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Gavin Gengan, Hsein Kew

ENVIRONMENTAL ASSESSMENT OF RECYCLED GLASS AGGREGATES IN REINFORCED CONCRETE

Kingston University, London, United Kingdom,
School of Engineering & Environment
k1804791@kingston.ac.uk

The sustainability of the concrete industry is in jeopardy due to the use of natural resources which impacts the environment. A swift shift towards sustainable thinking is required considering the emergency triggered by human activity on the climate. Glass concrete (GC) has sparked curiosity of the construction industry owing to its environmentally friendly approach. This article examines the environmental implications of partially replacing natural aggregates in concrete with recycled glass aggregate at various percentages i. e. 10 %, 25 %, 50 %, and 75 % which is then compared to controlled concrete specimen (CC). The assessment indicated 287 kgCO$_2$Eq were generated for control concrete (CC), whereas concrete with 20 % glass aggregate (GA) resulted in 258 kg CO$_2$Eq. global warming potential. Likewise, M25 concrete was reported to have 1.68 kg CFC^{-11}Eq compared to 1.85 kg CFC-11Eq for natural aggregate concrete. Even though glass concrete demonstrates lower values in several environmental effects, there is need for improvement in impact categories including acidification and respiratory organics.

Key words: Concrete, Glass aggregates, Environmental impact, Life cycle assessment and Carbon footprint.

Introduction

The extensive application of concrete in construction has raised multiple environmental concerns due to its high usage of raw materials, elevated energy consumption from cement manufacturing, logistics, and the creation of large volumes of old concrete from demolition wastes (Casini, 2022). The release of CO$_2$ from concrete has a notable impact on the environment, which poses a serious threat in construction industries (Limbachiya, Leelawat, & Dhir, 2000; Akan, G. Dhavale, & Sarkis, 2017). Cement being an intensive and primary raw material, is the main component of concrete. Its manufacture releases significantly high quantities of carbon dioxide (CO$_2$) into the atmosphere hence making the construction industry one of the primary contributors to global greenhouse gas (GHG) emissions which has a significant impact on global warming (Ni, et al., 2022). Approximately 6 % of all greenhouse gas emissions in the United Kingdom and up to 8 % of global emissions are presently produced by cement manufacture (Li, Han, Liu, & Chen, 2019). A collective study reported that annual cement production has quadrupled from nearly one billion to over 4 billion tonnes a year in 30 years (Villalba, Liu, Schroder, & Ayres, 2008). In the next decade it is expected to increase a further 500 m tonnes a year. Unless there is a dramatic change, cement emissions are expected to continue to rise beyond 2050 (Environment, L. Scrivener, M. John, & M. Gartner, 2018). There has been constant attention towards determining the solution towards sustainability to avoid using concrete to reduce environmental impacts. Various research on achieving sustainable concrete by utilising recycled aggregates have been considered by incorporating materials like fly ash, blast furnace slag and glass particles (Zhu, Li, Xu, Wang, & Kou, 2019; Limbachiya, Leelawat, & Dhir, 2000). Concrete incorporating waste is often reported to exhibit inferior mechanical performance and durability.

Therefore, various studies on replacing cement by alkali-activated binders have been utilised. The use of agate-based reinforcements (AR) benefits in enhancing the strength of concrete and further support in hydration and reduction of energy consumption and CO_2 emissions (Alyousef, et al., 2021). Various research on AR have been considered to enhance mechanical properties and, in some instances, remarkable enhancements have occurred (Castro & Brito, 2013; Manzoor, kumar, & Sharma, 2022; Nedeljković, Visser, Šavija, Valcke, & Schlangen, 2021). In recent years, the versatile applicability of glass products has brought a drastic increase in the amount of glass waste generated, urging to its proper utilization. Using waste glass in concrete is an excellent way to keep waste glass out of landfills and reduce the pollution. Large amount of greenhouse gases and natural resources can be reduced by employing waste glass while enhancing the essential properties of the concrete (Manzoor, Kumar, & Sharma, 2022). However, it is vital to evaluate the new materials in terms of their performance, quality and costs as well its environmental impacts. Therefore, to carry out a fair environmental comparison between AR concrete and conventional concrete (CC), any change in the concrete properties, modification of the mix design, and differences due to waste treatment must be thoroughly contemplated (M. Manjunatha, Malingaraya, H. G.Mounika, & Ravi, 2021). Life Cycle Assessment (LCA) is a powerful tool that can be used for such comparison. LCA results can contribute to a better understanding of the environmentally friendly conclusion and appropriate incorporation rate of a given solid waste by comparing AR concrete with CC. LCA also supports in balancing the use of material and energy as well quantify the environmental impact (Gursel, Masanet, Horvath, & Stadel, 2014).

