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Environmental impact assessment to support the development of new Photonic Meta-Concrete

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Abstract: The cooling demand in buildings has increased over the past decades due to global warming, the heat-island-effect in cities and the increased airtightness and thermal resistance of the building envelope. This led to an increased use of conventional air-conditioners, which now account for 7% of global greenhouse gas emissions and 10% of the total energy consumption. In this context, the MIRACLE project aims at developing a new Photonic Meta-Concrete (PMC) with remarkable photonic properties to reduce the CO₂ footprint of buildings, mitigate the heat-island-effect and global warming. Besides the positive effect that this innovative material can have on the environment during the use phase of buildings, also the environmental impact of the production needs to be minimized. Environmental impact assessment (EIA) is used along the development process of this innovative material to guarantee a low material environmental impact. This paper discusses how EIA is used along the development process and presents the preliminary results in the early stages of the development of the PMC. To investigate the impact of this new material, a cradle-to-gate analysis of the resources, energy and machinery needed to create the concrete mixture is performed. The broad set of environmental indicators of the EC PEF (Product Environmental Footprint) method, such as climate change, acidification, eutrophication, particulate matter, ecotoxicity, water depletion and human toxicity are being considered. Considering such a large set of indications ensures that burden shifting is avoided. The environmental impact of the PMC is moreover compared to the impact of conventional concrete to understand how both perform.

Keywords: Photonic Meta-Concrete, environmental impact assessment, radiative cooling

1. Introduction

In order to help mitigate climate change, reduce CO₂ emissions and the heat-island-effect, the Horizon2020 project ‘MIRACLE’ (Metaconcrete with Infrared RAdiative Cooling capacity for Large Energy savings) is developing an innovative radiative cooling material. Radiative cooling is a process where heat is transmitted with a wavelength within a certain range to enable passing through the atmosphere, into outer space [1]. This occurs when the temperature of the material is below ambient temperature [2]. For this reason, next to high mid-infrared emissions also low solar absorbance is needed. Materials that allow for nighttime radiative cooling is already studied for several decades, but only recently daytime radiative cooling materials have been developed. This is important because the peak cooling demand occurs during the day [2]. The currently developed cooling materials however face an important barrier for market uptake, i.e. the high cost of materials and processes used. To date



radiative cooling materials are created with nanometer-precision fabrication techniques which are known for their high energy consumption and large financial cost [3].

The Photonic Meta-Concrete (PMC) under development aims at tackling these problems by developing a daytime radiative cooling material based on conventional concrete. The advantage of this material is that concrete is the most used product in the world, which holds that it is abundantly available and relatively cheap.

The development of the material is in a primary phase, but the potential environmental impact of the first composition is studied to gain insight in the main environmental drivers and support decision taking in the development process. An environmental impact assessment (EIA) will be carried out along the development, from the first phase until the product is fully developed. This ensures a low material environmental impact and avoids burden shifting. The aim is to first minimize the impact of the materials and the production processes. In next steps of the research also the impacts during the use phase and the end of life phase will be assessed.

The first step is gaining a deeper understanding of the components in the first mixture of the PMC. In this paper only the materials are considered and assessed. Alternative materials or changes in the composition are furthermore explored to investigate potential reductions in the environmental impact. A Monte Carlo analysis is carried out to gain insight in the uncertainty of the results due to assumptions taken and modelling choices.

This paper builds upon a paper where the composition of the PMC was discussed its environmental impact compared with conventional concrete and concrete roof tiles [4]. Possibilities to reduce the environmental impact were highlighted and these are the starting point of this paper. This paper assesses potential ways to reduce the impact. It is important to state that this is a cradle-to-gate EIA since the application of the material is still unsure and hence the use phase and end-of-life phase are not yet known. Moreover, the service life time of these radiative cooling materials is not long e.g., 10-20 years. This makes it even more important to reduce the environmental impact of these materials. Additionally, the influence of the modelling choices in the LCA software are investigated and discussed.

2. Methodology

As mentioned, the structure and environmental impact of the materials in the first composition of the PMC are studied in a previous paper and benchmarked against conventional concrete and a concrete roof tile [4]. The Ecoinvent records used in that screening environmental impact assessment (EIA) are reconsidered here and a sensitivity analysis is performed to investigate the sensitivity of the material records used in the modelling. As the micro-additives are confidential and the environmental impact of water is negligible compared to the other materials, only cement, limestone and steel fibres are assessed in this phase of the assessment. These three components are each evaluated in a similar way. The impact generated by water and the micro-additives is however added to the EIA, but is not further discussed in this paper. The EIA is carried out in the Simapro software and the impact assessment method chosen is in line with the EN15804:A2 standard, using the generic Ecoinvent v3.6 life cycle inventory database. It is important to state that the assessment only considers the materials and no manufacturing processes are taken into account as the latter are still uncertain.

