Evaluation of the Carbon Footprint of Green Infrastructure Construction Materials

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Disclaimer

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This project was conducted under the mentorship of City of Vancouver staff. The opinions and recommendations in this report and any errors are those of the author and do not necessarily reflect the views of City of Vancouver or the University of British Columbia.

Territorial Acknowledgment

The author would like to begin by acknowledging that the land on which this work took place is the unceded territory of the Coast Salish Peoples, including the territories of the xʷməθkwəy̓əm (Musqueam), Skwxwú7mesh (Squamish), and səlilwətaɬ/Selilwitulh (Tsleil-Waututh) Nations.

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ABSTRACT

Green Infrastructure (GI) systems are designed to manage stormwater and runoff in urban areas and are often perceived as carbon-neutral solutions that contribute to climate-resilient urban design. This study examines the embodied carbon of GI assets across their life cycle, including construction, service life, and end-of-life phases. Findings indicate that while GI generally has low environmental impacts during operation, its construction phase can carry a significant carbon footprint. Moreover, material recycling during the decommissioning stage plays a critical role in achieving carbon neutrality.

The report starts with an introduction to GI and its important role in modern urban development. The current and most up-to-date information on the life cycle assessment and environmental footprint of GI units are then discussed. After defining the research goal, the CO_2 emissions of several frequently used GI materials are presented. The materials include crushed aggregates, soil and geotechnical systems, geosynthetics, and concrete. After setting the baseline emissions values for the materials, the CO_2 abatement strategies are introduced for each material.

Finally, a conclusion section summarizes the emission values and abatement strategies. It should be noted that the precise measurement of emission values can vary widely based on the location, producers and vendors, production and construction methods, etc. The current report is intended to set a baseline for CoV GI projects to be further refined and developed on a project basis.

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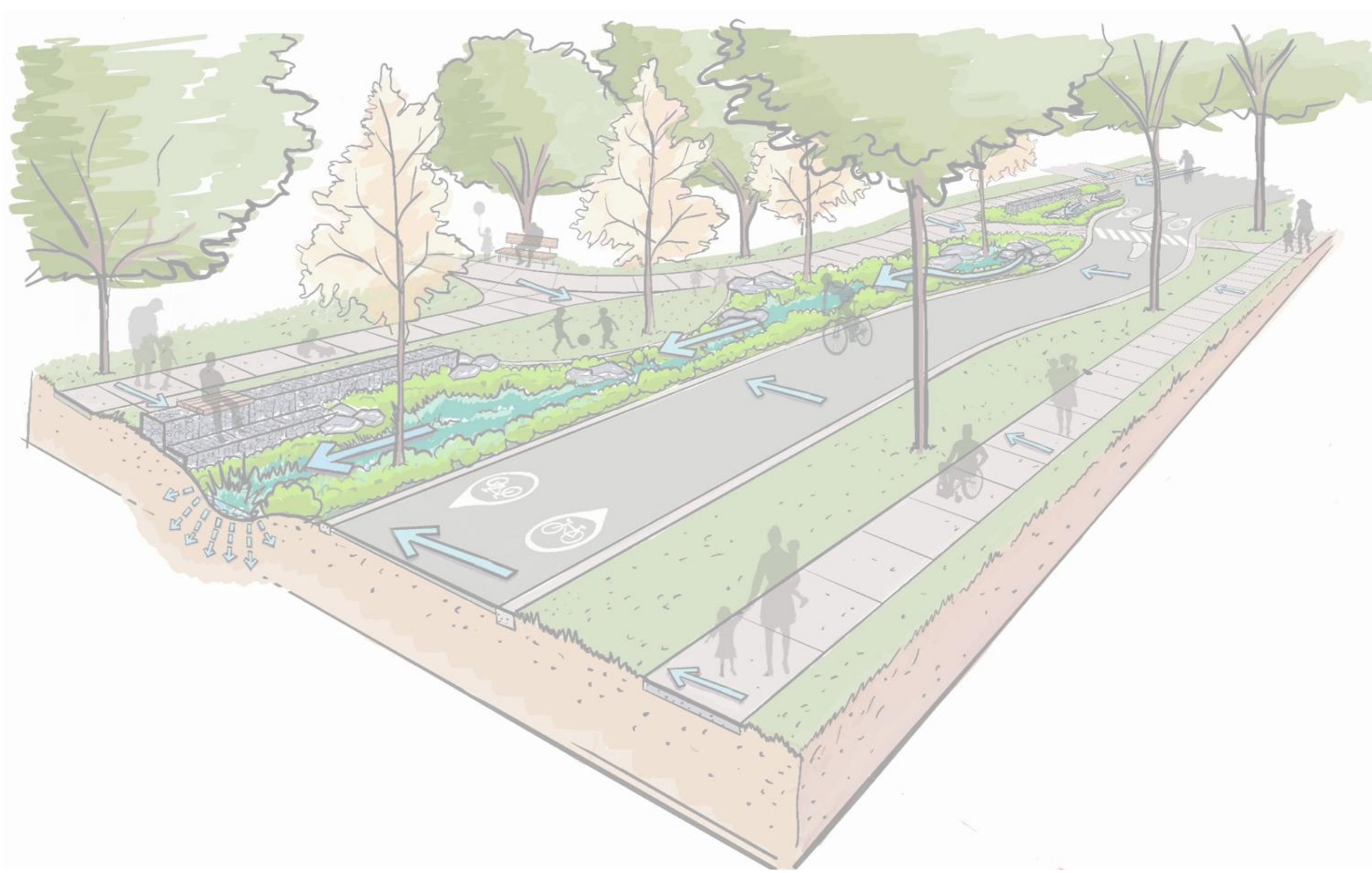
1. Introduction



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Green Infrastructure (GI) including urban forests, bioretention systems, and rain gardens is increasingly recognized as a cornerstone of sustainable urban development. GI plays a variety of roles such as stormwater management, heat island mitigation, air pollution reduction, water purification, biodiversity promotion, among others, which collectively advance climate adaptation and foster community well-being.

Despite the environmental benefits of GI, the construction materials and procedures carry significant embodied carbon that is often overlooked. Tracking the CO_2 emissions of GI is performed through a Life Cycle Analysis (LCA), taking into account the emissions attributed to the production, processing, transportation, and disposal of materials, as well as other activities during the construction and maintenance phases of the GI units. Previous LCA studies have shown that 40-80% of the embodied carbon in GI is attributed to the construction materials [1]. Since the carbon-neutrality of GI depends on the embodied carbon and the amount of avoided emissions and sequestered carbon during the life cycle of the GI, understanding the sources and magnitude of emissions in the construction phase becomes a necessity. The literature review therefore challenges the common net-zero or negative emission conviction about GI and calls for more in-depth examination of the embodied greenhouse gas emissions of the assets that may not be evident at the first glance. The current study is intended to help the City of Vancouver to get a better understanding about the environmental footprints of GI and move beyond the simplistic common beliefs.

With cities aiming for carbon neutrality, it is more important than ever to measure and reduce the carbon footprint of green infrastructure. To make real progress, we need practical tools that look at the full picture, considering emissions and carbon storage potential from the choice of materials through construction, use, and eventual replacement. This kind of holistic approach helps decision-makers weigh the trade-offs, choose smarter designs, and cut emissions without losing the environmental benefits that make green infrastructure valuable.

As of now, cities like Vancouver do not have a consistent way to measure the embodied carbon of materials and projects, nor do they have policies to guide the use of lower-carbon alternatives in green infrastructure projects. Closing this gap is essential to unlock the full climate benefits of these projects and make our urban spaces truly sustainable.