This article focuses on developing and understanding the environmental impact of concrete reinforced with aggregates glass material through LCA. For the purpose of LCA, Kingston University London is considered as the final transportation and preparation location, and the functional unit of the present study is one cubic meter of concrete reinforced with different percentages of waste glass aggregates as shown in Table 1.

Table 1

Mixture ratio and content percentage

Mix Name	Cement (kg/m^3)	w/c ratio	Water (kg/m^3)	Natural Aggregates (kg/m^3)		Glass Aggregates (kg/m^3)	
–	–	–	–	Fine	Coarse	Fine	Coarse
MC	350	0.52	183	552	1288	–	–
M10	350	0.52	183	496.8	1159.2	55.2	128.8
M25	350	0.52	183	441.6	1030.4	110.4	257.6
M50	350	0.52	183	276	644	276	644
M75	350	0.52	183	138	322	414	966

Materials and Methods

The methodology towards this research was based on the cradle-to-grave technique provided by ISO 14040. ISO 14040 defines LCA as the process of "compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle". The LCA framework consists of four interrelated cycles: goal and scope, inventory analysis, impact assessment and interpretation (Zhang, et al., 2019). As described above, function grade and locational gradient are required towards understanding the LCA of the study. Along with it, it is very much required to understand the scope of the LCA. In this research, LCA system boundaries were analysed using "cradle to gate" technique, considered one of the most utilised LCA techniques to understand environmental implications. This cycle involves the environmental implications of extradition/production of raw materials, transportation impact to location and impact of concrete production (Bianco, Tomos, & Vinai, 2021).

Goal, Scope & Assumptions

The goal and scope of this research are to understand the environmental implication of using glass aggregates in Kingston, a region located in Greater London were analysed in the research. The materials and its compositions are provided in Table 1. Along with the type of LCA, certain assumptions were considered towards the LCA, which are due to a lack of information from supplied companies about emission from different stages of production/extraction of raw material such as dust emission from quarry and demolition waste. The impact associated with moving waste was also not considered. In addition to this, an essential assumption that was evaluated was the cradle-to-grave cycle without application, maintenance, or demolitions. However, mechanical properties are reported in upcoming chapters to support the applicational sector. The LCA was carried out through GaBi V9, educational package provided to Kingston University, London. The software included the databases which followed cradle-to-gate technique and also followed IS0 14040.

Functional Unit

The functional unit towards this research was defined as 1 m^3 of concrete for facilitating draft data management and application. A further assumption was towards the different mixtures as stated in Table 1 indicated similar mechanical properties, workability and durability. The use of 1 m^3 concrete is done by various researchers as densities of the material are mostly similar (Density about 2400 kg/m^3).

System Boundaries

The system boundaries of concrete production and transport is illustrated in Fig. 1. The system boundaries also involve energy requirement, processing of raw materials, transportation and concrete production. Further to system boundaries, some treatments of artificial aggregates were eliminated due to limited data, and a total distance of raw material transportation was set to 10 km between the concrete mixing and concrete production plant and 50 km for plant and raw material retrieval.