First of all the environmental impact of the three materials is evaluated in detail. Multiple impact categories are explored and a reflection is made upon the data records chosen in the screening EIA. The screening EIA revealed that the MIRACLE concrete has a high impact on climate change (CC), particulate matter (PM), ecotoxicity freshwater (EF), resource use fossils (RF) and resource use metals and minerals (RMM). These impact categories are hence assessed in detail. Insight in the drivers of the environmental impact categories from the output of the EIA is validated by literature. As cement is industrially produced, an extra step is undertaken to evaluate the different generic Portland cement records in the Ecoinvent database with an EPD (environmental product declaration) of Portland cement in Europe.

A sensitivity analysis is moreover carried out to evaluate the different records available for these materials in the Ecoinvent v3.6 database. This allows to select the most appropriate record for each

material. Moreover, a Monte Carlo analysis is carried out on all data records used in order to gain insight in the influence of these on the uncertainty of the impact assessment results. For all materials, a threshold of 500 runs is chosen. This means that the environmental impact is assessed 500 times, each time with altered starting conditions. These starting conditions are based on the uncertainty of the data itself, given by specialists in the field. The 95% confidence interval is used to consider the extreme values of the environmental impact, the coefficient of variation (CV) is used to consider the dispersion. This allows to evaluate the uncertainty of the database and the impact of these uncertainties on the EIA.

Secondly, potential improvements by using alternative materials are suggested to decrease the environmental impact. Reductions of the impact in certain categories are explained by the outcome of the EIA and are again validated by literature. These potential improvements are integrated into the first composition of the PMC. The improvements are evaluated for one square meter with a thickness of five centimeter. The thickness of the final PMC is estimated to be between one and five centimeter, meaning that assuming a thickness of 5 cm is a conservative approach.

3. Results and discussion

One cubic meter of the first composition of the PMC consists of 484.86 kg cement, 1454.57 kg limestone aggregates, 242.43 kg water, 484.86 kg steel microfibres and 24.24 kg micro additives. The weighted environmental impact of this composition is shown in Figure 1. It is clear that the highest impacts are observed for the five categories mentioned earlier.

Figure 2 shows the weighted environmental impact by the Monte Carlo analysis on the first mixture of the MIRACLE concrete. The CV of water use (WU) is 11590.5% which indicates that this impact category is too uncertain for further calculations. Therefore, this impact category is left out of the EIA in the next steps. According to the PEF CR guidance document v6.3 of the EC PEF method [5], the three

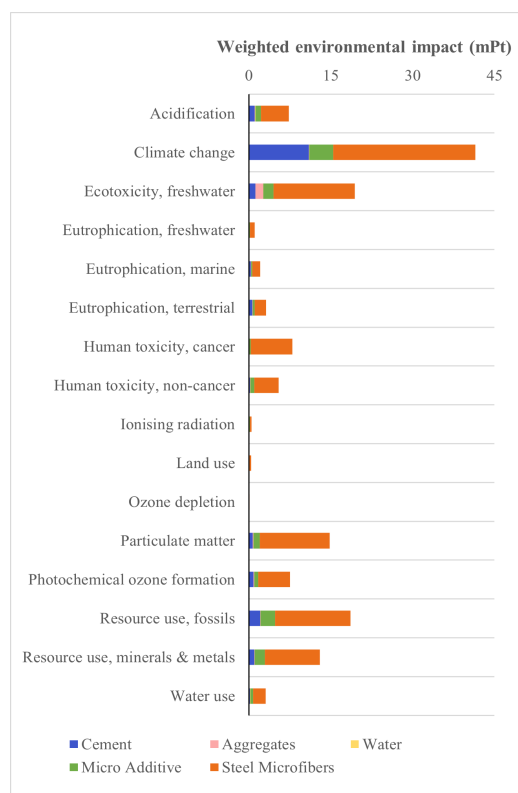


Figure 1. Weighted environmental impact of the different materials in the first composition of the PMC