Given the globally fast urbanization rate, permeable soil and vegetation are constantly replaced by impervious pavements and rooftops. The reduced permeability as well as surface water pollution due to human activities [2] have led to an increase in the amount of runoff water volume and water contamination. As such, stormwater control measures have emerged as solutions to address the aforementioned issues [3]. Therefore, bioretention systems help with runoff volume management [4], runoff water quality [5], ease of urban implementation [6], biodiversity improvement [7], and urban heat island mitigation [8].

Bioretention systems are composed of different materials, each performing certain functions in water management, i.e., top vegetation, the substrate growth media, drainage materials and underdrain (**Fig. 1**). A short description of each bioretention component follows.

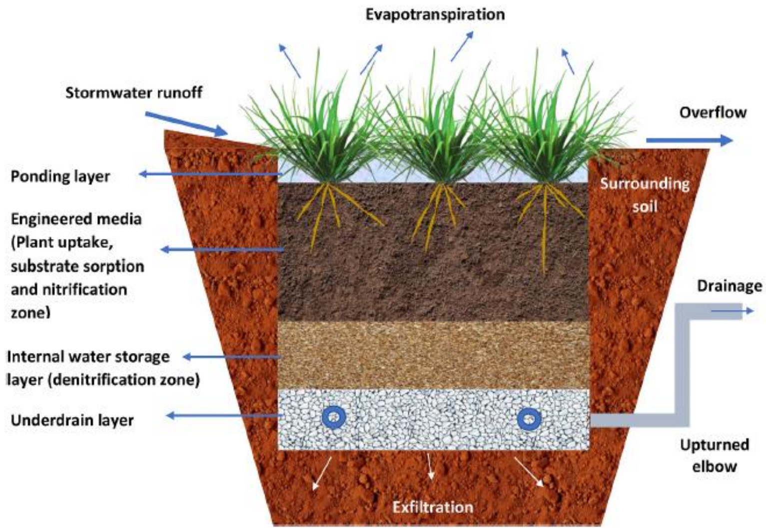

Fig. 1. Schematic representation of a bioretention system [3]

Plants

As the top layer of bioretention systems, plants play various environmental and aesthetic roles. Plants can enhance the runoff quality through phytoremediation [9]. Photodegradation can break down polycyclic aromatic hydrocarbons (PAH) to reduce the toxicity of contaminants [10,11]. Plants can play a role in removing heavy metals from runoff water through their hyperaccumulation properties [12]. Plants also remove nutrients from the water directly [13] or indirectly through soil microbial activity alteration [14]. Plants are known to improve the hydrologic properties of the system by reducing the stormwater volume by evapotranspiration and filter media clogging prevention [15,16].

Bioretention Media

Substrate plays a key role in plant growth, adjusting the infiltration rate, contamination removal, and bioretention system stability. An ideal bioretention soil is a mixture of different organic and inorganic particles in a traditional volumetric percentage of 20-30% fine soil, 30-60% sand, and 20-40% organic particles [17]. Bioretention media can improve the runoff water quality through bioremediation. Sorption capacity is an important characteristic of bioretention media, which can be practically enhanced by increasing the organic component of the soil such as seaweeds, biochar, and crustacean shells [18,19]. The influence of bioretention soil on hydrologic performance of the system should be considered in the design since the runoff is usually stored in the bioretention media and ponding zone before it is released to the sewer system and adjacent soil. Moreover, the water holding potential of the bioretention media should also be considered as an influential factor [20].

Geotextile

Geotextiles are commonly used in urban bioretention systems, with such roles as separation, filtration, drainage, protection, and reinforcement [21]. Geotextiles are separating materials that ensure distinct layers of the soils do not mix and the fine particles do not migrate in and out of the layers, thereby guaranteeing the long-term performance of the systems [22].

Crushed Aggregates

Crushed aggregates are often used in permeable pavement and bioretention systems as a transient detention mechanism, a durable reservoir and bedding layer, and a natural filter [23,24]. The aggregates are often manufactured by blasting and crushing rocks.

Structural Soil

Same as any other engineered structure, earthwork and structural soil is a main constituent. The structural soil ensures sufficient load bearing and controls pavement settlement to allowable limits.

Concrete

Concrete is the second most-consumed material on earth after water. It is used ubiquitously in the built environment due to its durability, high strength, versatility and fire resistance. As discussed later, concrete is one of the main materials used in bioretention system designs [25]. Concrete is often associated with high CO_2 emissions, accounting for around 8% of the global GHG emissions. Concrete industry is believed to emit equal to the value of emissions by all of the cars on the roads across the world.

2. Research Goal and Limitation

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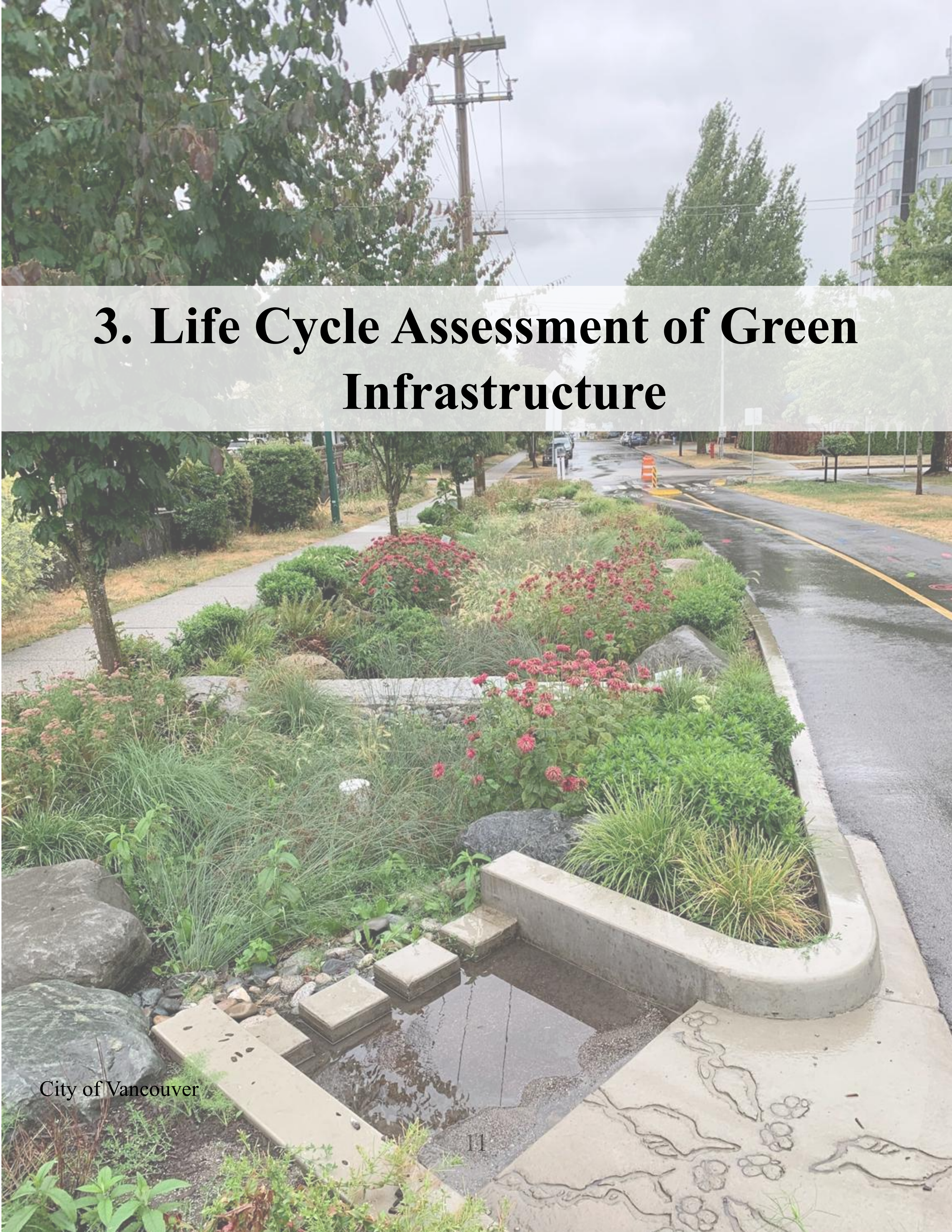
To gain a deeper understanding of the footprint of GI projects, the overall environmental impacts of GIs will be reported and validated in section 3. Based on the literature review, we will show that there is room for reducing emissions in the GI assets. Based on the coming studied literature such as Flynn and Traver [26] and Bhatt et al. [27], construction materials account for the majority of the negative environmental impacts of GIs. Specifically, the CO_2 emitted during production of the materials carries most of the global warming and climate change potential. As a result, section 4 is dedicated to the information regarding GHG emissions and environmental impacts of the construction materials often used in GI projects. LCA studies of GIs include a significant level of uncertainty in terms of the materials consumed. The assumptions commonly made in the LCA studies can add up to render the results useless, or even misleading. The current study aims to gather the most comprehensive information about the CO_2 emissions of the construction materials commonly used in the green infrastructure assets in city of Vancouver. After the CO_2 emission values are discussed, actionable tips and measures will be also suggested in section 5 to minimize the global warming impact of the materials. The discussed materials include geosynthetics, concrete, crushed aggregates, and soil (earthwork). The concluding remarks, key takeaways and the recommendations for future research are reviewed in section 6.