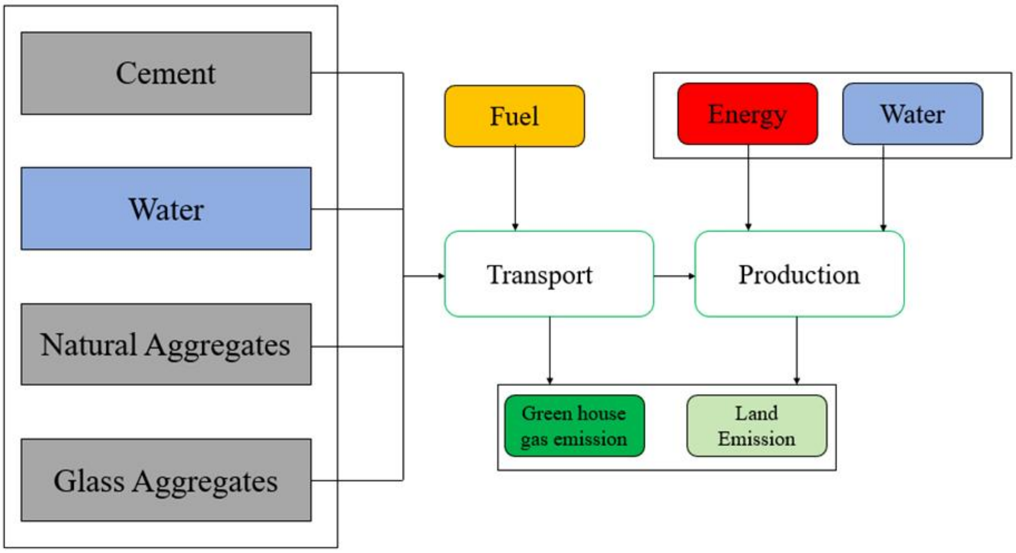

Fig. 1. Concrete production flowchart

Although numerous studies document the production of natural aggregates, recycled glass aggregates have their own Life Cycle Assessment (LCA) and process plan, as shown in Fig. 2. The recycled glass aggregates may be obtained from either residential or commercial areas, or a combination of both. Though the processing or accruing technique of the glass aggregates is not widely reported, it could be stated that the amount of recycled glass aggregates is very limited and most of the recycled aggregates could end on landfills. Fig. 2 illustrates a cycle which could be followed by glass recycled aggregates provided by our supplier information. From Fig. 2, two out of three glass recycling systems could be eliminated as it does not support/contribute towards the concrete development industries. These two systems are marked in dotted red line in Fig. 2. The remaining system contributes directly to the construction industries as it supplies manufacturers/suppliers with recycled glass aggregates.

Inventory Analysis

The Inventory phase relates to the phase of data collection required to achieve the goals set towards the research paper (LCI). The data towards this research were collected from various suppliers, as reported in Table 2, and some were assumed from standard data provided by The Concrete Society, United Kingdom. The European Life Cycle database were utilised to complete any missing data. Further, a literature review on certain LCA studies were also useful in accruing data. Inventory data on basic consumption for natural aggregates i. e., Electrical energy (1.85 kWh/t), diesel consumption (0.50 l/t) and water consumption (0.45 l/t) were requested from supplier. However, data on raw material extraction were limited and assumptions were created.

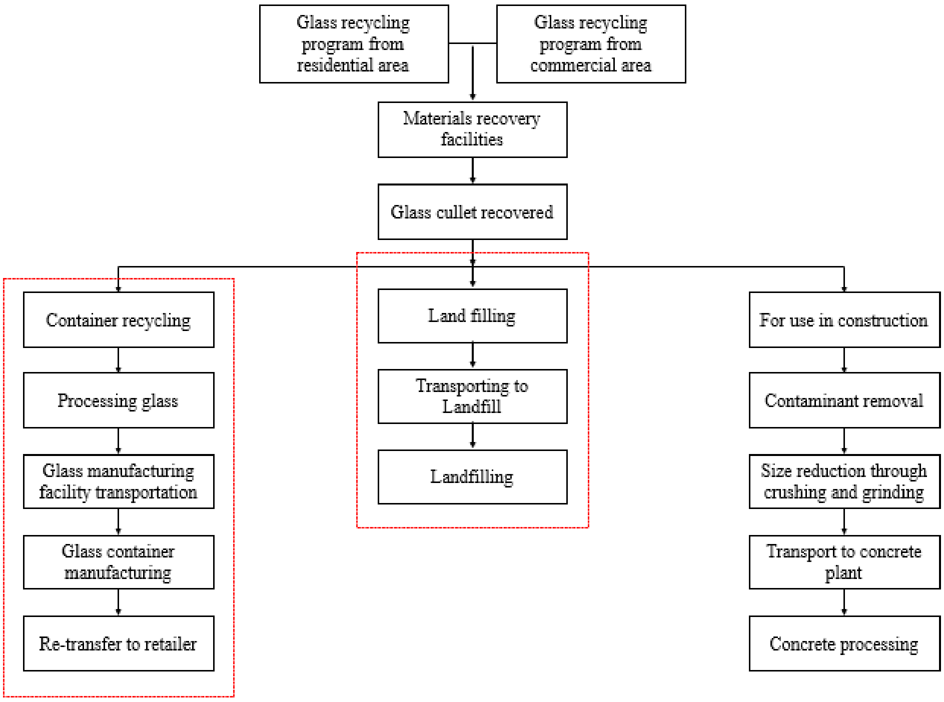

Fig. 2. Life cycle flowchart of glass attained from residential and commercial space to different application

Table 2

Sources and location for databases utilised.