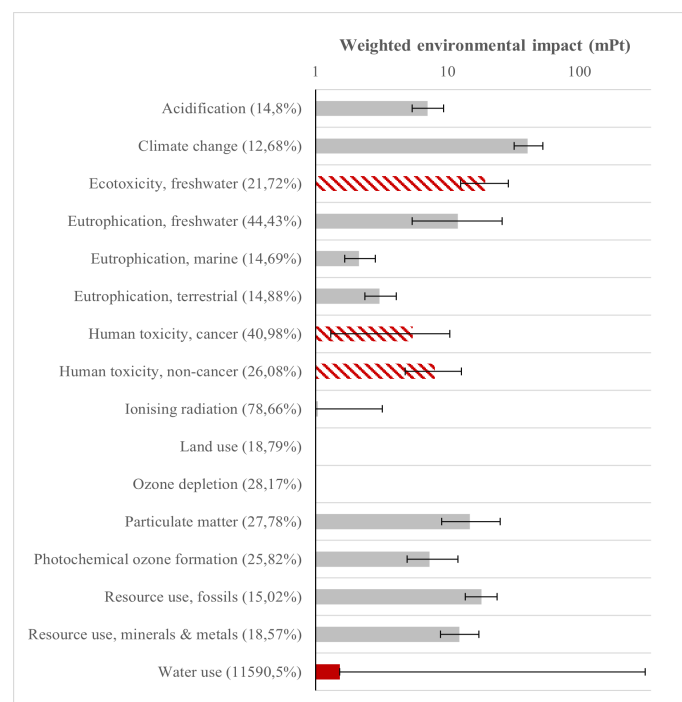


Figure 2. Weighted environmental impact from Monte Carlo uncertainty analysis. The error bar for Water Use goes to -370 mPt, this is not represented as this is a logarithmic scale. The solid red bar indicates the very high uncertainties, the dashed red bars the uncertain indicators according to EC PEF. The coefficient of variation is mentioned after every impact category.

toxicity indicators are uncertain and hence recommends to exclude these when identify the most relevant impact categories, life cycle stages, processes and elementary flows (hotspots). This is confirmed by our analysis, especially for human toxicity (Figure 2). In this paper these are not excluded, but their uncertainty is taken into account. Furthermore, compared to the other categories, the impact categories with the biggest contribution to the total environmental impact show relatively low uncertainties. As this is promising for the overall uncertainty of the environmental impact, the smaller impact categories still need to be assessed as they can be relevant for some components of the mixture.

3.1. Cement

Table 1. Information on the CH and EU Portland cement records in the Ecoinvent v3.6 database

	<i>Cement factory</i>		<i>Clinker</i>		<i>Gypsum, mineral</i>		<i>Limestone, crushed for mil</i>		<i>Steel</i>	
	Amount (P)	Origin	Amount (kg)	Origin	Amount (kg)	Origin	Amount (kg)	Origin	Amount (kg)	Origin
CH	2.37*10 ⁻¹¹	CH	0.904	CH	0.0495	RER	0.0477	CH	2.25*10 ⁻⁵	GLO
EU	5.36*10 ⁻¹¹	GLO	0.9025	EU	0.0475	RER	0.05	RoW	1.1 *10 ⁻⁴	GLO
RoW	5.36*10 ⁻¹¹	GLO	0.9025	RoW	0.0475	RoW	0.05	RoW	1.1 *10 ⁻⁴	GLO

Figure 3 shows that, just like the PMC, Portland cement has the biggest impact on CC, acidification (AC), EF, RF and RMM. This is due to the Portland clinker production, except for the impact on RMM. The latter is caused by two components which are both responsible for half of the impact e.g., the clinker production and the construction of the cement factory. The use of coal and the energy needed to create Portland cement are the main drivers for CC, AC and RUF. For RMM the mining operation and its construction play an important role, according to the Ecoinvent record.

Three data records were found in the Ecoinvent database for Portland cement. The first is a global dataset (Cement, Portland {RoW}| production | Cut-off, U), the second a European one excluding Switzerland (Cement, Portland {Europe without Switzerland}| production | Cut-off, U) and the third one a Swiss Portland cement (Cement, Portland {CH}| production | Cut-off, U). In the screening EIA, the European record was used. Table 1 summarizes the components of these materials and their origin.

When the ratios of materials are compared with a European EPD [6], it is noted that these are very similar. The Portland cement from the European EPD has the following ratios: 92.2% clinker, 5.9% gypsum and 1.5% limestone. The remaining percentages are additives. Only the amount of limestone is three times higher for these three Ecoinvent records, but this is a negligible small amount. It can hence be assumed that the Ecoinvent records are well representing Portland cement in Europe, keeping in mind that there can be small fluctuations in the amount of the ingredients.

The weighted environmental impact of the various datasets are shown in Figure 3. The generic datasets cause a similar impact in most categories, except for EF and RUMM where the difference between the global record and the other two is significant, especially for the latter one. This is due to the use of global records, which are constructed by combining multiple records from smaller regions. It is clear that if this global cement record was chosen for this EIA that the outcome would be very different. As this screening EIA aims to support decision making during the development of this material, different conclusion could have been made. The small deviations in some categories are caused by differences in the amount of some of the raw materials, difference in amount of cement factory allocated to 1 kg of cement or by differences in the origin of the records, as shown in Table 1.