It is worth noting that local LCA studies are not available in most cases. As a result, the current research gathers available information from different countries and locations. The information in presented in no particular order. A more precise LCA study of each construction material for the case of GI projects in the City of Vancouver is required to reach more realistic emission values. Such studies should be tailored to the specific projects and may likely differ on a project basis within the same city. As a result, the reported information should not be treated as accurate and final emission values and are intended to help GI office to reach a baseline emission information and prioritize further research toward reaching net-zero or negative emissions in GI projects. The constructability of the low-carbon recommendations is also beyond the scope of the current study.

3. Life Cycle Assessment of Green Infrastructure



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With Low-Impact Development (LID) practices becoming more common throughout cities, structures such as Green Infrastructure (GI) are receiving more attention as sustainable methods for stormwater management. Life Cycle Assessment (LCA) is an analytical tool that captures the environmental footprint of a product across the different life phases, normally studied from cradle to gate (i.e., material acquisition, processing, and manufacturing), cradle to site (i.e., cradle to gate plus transportation to the consumption site), cradle to grave (i.e., material acquisition to end-of-life and decommission), etc. [28]. Despite the general sustainability of GI, running LCA provides the decision-making grounds to minimize the emissions of GI units. In one of such studies, Flynn and Traver [29] conducted LCA analysis on GI available on the campus of Villanova University, representing the GI in Philadelphia. These GIs included rain gardens, green roofs, subsurface infiltration beds, permeable pavements, and engineered wetlands. According to Flynn and Traver [26], the decommissioning scenario plays a significant role in the impact of GIs, where GI shows a 287.530 tCO_2 eq saving during 30 years of service life per hectare of impervious drainage area (DA) when media reuse after decommissioning is assumed (**Table. 1**) versus 34,917 $kgCO_2$ eq saving without reuse after decommissioning (**Table. 2**). For reference, Climate Emergency Action Plan report (CEAP 2025) has reported 499,000 tCO_2 eq reduction in Vancouver since 2007. Furthermore, Flynn and Traver [26] shows that most of the environmental impacts of GI stem from the construction phase, whereas the operation phase accounts for most of the evaded impacts (**Fig. 2**).

Table. 1. Rain garden total life cycle impact (30 years) with reuse decommissioning [26]

Impact category	Rain garden impact	Impact per hectare impervious DA
Global warming potential (kg CO_2 eq.)	−58,228	−287,530
Acidification potential (H+ moles eq.)	2705	13,357
Human health – cancer (kg benzene eq.)	−1.26	−6.22
Human health – non-cancer (kg toluene eq.)	−68,297	−337,251
Respiratory effects (kg PM2.5 eq.)	12.82	63.31
Eutrophication potential (kg N eq.)	−71.92	−355.14
Ozone depletion potential (kg CFC-11 eq.)	0.000192	0.000948
Eco-toxicity (kg 2,4-D eq.)	−18,401	−90,864
Smog formation potential (kg Nox eq.)	101.06	499.03
Onsite labor (h)	336	1659
Cost (2001 USD)	38,258	188,918

Table. 2. Rain garden total life cycle impact (30 years) with decommissioning disposal [26]

Impact category	Rain garden impact	Impact per hectare impervious DA
Global warming potential (kg CO_2 eq.)	−7071	−34,917
Acidification potential (H+ moles eq.)	3973	19,619
Human health – cancer (kg benzene eq.)	17,226.00	85,061.99
Human health – non-cancer (kg toluene eq.)	557,244,333	2,751,672,516
Respiratory effects (kg PM2.5 eq.)	16.62	82.07
Eutrophication potential (kg N eq.)	559.75	2,764.05
Ozone depletion potential (kg CFC-11 eq.)	0.000553	0.002731
Eco-toxicity (kg 2,4-D eq.)	4,140,160	20,444,110
Smog formation potential (kg Nox eq.)	128.05	632.31
Onsite labor (h)	336	1659
Cost (2001 USD)	38,708	191,140

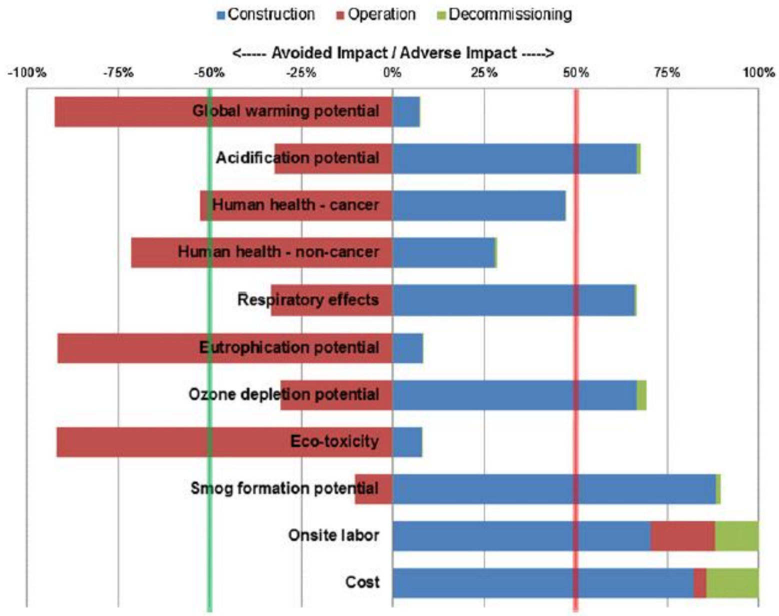


Fig. 2. Environmental impacts and benefits of GI at different life phases [26]

Despite the benefits of GI, many municipalities around the world such as those in Sweden still lack design guidelines, which leads to significant design variations of these elements [30]. Life cycle assessment of bioretention and GI systems has recently started in an attempt to identify the most sustainable design for the systems, which can help the decision makers to suitably codify the design guidelines. Recently, Sagrelius et al. [30] performed a design and construction component-based LCA on bioretention systems with geometries shown in Fig. 3 and materials in Table. 3. Unlike Flynn and Traver [26], Sagrelius et al. [30] only considered impacts from production, transportation, and installation phases, and avoided including operation, maintenance, and decommissioning phases due to the ambiguities.