Material	Details	Supplier	Location
Cement	Portland Cement	Tarmac Pvt Ltd.	UK
Water	Tap Water	Kingston university	UK
Natural Aggregates (Fine)	River sand	Brett Aggregates Limited	UK
Natural Aggregates (Coarse)	Crushed Stone	Brett Aggregates Limited	UK
Glass Aggregate (Fine)	Recycled glass	Specialist Aggregates Limited	UK
Glass Aggregate (Coarse)	Recycled glass	Specialist Aggregates Limited	UK

Impact Analysis & Interpretation

The data of the Life Cycle Inventory (LCI) are used to evaluate the relevance and probable environmental implications during the Life Cycle Impact Assessment (LCIA) phase. The inventory data is linked to the specific impact categories. This stage provides data to the interpretation phase. During the LCIA phase, impact categories, category indicators, and characterization models must be identified, and outcomes assigned and calculated. The LCIA only assesses the environmental concerns identified in the aim and scope and does not provide a full assessment of all environmental issues related to the investigated system. Table 3 list the potential impact indicators that are most used.

Table 3

Impact assessment as per Gabi V9

Impact Categories	Nomenclature	Units
Global warming Potential	GWP	kgCO_2Eq.
Ozone Layer Depletion	ODP	kgCFC^{-11}Eq.
Acidification Potential	AP	kgSO_2Eq.
Eutrophication Potential	EP	kgPO_4Eq.
Photochemical Oxidants Potentials	POCP	kgC_2H_2Eq.
Abiotic depletion	ADP	kgSb_2Eq.
Energy Equivalent	EE	MJ

Results and Discussion

Environmental Assessment

The results and discussion section provides the interpretation of the results attained towards this research through Gabi V9. This approach allows an understanding of many impact categories, including human health, resource depletion and quality. Although GaBi can be used to access different impact categories towards this research, four major impact categories were analysed for environmental assessment: global warming potential (GWP), acidification, ecotoxicity and energy categories. Fig. 3 shows the percentage impact of all mixtures on various environmental aspects.

