
Particulate matter formation	PMFP	kg PM_{10}- Eq
Photochemical oxidant formation	POFP	kg NMVOC
Terrestrial acidification	TAP100	kg SO_2- Eq
Terrestrial ecotoxicity	TETPinf	kg 1,4-DCB-Eq
Urban land occupation	ULOP	m^2a
Water depletion	WDP	m^3

considering the recycling of the steel incorporated in the concrete to be recycled, mainly because the aim of the study was to define the environmental impact of recycling the concrete waste exclusively and also to avoid dealing with the problem of allocation, even though the energy needed for separating the steel from the concrete in the different scenarios could have slightly altered the impact results if taken in account.

4. RESULTS AND DISCUSSION

The results obtained by this LCA study provide useful information for establishing the mixture, which has the lowest environmental impact. This information can be useful for further studies on other recycled aggregate recipes or as a supporting tool for decisions on future construction.

Climate change indicator, which shows the equivalent amount of CO_2 emissions into the air, indicates the lowest amount in R6 and R7 compared to standard recipe (RB) (Figure 3). This reduction can be attributed to elimination of virgin material extraction phase, and part of transportation phase, because no virgin aggregate is being consumed in R6 and R7.

The spider grams shown in Figure 4 and Figure 5 present the impact associated to each recipe by broken lines that connect their standardised values for each impact category. In both figures, there is a red broken line, which indicates the environmental impact of the average concrete, used as a reference for normalizing the impact values of the other recipes. All the points outside of its confined area correspond to higher values of impact, while the points inside its area indicate a lower impact.

The points of the broken lines of both recipes R6 and R7 fall closer to the center of such area, in comparison to those of the other mixtures, indicating that they have the lowest impact values, which are identical for almost all of the considered impact categories, due to the fact that R6 and R7 have extremely alike compositions and characteristics, as shown in Table 1.

These two recipes are made exclusively of recycled aggregates, which is the reason behind the extremely low values of impact in certain categories such as "Natural land transformation" (NLTP), with an impact of -41%, followed by the recipe R3 with -30%, or "Urban land occupation"(U-

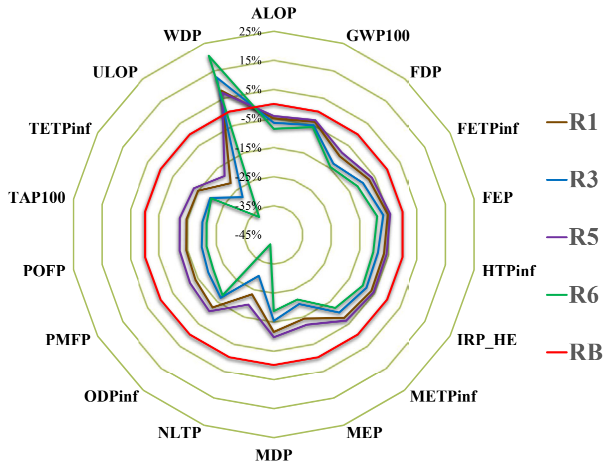

FIGURE 4: Standardised Life Cycle Impact Assessment results, part 1.

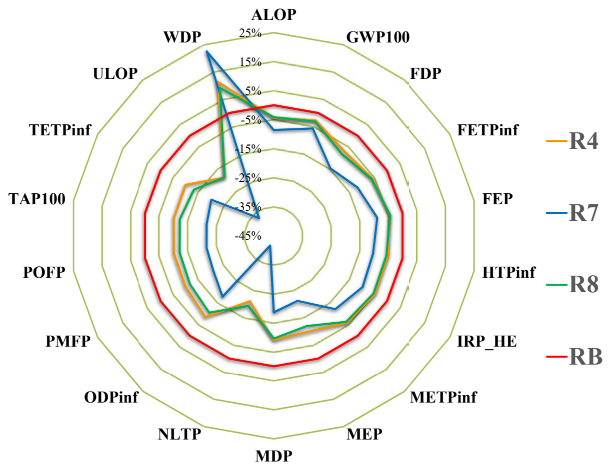

FIGURE 5: Standardised Life Cycle Impact Assessment results, part 2.

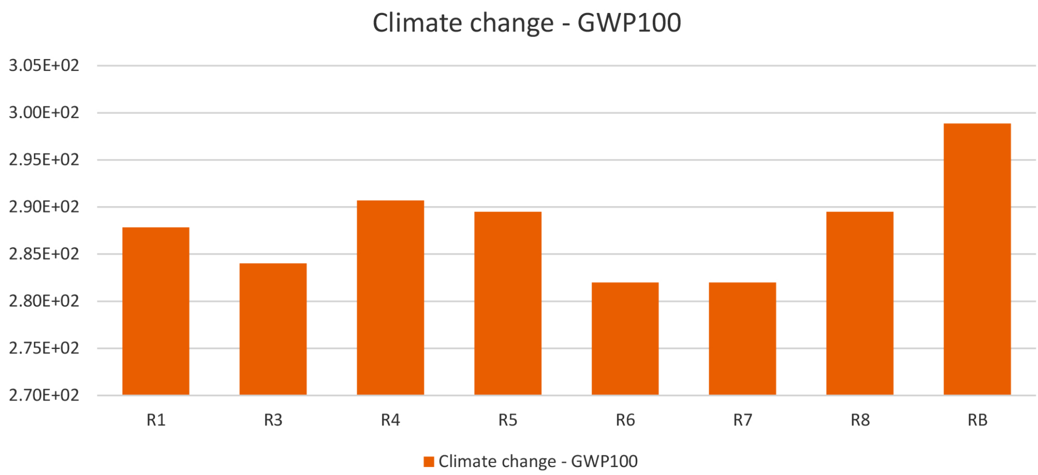

FIGURE 3: Environmental Impacts of different recipes in terms of Climate Change indicator.

LOP), with a value of -38%, while the next best result is for R3. The impact in these categories is mostly connected to the extraction phase but considering that, the two mixtures use no virgin aggregates; this phase does not take place for them, which has a positive influence on the reduction of the overall environmental impact of concrete production. For other impact categories, it is still possible to notice a reduced impact if compared to an average concrete, but the gap is more similar to that of the other recipes.

On the contrary, in the case of the "Water Depletion" (WDP) category the impact is higher in comparison to the standard recipe. Indeed, the water consumption was found to be 21% (R6) and 23% (R7) higher than the reference, due to the fact that recycled aggregates have a larger surface area and are usually drier than natural aggregates, causing a need for additional water (Knoeri et al., 2013; Ding et al., 2016).

5. CONCLUSIONS

In this paper, an LCA study of different types of recycled and virgin concrete was reported, to investigate the opportunities, but also the flaws, in the execution of this approach to establish the sustainability of concrete itself. The present LCA shows that recipes R6 and R7 are the options with the best performance from an environmental point of view, but because R6 has, the lowest impact on Water Depletion among the two, it can be considered the most environmental-friendly mixture of the present study.

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