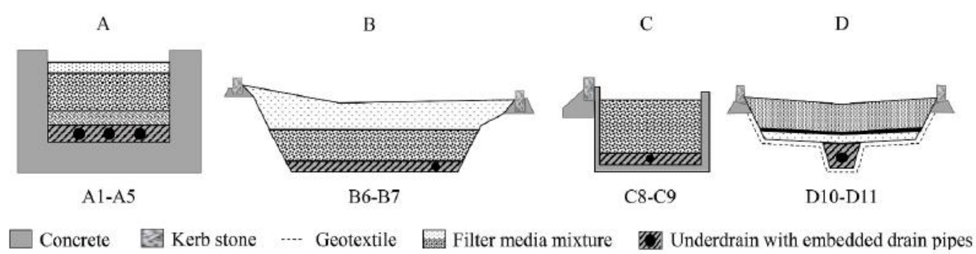


Fig. 3. Profile schematics of bioretention systems studied by Sagrelius et al. [30]

Table. 3. Materials specifications of bioretention systems studied by Sagrelius et al., taking different designs into account [30]

		A					B		C		D	
		A1	A2	A3	A4	A5	B6	B7	C8	C9	D10	D11
Bioretention area	m^2	91	91	91	30	30	300	368	99	99	52	115
Catchment area	m^2	1590	1590	1590	530	530	1500	1500	2000	2000	1400	3100
Excavation	m^3	360	360	360	120	120	450	550	100	100	105	225
Construction material												
Concrete	m^3	68	68	68	23	23	7	9	6	6	3	4
Reinforcing steel	kg	1200	1200	1200	400	400	68	92	66	66	27	45
Kerb stone	kg	540	540	540	180	180	7150	9900	6820	6820	2750	4950
Geotextile	m^2	0	0	120	0	0	0	0	0	0	76	135
PVC pipe 110	m	75	75	75	25	25	45	55	60	60	0	0
PEH pipe 110	m	0	0	0	0	0	0	0	0	0	18	31
Filter media mixture												
Sand	m^3	176	189	361	5	5	9	11	84	84	2	2
Gravel	m^3	127	115	120	36	36	51	63	11	11	13	19
Pumice	m^3	177	177	0	0	9	15	0	0	0	2	6
Biochar	m^3	0	0	0	0	0	0	0	0	11	0	0
Soil	m^3	0	0	0	119	118	241	331	17	6	16	52
Compost	m^3	0	0	0	25	9	15	0	0	0	2	6

The normalized environmental impact of different GI designs is shown in **Fig. 4**, where A1 and A2 systems incur the highest environmental impacts compared to the other designs. The high climate change impact of these two designs is attributed to the large concrete consumption, and using pumice in the filter media mixture, which is transported by ferry in Sweden (i.e., high transportation emissions). On the other hand, the C8 and C9 designs leave the lowest environmental impacts, which can be linked to the concrete replacement by granite kerb stones, as well as a filter media with shorter transportation. Bioretention area to catchment area (B/C) is another parameter that significantly affects the environmental impacts of GI designs. As such, system B with a B/C ratio of 20-25% shows the second largest environmental impacts, while similar components and filter media as system D (B/C ratio 4-6%) is used.

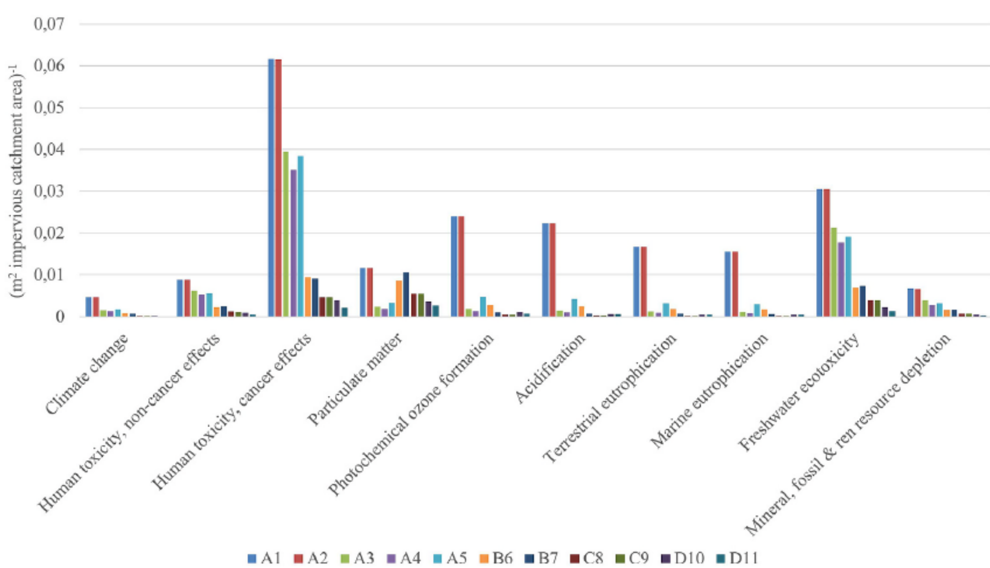
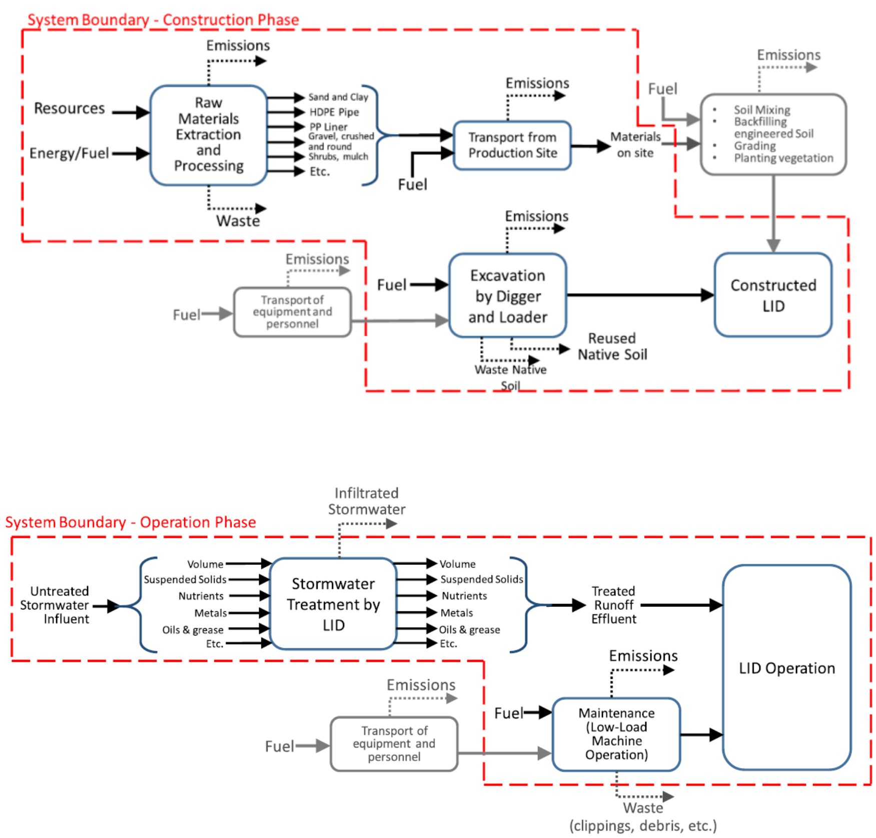


Fig. 4. Normalized environmental impacts per functional unit (m^2 impervious catchment area) by Sagrelius et al. [30]