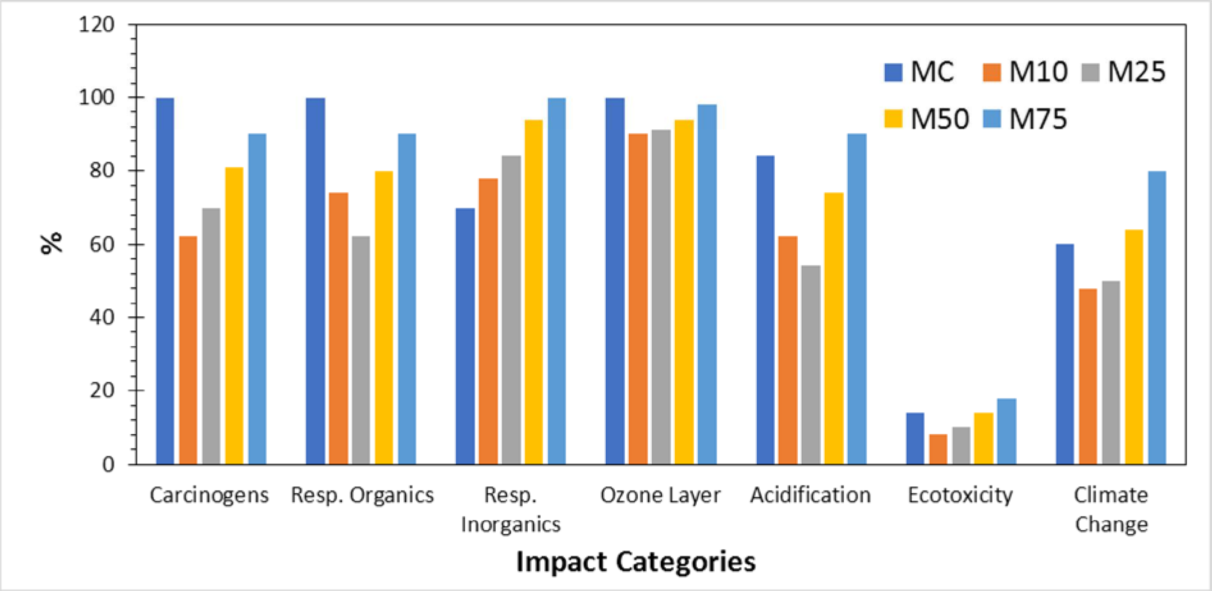

Fig. 3. Various Impact of concrete and its types on environments

The analysis highlighted that conventional concrete (MC) had the highest impact in most of the categories and in some cases, glass aggregate concretes indicated close match to normal concrete. However, in most impact categories, 10 % and 25 % recycled glass reinforced concretes had very little impact on all categories. The M10 is not as carcinogenic, ecotoxic and influential to climate change as the rest of the composition. This could have been due to the small amount of glass reinforcement used to prepare the concrete mixture. These results indicate that with an increase in glass aggregate in concrete, there is an enhancement in all impact categories. This might be a result of recycled glass aggregates made of silica, which has the potential to cause human cancer through respiratory inorganics. The U. S. National Toxicology Program has classified crystalline silica of respirable size as a human carcinogen. The basis for these classifications is sufficient evidence from human studies, indicating a causal relationship between exposure to respirable crystalline silica in the workplace and increased lung cancer rates in workers (A. Soliman & ArezkiTagnit-Hamou, 2017). On the other hand, the impact on the ozone layer remains high regardless of the percentage of embodied energy within the glass aggregates. This might be because a massive amount of energy is needed to heat the raw materials to make glass. Other than that, during the melting of the raw materials for glass, gas pollutants such as sulphur dioxide and carbon dioxide, which can react with the ozone layer in detrimental ways, can be released. Also, since glass requires materials such as silica sand, soda ash and dolomite to be mined for its production, it poses all the environmental impacts associated with mining which all, directly and indirectly, contributes the thinning of ozone layer. On the contrary, Environmental toxicity stood out as being the least impacted factor in using waste glass aggregates in concrete (Bianco, Tomos, & Vinai, 2021). This factor measures two separate impact categories, which examine freshwater and land, respectively. The key reason for that is that the quarrying production of aggregates and silica is not detrimental and do not trigger the emission of toxic substances that can have impacts on the ecosystem or the environment when it is done with proper control measures (Limbachiya, Leelawat, & Dhir, 2000). In the United Kingdom, the concrete industry contributes significantly to biodiversity and nature conservation by managing and restoring quarrying sites. The industry strategy prioritises the quarry actions and since 2020, all sites have been following an action plan for site restoration, biodiversity, or geodiversity (Ni, et al., 2022).

Table 4 displays the gaseous emissions associated with the different mixes emitted into the air.

Table 4

Gaseous emissions from concrete and its types

Substance	Units	MC	M10	M25	M50	M75
Carbon dioxide, Bio.	kg	286.75	270.41	258.42	274.16	283.45
Carbon dioxide, Fossil	kg	26.45	21.14	20.08	24.16	25.98
Carbon monoxide	g	248.09	218.18	198.75	210.48	239.15
Aluminium	g	6.75	4.62	3.68	3.98	5.16
Ammonia	g	14.64	16.42	19.41	26.48	44.26
Ethane	g	0.78	1.2	1.35	1.74	1.99
Nitrogen based Oxides	g	577.45	608.15	644.36	690.45	715.44
Silicon dioxide	g	19.42	37.41	57.65	92.48	148.22
Sulphur dioxide	g	125.07	119.41	108.49	149.42	168.44