Figure 4 elaborates on the CV for all impact categories of the three cement datasets. HT is, as expected, the category with the highest CV. When comparing Figure 3 and Figure 4 it is clear that the impact categories with the biggest impact have the lowest CV, especially climate change. This holds

that the share of the environmental impact of the first mixture caused by cement is relatively certain, as also the overall CV is between 5 and 8%.

As the impact, in the five earlier mentioned impact categories, is mainly caused by the energy needed and the mining operations during the clinker production, it is clear that a potential strategy to reduce the environmental impact is to choose another cement type, where clinker is partially replaced by other materials e.g., fly ash and blast furnace slag. CEM II A and B respectively replace Portland clinker by 6-20% and 32-35% in mass with fly ash [7], which is a waste product created by the combustion of coal for energy production all over the world [8-9]. CEM III A, B and C, respectively replace Portland clinker by 36-65%, 66-80% and 81-95% in mass with blast furnace slag [7], which is a by-product from blast furnaces which are used to manufacture pig iron from iron ore, limestone and coke [10-11]. As these materials are waste products from other production processes, their environmental impact is lower than the impact of Portland cement. For one kilogram of cement, a significant decrease of almost 50% can be achieved when considering the single score. Especially the impact on CC can be reduced by almost 75%. It has to be noted that the impact on EF and RMM increases. For EF an increase of 5-10% is noted, while for RMM a significant increase of almost 35% is seen. The reason for this increase is unclear, as the Ecoinvent record doubles the amount of infrastructure needed in comparison to Portland cement. Although these increases do not weigh up to the decreases in the other categories, this should be kept in mind.

Finally, these different cement types are implemented in the PMC composition. To show potential impact reductions, the MIRACLE concrete has been modelled with CEM III/C instead of Portland cement. Figure 9 shows the impact of this new mixture, named 'Improvement 1' (Im. 1). It is clear that especially the impact on CC can be reduced to an important extent. The impact reduction on other categories is insignificant, as cement is not responsible for a great share of the impact in these categories. At this moment in the development of the PMC, it is unsure if Portland cement can be replaced by other cement types as the effect of changing the cement type on the performance of the concrete needs to be evaluated. However, it is recommended to investigate this further in the development as an important impact reduction for the production of the concrete could be achieved.

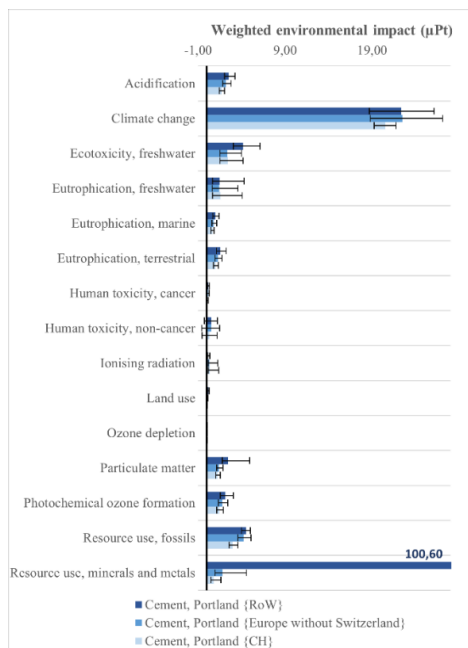


Figure 3. Weighted environmental impact of three Portland cement datasets (1kg), with error bars showing the 95% confidence interval.

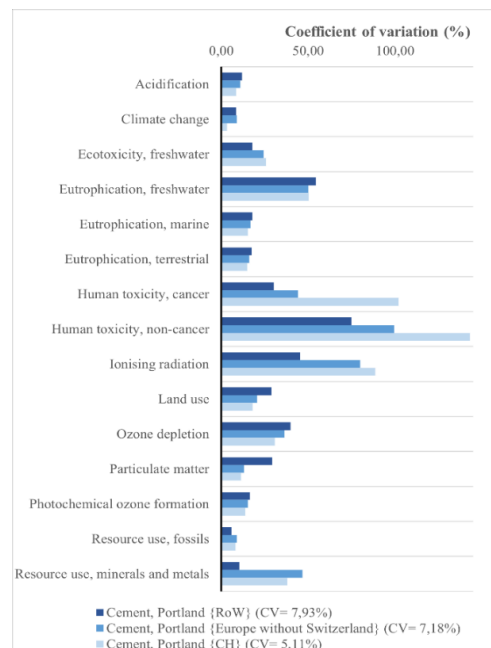


Figure 4. Coefficient of variation for three Portland cement datasets in every impact category. The CV for the single score environmental impact is indicated in the legend.