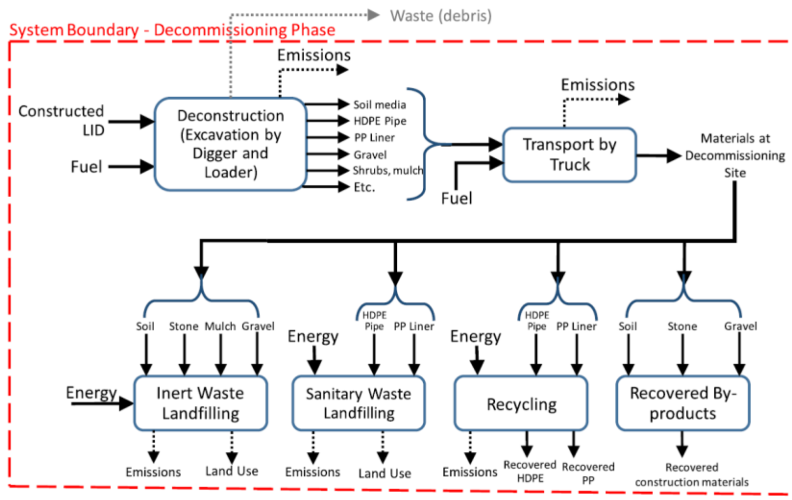
A cradle-to-grave study of three bioretention cells, three permeable pavement systems (PPS), and a hypothetical stormwater management pond was reported in Mississauga, Ontario by Bhatt et al. [27]. As stated in the report, many processes such as mixing soils to produce the soil media, surface grading, backfilling of materials, planting vegetation, etc. have not been modeled due to the LCA database limitations. Moreover, the HDPE pipes and PP geotextile liners manufacturing process are also neglected due to the data limitations, and these items are replaced with the data for manufacturing the raw HDPE and PP materials. The system boundary for the GI construction phase in depicted in **Fig. 5a**. The LCA database on GI maintenance is also significantly limited, and Bhatt et al. [27] therefore only considered the generic machine operation processes which consume diesel (**Fig. 5b**). The carbon sequestration by vegetation was not considered given the cell size without tree plantings. A 50-year service life was considered for the LCA, after which 80% recycled materials is considered upon decommissioning as observed in **Fig. 5c**.

The bioretention soil is considered to be 85% sand, 10% fines, and 5% organic matter. The amount of required material is considered based on the design, i.e., 600 mm soil depth, 200 mm pipe diameter, 150 mm base depth, and 75 mm mulch depth. The proprietary treatment technology for IX-2 and IX-3 cells were also partly considered due to the library limitations. Three different scenarios (optimistic, pessimistic, and average) were considered by Bhatt et al. [27] due to the uncertainties around transportation distances, life span, and disposal practices.



(a)

(b)



(C)

Fig. 5. System boundary (activities considered) of LCA study for the of GI in Mississauga, Ontario: a) construction, b) maintenance, and c) decommissioning [27]

Fig. 6 presents the cradle-to-grave results for the three bioretention systems (i.e., IX-2, IX-3, and IX-4) and three permeable pavement systems (i.e., IX-5, IX-6, and IX-7). The different LCA parameters are shown as ozone depletion (OD) [kg CFC-11], global warming (GW) [kg CO_2 eq], smog (S) [kg O_3 eq], acidification (A) [kg SO_2 eq], eutrophication (E) [kg N eq], carcinogenic (C) [CTUh], non-carcinogenic (NC) [CTUh], respiratory effects (R) [kg $PM_{2.5}$ eq], ecotoxicity (ECO) [CTUe], and fossil fuel depletion (FF) [MJ surplus]. The impacts are calculated per 1m^2 of drainage area and are normalized by per capita emissions in Canada in the year 2005. Based on Fig. 6, bioretention cells show remarkably reduced environmental impacts compared to the permeable pavement systems across most of the categories, with around 90% reduced GHG emissions (i.e., GW category). Please note the comparative nature of the study (e.g., IX-7 system incurring 100% GWP and the reduction in other systems are measured)

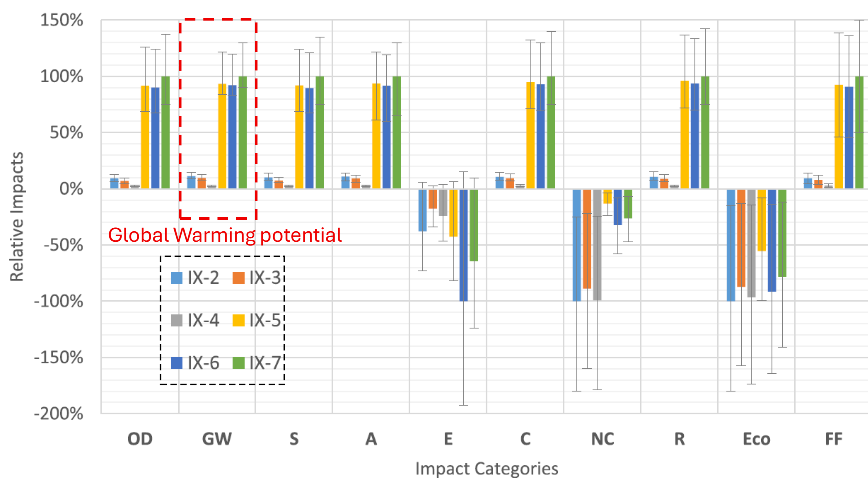


Fig. 6. Environmental impacts of three bioretention cells (IX-2,3,4) and three permeable pavement systems (IX-5,6,7) located in Mississauga [27]

A breakdown of the different life cycle parts in **Fig. 7** shows that materials manufacturing process accounts for around 50% of the environmental impacts and transportation is responsible for roughly 30% of the impacts, while the remaining portions stem from construction and maintenance.