Carbon dioxide is the most prominent emission in all mixtures, with most of it coming from the production of cement present in the concrete. Furthermore, there has been a 20 % reduction in the emissions of gases such as sulphur dioxide. This gas is known to be the primary cause of acidification. However, emission generally increases with an increase in the glass ratio. This could be because glass and concrete production are both energy-intensive processes depending mainly on fossil fuels. It might also be due to the inclusion of silica in the glass production cycle for aggregate production, which could all lead to pollutive gas emissions. The global warming potential (GWP) and ozone depletion potential (ODP) of all concretes are listed in Table 5. Results shows that GWP is highest with emission of 286.75 Kg for normal concrete. However, the CO_2 emission reduces by 10 % in the M25 mix before increasing with a higher amount of recycled glass (M75). The trend was similar for ozone depletion potential as it showed reduction till M25 and further increase. On both cases, this could have been due to the rise in glass content within the concrete. According to a study, each glass bottle produced in the United Kingdom emits approximately 500 g of carbon dioxide, with the figure rising to almost 2 tonnes of CO_2 per tonne of glass when transportation is considered. (Environment, L. Scrivener, M. John, & M. Gartner, 2018). All results indicated in Fig. 3, Table 4 and 5 demonstrates that the M10 and M25 mixtures prepared are considered to be better in terms of impact factors than normal concrete or any other of glass concrete matrix.

Table 5

GWR and Ozone values of concrete & its mixtures

Impact Categories	Units	MC	M10	M25	M50	M75
Global Warming Potential	$kgCO_2Eq$	286.75	270.41	258.42	274.16	283.45
Ozone Depletion	kgCFC11Eq	1.85E-11	1.74E-11	1.68E-11	1.98E-11	2.22E-11
Ozone Formation, Human Health	kgNOxEq	5.14E-03	4.86E-03	4.24E-03	5.46E-03	5.76E-03
Mineral Resource Scarcity	kgCuEq	2.18E-03	2.41E-03	2.68E-03	2.98E-03	3.16E-03

Energy Assessment

Fig. 4 indicates the cumulative energy required from the renewable and non-renewable resources for 1 m^3 of concrete and its mixtures.