3.2. Limestone

There are four limestone datasets in the Ecoinvent database, two global and two Swiss ones, i.e. 'Limestone, crushed, for mill {RoW}| production | Cut-off, U', 'Limestone, crushed, washed {RoW}| production | Cut-off, U', 'Limestone, crushed, for mill {CH}| production | Cut-off, U' and 'Limestone, crushed, washed {CH}| production | Cut-off, U'. The third dataset was used in the screening EIA of the PMC and revealed that limestone is responsible for a small share of the environmental impact of the MIRACLE concrete, except for EF. To investigate potential divergence in results based on the dataset used, the weighted environmental impact by the Monte Carlo analysis of all four datasets is compared in Figure 5, revealing that there is no significant difference between them. Figure 5 furthermore reveals that the highest impact (69% of the total impact) of limestone is related to EF. This is caused by the blasting technique that is used to mine the limestone. Conventional quarrying methods use excavation machines, but limestone is mined by the use of explosives. This is done to reduce the use of energy and fossil fuels, but apparently this results in a burden shift to EF [12-13].

Figure 6 shows that the CV of most impact categories is in line with these from cement (Figure 4), although the CV for HT is very high, especially for the Swiss datasets. The reason for this is unclear. The CV for land use (LU) also increases due to the uncertainty of the blasting technique. The overall CV of the single score is between 25% and 31%, this is high compared to cement (Figure 4). As limestone is not responsible for a large share of the environmental impact, this will not influence the environmental impact of the full composition to an important extent.

To possibly reduce the impact of the aggregates in this mixture, limestone might be replaced by conventional aggregates for concrete, i.e. gravel and sand. Sand and gravel have the same impact as the inventory data of both is identical in the Ecoinvent database, as this is the same material with a different grain size [14]. Sand and gravel have a lower impact than limestone on many categories, but the decrease for EF is most significant, due to the absence of the blasting process mentioned. On the contrary, there is a higher impact for RF and RMM. For RF this is due to the extra fuel needed in the mining operation,

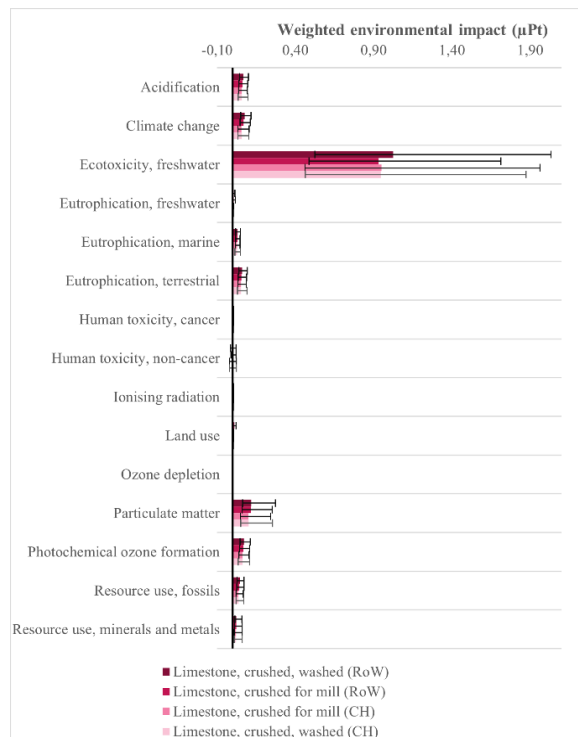


Figure 5. Weighted environmental impact of four limestone datasets (1kg), with error bars showing the 95% confidence interval.

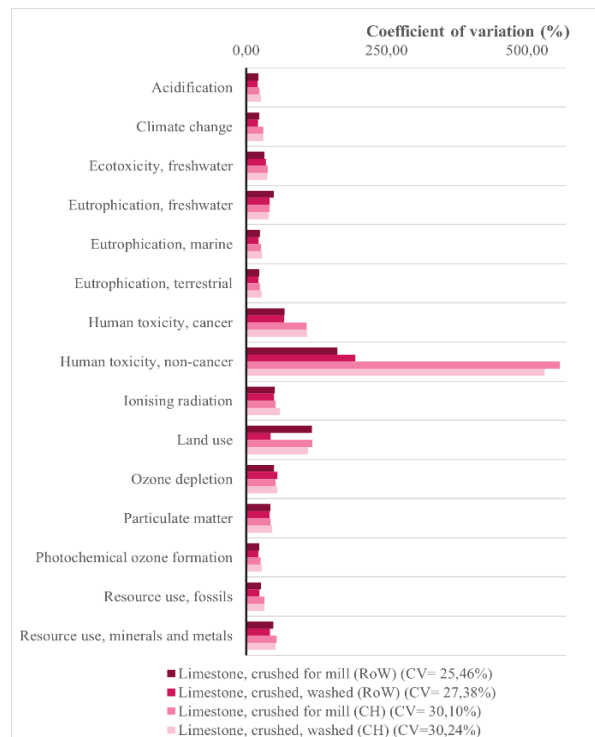


Figure 6. Coefficient of variation for four limestone datasets in every impact category. The CV for the single score environmental impact is indicated in the legend.