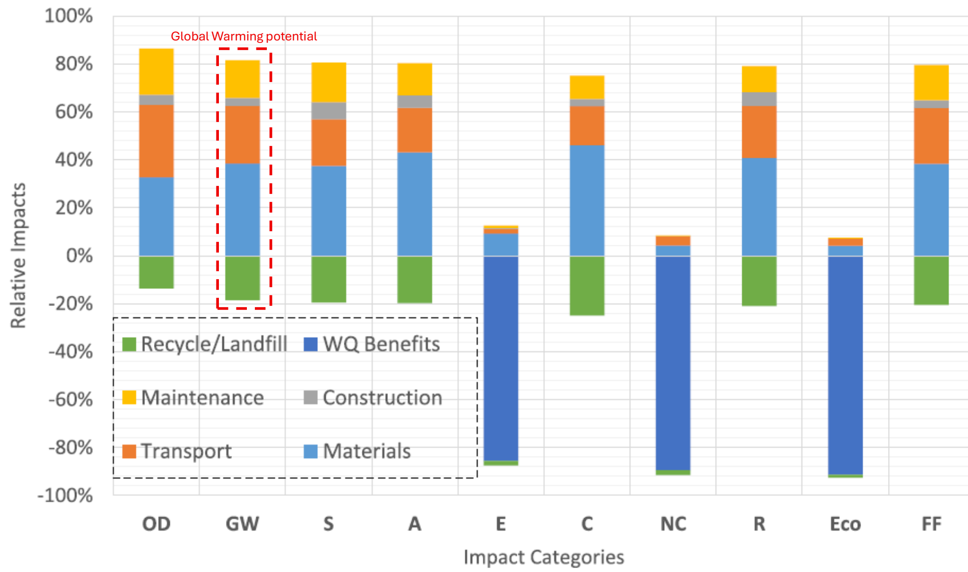
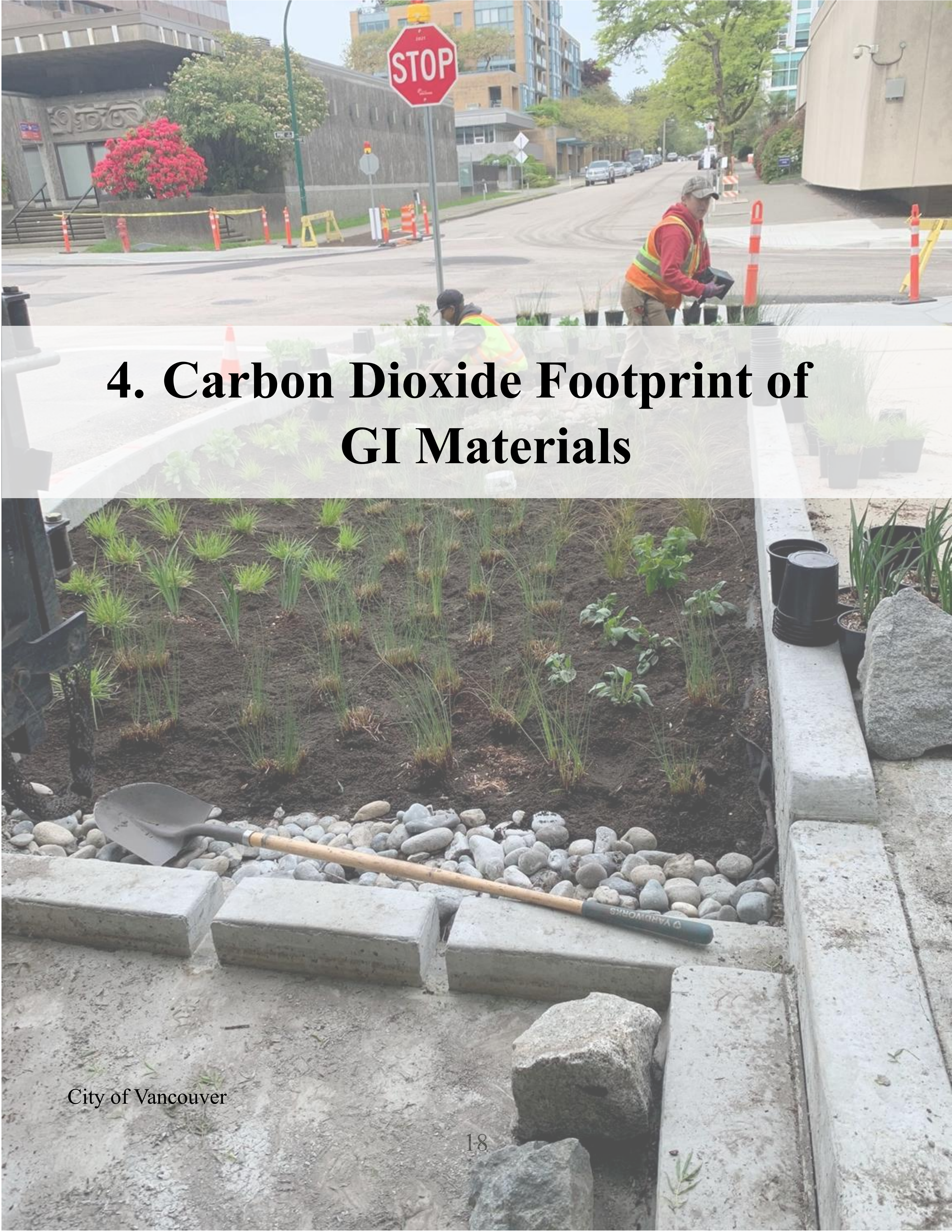


Fig. 7. Breakdown of environmental impacts of GIs located in Mississauga [27]

4. Carbon Dioxide Footprint of GI Materials



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4-1- Crushed Aggregates

Aggregates are consumed in large quantities across the globe, with an estimated 34 billion metric tons worldwide annual extraction [31]. Virgin gravel and sand account for 41% and 31% of the non-mineral resources extracted globally, respectively [31]. Given the large quantity of the aggregate consumption, it is safe to assume that a minor reduction in CO_2 emissions in this sector can have a significant global influence. de Bortoli conducted a comprehensive review of the literature on greenhouse gas emissions of aggregates, with a focus on Life Cycle Inventories (LCIs) [32]. The study reported significant shortcomings stemming from the poor input data, small sample sizes, obsolete data, missing information, changing system boundaries, and lack of reproducibility. Mining hard rocks requires a significant amount of explosives, whose influence is excluded from most of the literature. The amount of explosives consumed changes essentially with the type of rocks, which needs to be further understood for a more realistic LCA. de Bortoli's study [32] attempts to solve the issue by studying five aggregate production units in Quebec, including three fixed units of Laval (limestone), Saint Philippe (limestone), Saint Bruno (volcanic rock). Two mobile production units were used in Val-des-Monts (SDE unit) and Roxton Pond and Sainte Justine (SBE unit). The study considered both cradle-to-quarry gate and cradle-to-customer scenarios to consider the influence of transportation.

Crushed aggregates exploitation starts with drilling and blasting, after which the stones are transported from the pit to the crushing units, either using tracks or electric conveyor belts. The crushing units are either electrified or run on diesel (for mobile units). Blasting depends heavily on the type of rock, which is presented in **Table. 4**, according to which limestone requires the least amount of explosive, while hard rocks such as sandstone or volcanic rocks need more than double the amount of explosive. Moreover, blasting can also depend on the type of installation (i.e., on average mobile units may need more blasting than fixed units).

Table. 4. Explosives consumption for aggregate production based on the type of rocks [32]

Type of rock	Explosive consumption	
	kg/m^3 of rock	kg/t of rock
Limestone rocks	0.45	0.17
Dolomitic rocks and slate	0.70	0.26
Hard rocks (volcanic, sandstone)	1.00	0.37

Energy and water consumption also drive a significant portion of environmental impacts of aggregates. The average values are presented in **Table. 5**, where diesel is mainly used for stationary heavy machinery operation, gasoline for transportation and trips, LFO for heating buildings, electricity for pumping. The influence of wear and tear and amortization are also considered by de Bortoli [32]. Aggregate transportation is considered by de Bortoli [32] based on **Table. 6**.

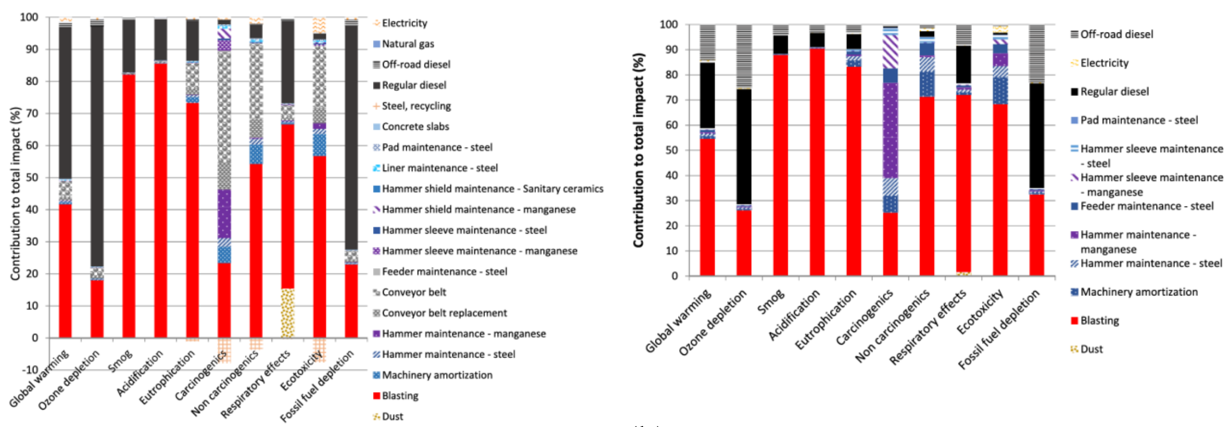
Table. 5. Average fuel and water consumption for aggregate production [32]