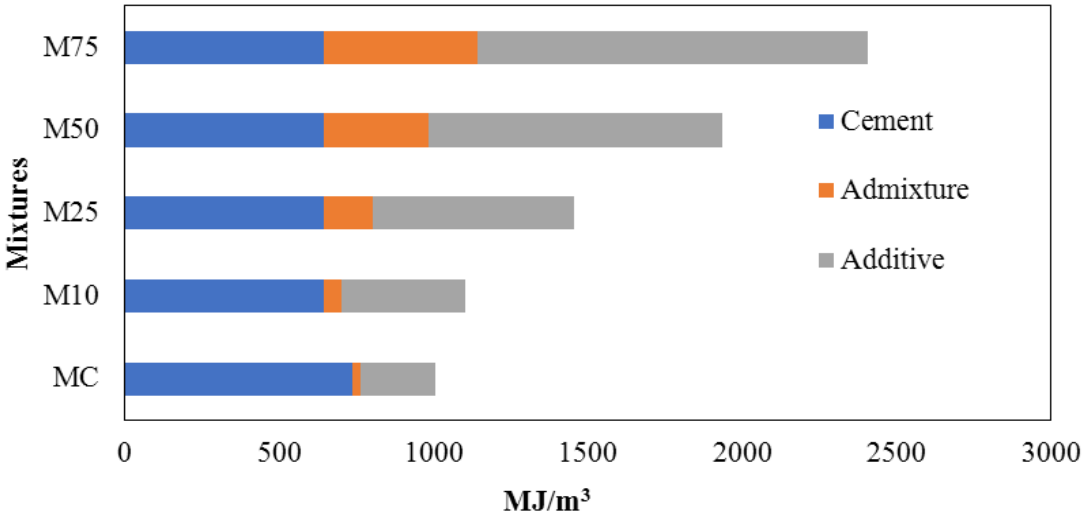

Fig. 4. Cumulative energy consumption by concrete production

The energy required for the concrete preparation was the same for all the different mixes. In contrast, the energy demand to produce raw materials and additives is higher for glass concrete. This indicates that the overall production processes of glass concrete consume more energy. Although there is no definite documentation on glass recycling and certain assumptions were maintained to understand the total impact, it could be said that the energy depends mainly on the cradle i. e., the raw material synthesis and quantity of material procured. Thus, there is over a 100 % increase in energy requirement from MC to M75. Producing glass consumes a lot of energy as high temperatures are needed to melt the raw materials. Due to its high share of energy per tonne of product, the glass industry is usually referred to as an energy-intensive industry in the literature (Manzoor, Kumar, & Sharma, 2022). The bulk of energy consumed in the glass manufacturing industry comes from natural gas combustion used to heat furnaces to melt raw materials to form glass. These furnaces are mainly natural gas-fired, but there are a small number of electrically powered furnaces. Many glass furnaces use electric boosting (supplementary electric heating systems) to increase throughput and quality. After the melting and refining process, the glass is formed and finished to create the final product (W. Griffin, P. Hammond, & C. McKenna, 2021). Specific manufacturing processes depend on the intended product and can include annealing (slow cooling), tempering, coating, and polishing, which require additional energy. It is reported that glass factories alone emitted 2.2 Mt of CO_2 in the early 2010s with approximately 3MWh/t of energy consumption (W. Griffin, P. Hammond, & C. McKenna, 2021; Schmitz, Kamiński, Scalet, & Soria, 2011).

Conclusion

Life cycle assessment of the concrete and its recycled glass mixtures through GaBi software was conducted to understand the environmental impact of the mixtures in nature. However, certain assumptions were considered with GaBi conducted through 1 m^3 samples. It could be concluded that M10 and M25 had reduced environmental impacts compared to concrete other than energy showing its suitability for the future. However, care should be taken in the production of M10 and M25 as according to LCA, the production may lead to respiratory inorganics and carcinogenic in nature. The GWP also showcased that the M10 and M25 had ~5–10 % lower GWP than concrete. Thus, the percentage of recycled glass aggregates could have a higher impact on the GWP but affect energy production. The investigation revealed that conventional concrete had the most significant influence in most categories, with glass-reinforced aggregate concrete having almost same impact in some areas. In contrast, 10 % and 25 % of recycled glass-reinforced concrete had a negligible effect on climate change, respiratory organics, and acidification. The results suggested that impact categories increase with greater amounts of glass aggregate in the concrete matrix. This is possibly due to the recycled glass reinforcements prevalence for silica, a carcinogen that affects people via inorganic respiratory particles.

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Г. Генган, Х. К'ю
Кінгстонський університет, Лондон, Великобританія,
Школа інженерії і навколишнього середовища

ЕКОЛОГІЧНА ОЦІНКА ВИКОРИСТАННЯ ЗАПОВНЮВАЧІВ, ОДЕРЖАНИХ З РЕЦИКЛІНГУ СКЛЯНИХ ВІДХОДІВ, В ЗАЛІЗОБЕТОНІ

Сталий розвиток бетонної промисловості є під загрозою через використання природних ресурсів, що негативно впливає на навколишнє середовище, включаючи вуглецевий слід. Необхідний швидкий перехід до сталого мислення, враховуючи надзвичайну ситуацію, спричинену впливом людини на зміни клімату. Бетон з добавкою відходів рециклінгу скла викликав зацікавленість у будівельній галузі завдяки своєму екологічному підходу. Розглянуто екологічні наслідки часткової заміни природних заповнювачів у бетоні заповнювачем, одержаним із рециклінгу скляних відходів, із різним їх відсотковим вмістом, а саме 10, 25, 50 і 75 мас. %, які потім порівнюються з контрольованим складом бетону. Оцінку життєвого циклу (LCA) було проведено через GaBi V9, освітній пакет, наданий Кінгстонському університету (м. Лондон, Великобританія). Програмне забезпечення включало бази даних, які відповідали технології “від колиски до могили”, а також IS0 14040. Результати досліджень свідчать, що 287 кг CO_2Eq. генерується під час виробництва звичайного контрольного бетону, тоді як бетон із добавкою 20 мас. % відходів рециклінгу скла призводить до зменшення потенціалу глобального потепління, який становить 258 кг CO_2Eq. Як видно з результатів досліджень, бетон М25 містить 1,68 кг CFC-11Eq. порівняно з 1,85 кг CFC-11Eq. для бетону з природного заповнювача. Бетони М10 і М25 з добавкою 10 та 25 мас. % відходів рециклінгу скла мали незначний вплив на показники зміни клімату, респіраторних органічних речовин та підкислення. Незважаючи на те, що бетон з добавкою відходів рециклінгу скла характеризується кількома нижчими показниками впливу на навколишнє середовище, існує потреба у покращенні деяких факторів, а саме підкислення та респіраторних органічних речовин.

Ключові слова: бетон, скляні заповнювачі, вплив на навколишнє середовище, оцінка життєвого циклу та вуглецевий слід.