as no blasting technique is used. For RMM the reason is less clear, but in contrary to the gravel and sand datasets, the limestone dataset does not account for any part of the building hall and the single score environmental impact for RMM of limestone quarry operations is six times lower. The reason for this bigger impact for the sand and gravel quarry operation is again the use of industrial machinery, which is also accounted for in the quarry operation dataset. The fact that a building hall is not considered for the limestone dataset is unclear.

The assessment reveals that replacing limestone by sand and gravel might reduce the overall environmental impact of the PMC, especially for EF. Therefore, the PMC has been modelled with sand and gravel instead of limestone. Figure 9 shows the single score environmental impact of the MIRACLE concrete when limestone is replaced by sand and gravel (Im. 2), revealing that the influence is very small. Investigating this path during the development of the PMC is hence not recommended, especially because the limestone is expected to be important for the performance of the PMC.

3.3. Steel

The screening EIA of the PMC revealed that steel accounts for 66% of the total weighted impact. This is mainly due to the production of pig iron in blast furnaces, which especially has a high impact on greenhouse gas emissions and fossil fuel consumption [15-16]. Improving this component might hence be an important priority to reduce the environmental impact of the PMC. Two Ecoinvent records were found for reinforcement steel e.g., ‘Reinforcing steel {ReR} production | Cut-off, U’ and ‘Reinforcing steel {RoW} production | Cut-off, U’, this first record was used in the screening EIA of the PMC. As the production process of the steel fibres used in the PMC is still unclear, the hot rolling production process is excluded from the dataset in this paper. The weighted environmental impact by the Monte Carlo analysis of one kilogram of these two steel datasets is shown in Figure 7. Both records lead to the same impact in all categories, this is due to the fact that even the European record is constructed by only global steel records. As steel has the biggest share in the impact of the PMC, it is clear that the most impactful categories of the PMC (Figure) are in line with those of steel. Also the CV of the different impact categories is evenly distributed over all categories (Figure 8). EF and HT have a higher CV

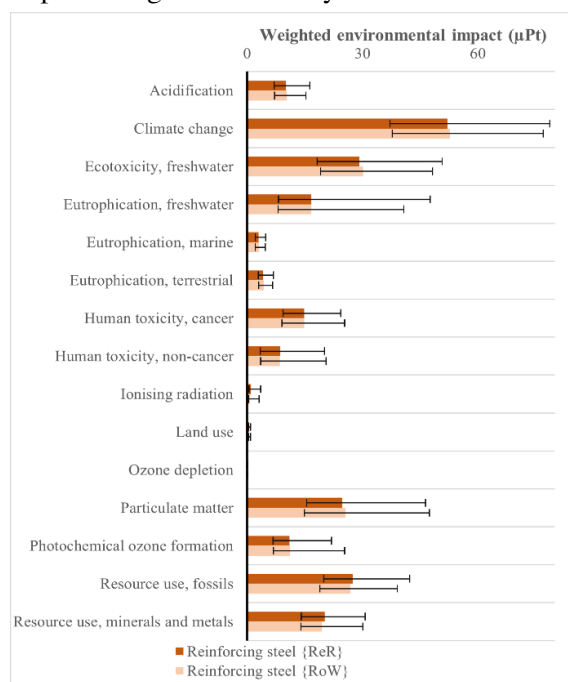


Figure 7. Weighted environmental impact of two steel datasets (1kg), with error bars showing the 95% confidence interval.