Production type	Diesel (L/t)	Gasoline (L/t)	LFO (L/t)	Natural gas (m3/t)	Electricity (kWh/t)	ORD (L/t)	Water (m3/t)
Fixed	1.87 E+1	4.94E-1	6.36E-4	4.25E-3	1.95 E+0	4.52E-3	1.31E-5
Mobile	8.43 E+0	0	0	0	9.40E-1	4.61E0	1.31E-5

Table. 6. Average transportation distances of aggregates [32]

Production zone	Vehicle type	Average distance from quarry to consumer (km)	Average full load (t)
GASPESIE QUARRIES	Semi-trailer	45.5	35
NORTH MATERIALS	12-wheel trucks & semi-trailer	3.1	22
AGGREGATES SAINTE-CLOTILDE	Semi-trailer	32.9	36
EASTERN TOWNSHIP QUARRIES	Semi-trailer	6.7	34
RSMM QUARRIES	Semi-trailer	19.9	37
OUTAOUAIS QUARRIES	Semi-trailer	7.9	34
QUEBEC WEIGHTED AVERAGE		***16.9***	***35.5***

The life cycle analysis for aggregate production via fixed and mobile crushing units are illustrated in Fig. 8a and Fig. 8b, respectively. Accordingly, blasting is proved to have a 42% and 55% global warming effect in aggregate production (cradle-to-gate). Burning diesel is also a major contributor to CO_2 emissions in aggregate production facilities in Quebec.



(a) (b)

Fig. 8. Hotspot analysis of crushed aggregate production using: a) fixed and b) mobile crushing units [32]

The environmental impacts of crushed aggregates are shown in details in **Table. 7**. According to this table, the studied sites emitted **2.97 and 3.03 kg$CO_{2\,eq}$/t** in 2020 and 2021, respectively, with site-specific emissions in the range of **2.28-3.59 kg$CO_{2\,eq}$/t**.

The type of rock is an influential parameter, where **Fig. 9** shows that limestone emits the least amount of CO_2 among the studied rocks.

Table. 7. Breakdown environmental impacts of crushed aggregates in Quebec [32]

Impact category	Unit	Average. 2021	Average. 2020	St Bruno	St Philippe	Laval	*SBE	**SDE
Global warming	kgCO_2eq	3.03 E+00	2.97 E+00	3.59 E+00	2.51 E+00	2.86 E+00	2.28 E+00	3.07 E+00
Ozone depletion	kgCFC-11eq	4.24E-07	4.13E-07	4.58E-07	3.89E-07	4.60E-07	3.26E-07	3.76E-07
Smog	kgO_3eq	2.83 E+00	2.82 E+00	3.58 E+00	1.85 E+00	1.94 E+00	2.15 E+00	3.48 E+00
Acidification	kgSO_2eq	1.18E-01	1.18E-01	1.51E-01	7.60E-02	7.90E-02	8.95E-02	1.47E-01
Eutrophication	kgNeq	1.11E-02	1.10E-02	1.43E-02	7.75E-03	8.16E-03	8.31E-03	1.32E-02
Carcinogenics	CTUh	4.78E-07	4.80E-07	5.53E-07	3.94E-07	4.20E-07	4.64E-07	6.19E-07
Non carcinogenics	CTUh	6.91E-07	6.79E-07	9.41E-07	5.58E-07	5.93E-07	5.02E-07	7.48E-07
Respiratory effects	kgPM2.5eq	7.14E-03	6.97E-03	9.06E-03	5.95E-03	2.09E-04	4.95E-03	7.30E-03
Ecotoxicity	CTUe	5.45 E+01	5.40 E+01	7.21 E+01	4.21 E+01	4.54 E+01	4.31 E+01	6.41 E+01
Fossil fuel depletion	MJsurplus	4.06 E+00	3.96 E+00	4.47 E+00	3.64 E+00	4.27 E+00	3.11 E+00	3.71 E+00

* SBE: Mobile crushing unit installed in Roxton Pond and Sainte Justine

** SDE: Mobile crushing unit installed in Val-des-Monts and Shawinigan sites

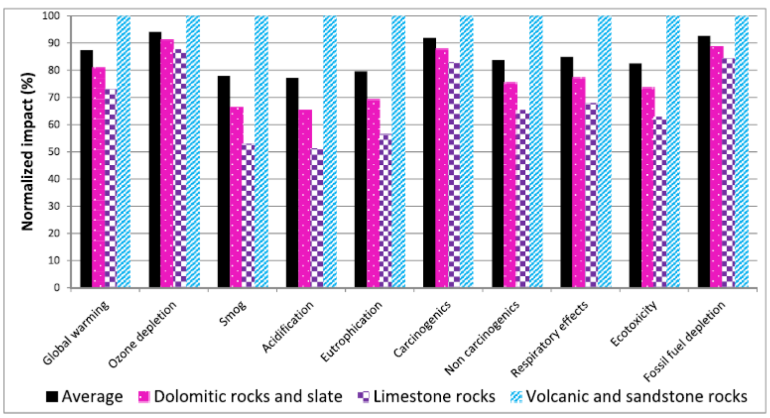


Fig. 9. Normalized comparison of the rock type influence on the environmental impacts of crushed aggregates [32]

The influence of transportation on CO_2 emissions of aggregates can be observed in **Fig. 10**, which shows that on average, transportation adds 46% to the carbon footprint from cradle to gate. The transportation emissions can increase the overall CO_2 emissions to more than double, with transportation distances as long as 45.5 km. Hence, it is safe to conclude that transportation is a significant factor, especially in the case of natural materials with intrinsically low emission values. A smarter procurement strategy with transportation minimization can halve the emissions for crushed aggregates.

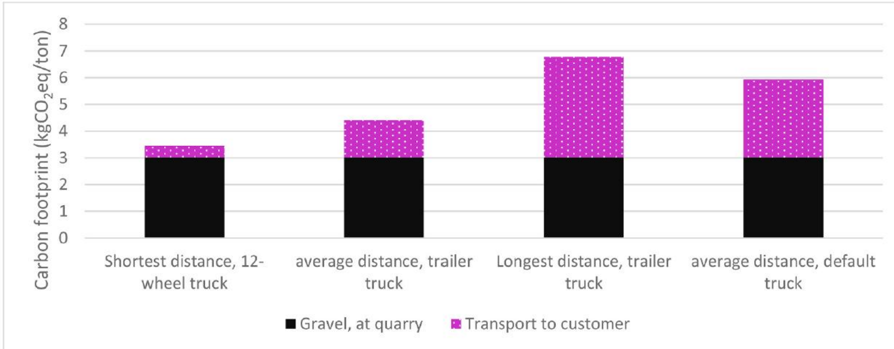


Fig. 10. The influence of transportation on CO_2 emissions of crushed aggregates [32]

Finally, **Table. 7** compares the CO_2 emissions from crushed aggregate production in Quebec to Switzerland, Brazil, and India for a cradle-to-gate scenario. According to the literature, CO_2 emissions of 2.33-3.4, 4.9, and 7.3 $kgCO_{2\ eq}/t$ have been estimated in Switzerland, Brazil, and India, respectively.