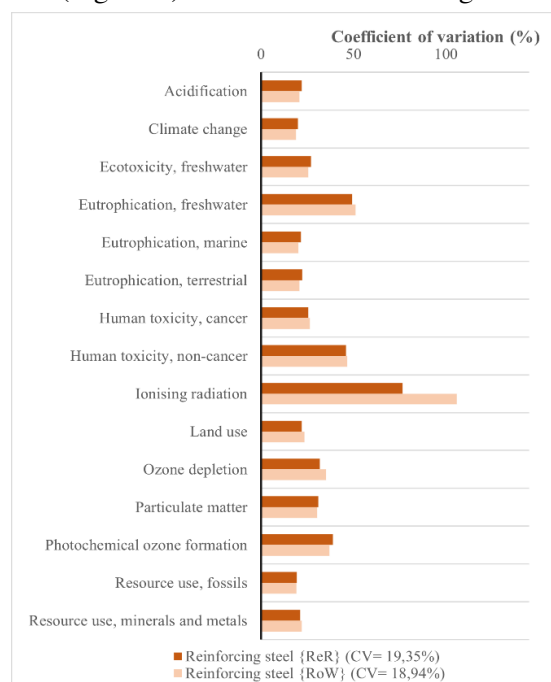


Figure 8. Coefficient of variation for two steel datasets in every impact category. The CV for the single score environmental impact is indicated in the legend.

compared to the other categories, as already mentioned by the PEFCR. Although the share of the overall impact of these categories is small, this still has to be kept in mind and a further analysis is required. The overall CV of the single score environmental impact is between 18 and 20%. This, however, becomes problematic as steel is responsible for 66% of the total impact.

Two different ways to reduce the impact of the steel fibres are explored in this research, i.e. reducing the amount of steel, which will also reduce a large part of the uncertainties, and replacing the steel fibres with other types of fibres.

It is investigated how the impact could be reduced by changing the steel fibres by 100% recycled steel, aluminium and recycled aluminium. Recycled steel production uses steel scrap and only a third of the energy needed to manufacture steel from virgin sources is needed [17]. The option to replace steel by aluminium was proposed by the developers of the PMC material in the MIRACLE consortium. It is assumed that the volume of the fibres remains identical and hence the mass is lower as the density of aluminium is only 34% of the density of steel. One kilogram of steel is hence replaced by 0.34 kg of aluminium in this scenario. This results in a MIRACLE mixture with a lower density. For the virgin aluminium, the Ecoinvent dataset 'Aluminium, primary, ingot {IAI Area, EU27 & EFTA}| production | Cut-off, U' is used. To complete this comparison, recycled aluminium is considered as the third alternative. For recycled Aluminium two European datasets were available: 'Aluminium, cast alloy {RER}| treatment of aluminium scrap, post-consumer, prepared for recycling, at refiner | Cut-off, U' and 'Aluminium, wrought alloy {RER}| treatment of aluminium scrap, post-consumer, prepared for recycling, at remelter | Cut-off, U'. The first record generates a single score impact that is almost eight times higher than virgin aluminium. This is only due to the RMM impact, which accounts for 98% of the total impact. As this result seems incorrect, i.e. the impact of recycled aluminium should not be higher than virgin aluminium, only the second dataset is used. This again shows that choosing certain datasets can heavily influence the environmental impact in the early stage of the development. This is problematic as no clear reasoning is found for the difference between these two datasets. For this second dataset the single score is 27% of that from virgin aluminium. Here the impact on RMM increases for the recycled material, this is due to copper and zinc needed during the recycling process.

The recycled steel generates a lower impact in every category, except for human toxicity non-cancer effect. This is due to dust emissions, which is a process specific burden for the recycling of steel [18]. It is important to note that research is ongoing to recycle this dust in the steel making process [19]. Virgin aluminium has a higher impact on almost all categories. This is partially due to the fact that the production of virgin aluminium uses five times more electricity than the steel production [20]. An uncertainty analysis on these alternative datasets, which are included to reduce the environmental impact of the PMC, is not yet conducted.

These three alternatives are implemented into the PMC, as shown in Figure 9 (Im. 3, Im. 4 & Im. 5). Using recycled steel clearly reduces the environmental impact of the mixture, but the question is if this is possible in the current European market as there is not sufficient steel scrap available to date [20]. Replacing steel with virgin aluminium is questionable as it generates a higher impact, but the partners in the MIRACLE project who are developing the PMC state that the performance of the PMC with aluminium could be better. This holds that a possible reduction of the volume of aluminium fibres, compared to the volume of steel fibres is possible. Either way, this still remains speculation. When the performance of the PMC would increase by using aluminium instead of steel, it is highly recommended from an environmental point of view to use recycled aluminium instead of virgin aluminium, this is even preferred above the use of recycled steel fibres in case the volume of the fibres is not influenced by the material choice. This is because for recycling aluminium less energy is needed compared to the recycling of steel [20]. Again, the question remains if only using recycled aluminium is possible in the current European market. Due to the uncertainties on the modelling of the steel and the manufacturing process of the fibres, it is too early to conclude if this is a possible improvement.

According to the developers of the PMC it might be possible to reduce the amount of steel by limiting the fibres to the top layer of the concrete. Additionally, it might be possible to make thinner PMC products and hence reduce the thickness to a minimum of 1 cm, instead of the original assumed thickness

of 5 cm. Figure 9 shows both of these reductions, called ‘Im. 6’ and ‘Im. 7’. The single score environmental impact reduces significantly with 66% when steel is only used in the top half centimetre of the PMC. The impact reduces with another 56% when the thickness of the PMC is reduced to one centimetre. This shows that the total impact can be reduced by 86% if the minimum amount of steel and the minimum thickness are technically feasible. Also, by using less steel and less material, the uncertainty which comes along with these records will reduce drastically, especially for steel.

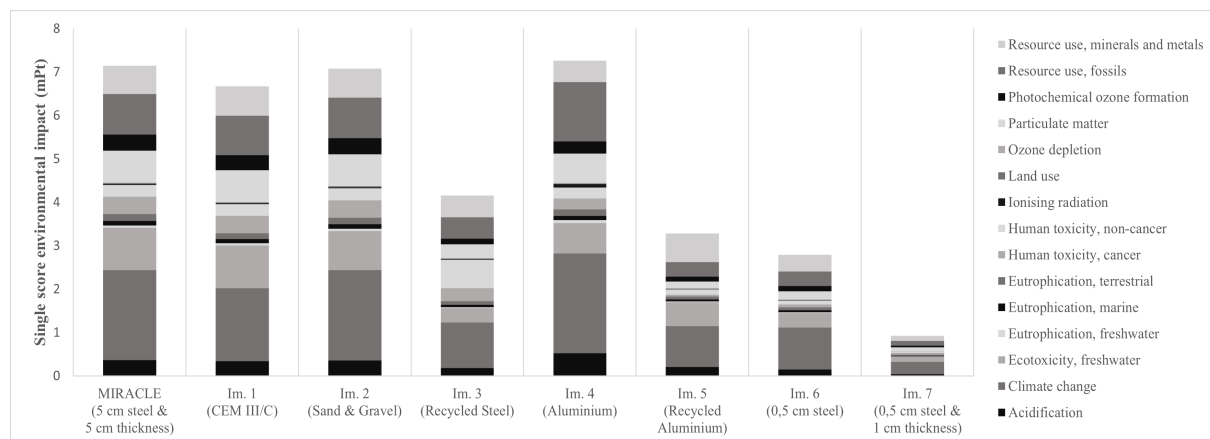


Figure 9. Single score environmental impact for the first composition of the MIRACLE mixture (5 cm thickness & steel microfibers distributed over 5 cm thickness) compared to possible improvements suggested in the paper.

4. Conclusion

This paper focused on the environmental impact assessment of the first mixture of the PMC concrete, identified the main drivers and suggested potential strategies for impact reductions. The results showed that all three materials, i.e. Portland cement, limestone and steel fibres have their share in the environmental impact and all three of them can be adapted to decrease this impact. The assessment revealed that the steel fibres and the thickness of the PMC product are the two main characteristics that influence the environmental impact. Further development of the material should therefore strive to limit the thickness of the concrete product and limit the amount of fibres. Reducing the impact of all other components remains an important opportunity too, especially when the amount of steel is reduced, the share of the other components in the overall environmental impacts will increase. Additional impact reductions can then be achieved by changing the cement type and using less limestone aggregates.

This study highlighted that there are still a lot of uncertainties, both from an EIA modelling point of view and for the composition of the PMC itself. The latter is inherent to this stage of the PMC development and will be reduced along the development process. The uncertainty related to the EIA modelling is mainly due to the data uncertainty. Insight in the uncertainty is important to be aware of the uncertainty of the results and therefore multiple generic datasets were used in the model to transparently report the influence of data uncertainty on the impact assessment results. This clearly showed that choosing different datasets for a certain material can have major impact on the environmental impact. This can lead to false results and can steer the development of new materials in a wrong direction. More information and background on different datasets is needed in order to ensure the right records are used. Therefore increasing transparency in the LCI (Ecoinvent) datasets is recommended. The Monte Carlo uncertainty analysis moreover showed that the Ecoinvent datasets are characterised by a high level of uncertainty. This is mainly due to the origin of data and the amount of materials that are in the dataset. In the next steps of the research, the uncertainties will be further considered and transparently communicated by displaying ranges of results rather than a single value.

This will allow to steer the production process of the PMC concrete in a more robust way from an environmental point of view.

Finally, it is important to note that due to the uncertainty of the manufacturing processes at this stage in the research, these were excluded from the system boundaries. In consequence the environmental impact reported in this paper underestimates the real impact. The additional impact due to the manufacturing process will be assessed in the next steps of the research and added to the impact assessment.

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