Table. 8. Carbon footprint comparison of crushed aggregates in Quebec, Switzerland, India, and Brazil [32,33]

Source	Geography	Carbon footprint (kgCO2eq/t)	Diesel consumption (MJ/t)	Electricity consumption (kWh/t)	Explosive consumption (g/t)	Type of rock	Comments
This study	Saint-Philippe	2.51	15.5	2.47	167	Limestone	
This study	Laval	2.86	19.8	4.11	167	Limestone	
This study	QC, Eurovia	3.28	18.7	1.95	275	Mixed	"gravel, fixed, average, 2021"
ecoinvent	CH	3.44	14.3	3.98	0	?	"gravel, crushed"
This study	Saint-Bruno	3.59	15.5	2.47	370	Volcanic (hard rock)	
ecoinvent	QC, EI	3.68	14.3	9.06	0	?	
ecoinvent	BR	4.86	27.2	2.74	370	Granite (hard rock)	
ecoinvent	IN	7.28	29.7	2.79	70.9	Granite and black trap stone	Basting emissions excluded

4-2- Soil and Geotechnical Systems

Earthwork is undoubtedly one of the main steps in any construction project, including GI construction. Depending on the measures taken on site, different geotechnical practices may widely differ in the environmental impact and carbon footprint. LCA studies on excavation are conducted in three different methods, i.e., performance assessment by counting the activity hours and fuel consumption, direct emission calculation from the excavators, and simulation and modeling-based analysis [34]. An Australian study by Forsythe and Ding [35] looked into the environmental impacts of cut and fill excavation on residential construction sites. According to the study, the slope of excavation area and type of soil play an important role in GHG emissions. Forsythe and Ding [35] studied 52 different sites with a wide range of soil type and slope, as indicated in **Table. 9**. The estimated emissions are presented in **Table. 10**, according to which the emissions range between **10.4 to 81.6 kgCO_2 eq/m^2** for a 1:10 slope, depending on the type of the soil.

Table. 9. Summary of excavation projects studied by Forsythe and Ding [35]

Soil type / Slopes type	Sand	Clay	Soft soil	Rock
1 in 10	5 Sites	5 Sites	4 Sites	1 Site
1 in 6	3 Sites	7 Sites	5 Sites	2 Sites
1 in 4	6 Sites	3 Sites	2 Sites	3 Sites
1 in 2	-	-	-	6 Sites
Totals	14 Sites	15 sites	11 Sites	12 Sites

Table. 10. Summary of earthwork emissions studied by Forsythe and Ding [35]

Item / Slope	Sand		Clay		Soft Soil		Rock	
	BF	GFA	BF	GFA	BF	GFA	BF	GFA
	(kgCO_2-e/m^2)		(kgCO_2-e/m^2)		(kgCO_2-e/m^2)		(kgCO_2-e/m^2)	
1:10	72.0	44.7	39.1	30.8	19.7	10.4	137.4	81.6
1:6	224.5	98.1	80.9	54.7	100.7	49.2	189.7	164.8
1:4	248.4	99.2	116.3	72.0	43.1	20.8	260.4	145.6
1:2	-	-	-	-	-	-	2394.7	892.5
Note: BF – Building footprint GFA – Gross floor area								

Lou et al. [36] recently studied the carbon footprint of earthwork on a road project in Norway by considering all three major tasks in an earthwork, i.e., excavation, transportation, and compaction. The machinery considered in the study are tabulated in **Table. 11**. Furthermore, different ground conditions and operating modes were included as discussed in **Table. 12** and **Table. 13**, respectively.

Table. 11. Machinery and volumes used to measure CO_2 emissions of earthwork [36]

Earthwork Type	Machinery	Treated soil volume (m^3)
Excavation	Excavator	319,285
Transport	Wheel dozer	42,492
	Tractor scraper	140,207
	Articulated dump truck	49,969 (site - site)
		86,617 (site - dump pit)
Compaction	Sheepsfoot roller	116,334
	Vibratory roller	116,334

Table. 12. Excavation information for different ground conditions [36]

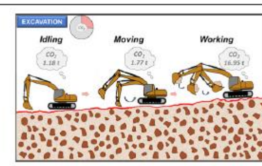
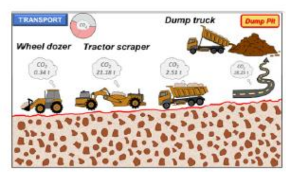
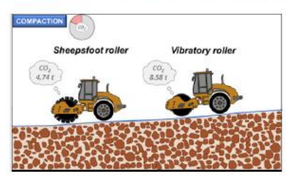
Excavation class	Workability	Ground condition	
		Soil geomaterial	Surface slope
1	Easy	Frictional	0–10°
2	Medium	Cohesive	10–20°
3	Hard	Rocky	20–35°

Table. 13. Excavation operation modes [36]

Operating modes	Excavator status	Operating time (%)	Operating power (%)
Idling	The engine runs at a lower speed (600–800 rpm) but does not perform any digging, lifting or loading tasks	25 %	10 %
Moving	The machine travels between job sites but does not perform any digging, lifting or loading tasks	15 %	25 %
Working	The machine is utilized for its functions (e.g., digging, lifting, loading)	60 %	60 %

The results of the study show that 75.5 tCO_2 is emitted during the road project, which are mentioned in detail in **Table. 14**. According to this table, transportation plays the most significant role in emissions with 56% of overall emissions, while excavation and compaction contribute to 26.36% and 17.64% of emissions. The volumetric calculations show that 319,285 m^3 soil needs to be excavated and transported, while 86,617 m^3 soil needs to be disposed. Considering the overall volume of the earthwork equal to 405,902 m^3, the CO_2 emissions are calculated as **0.186 kg CO_2/m^3**.

Table. 14. Carbon footprint of cut and fill road project [36]

Earthwork activity	Machinery	Status	CO_2 emissions			Schematic diagram
			Actual value (t)		Percentage (%)	
Excavation	Excavator	Idling	1.18	19.9	26.36	
		Moving	1.77			
		Working	16.95			
Transport	Wheel dozer	Work with load	0.18	42.28	56.00	
		Work without load	0.16			
	Tractor scraper	Work with load	10.93			
		Work without load	10.25			
	Dump truck	Work with load	8.90			
		Work without load	11.86			
Compaction	Sheepfoot roller	Working	4.74	13.32	17.64	
	Vibratory roller		8.58			

Devi and Palaniappan [34] studied the energy consumption and CO_2 emissions for excavation project of an institutional building in India that included 3-meter excavation and transportation of the soil, and did not include any soil compaction. The total volume of the excavation was 12,828 m^3 and the type of soil was soft disintegrated rock. The dump site was 2.5 km away. Devi and Palaniappan [34] considered three scenarios with different machinery used on site. The total emissions are presented in **Table. 15**. Based on this table, the measured emissions range between **15.92-20.35 kg CO_2/m^3**.

Table. 15. Energy requirement and carbon footprint of an excavation in India using three different scenarios [34]

Parameter	Scenario 'A'	Scenario 'B'	Scenario 'C'
Input			
Number of excavator(s)	1	1	2
Bucket capacity (cu.m.)	0.9	2	0.9
Number of trucks	3	6	6
Truck capacity (cu.m.)	6	6	6
Output			
Time (Days)	35	22 (−**38%**)	24 (−**32%**)
Cost (Rs.)	596,491	670,943 (+**12%**)	817,111 (+**37%**)
Energy (MJ)	214,390	204,181 (−**5%**)	261,078 (+**22%**)
Emissions (kg CO_2)	13,575	12,929 (−**5%**)	16,532 (+**22%**)

Based on the literature, it can be deduced that CO_2 emissions of earthwork rely heavily on the project, as no emission is associated with the natural and unprocessed materials. Some of the main influential parameters include transportation, type of the soil, depth of excavation, volume of excavation, slope of the area, duration of the project, type and age of machinery used, volume of the excavation and compaction. Comparing Lou et al. [36] and Devi and Palaniappan [34] may suggest that using the local soil on site versus moving the soil away can significantly increase the amount of emissions, given that transportation is the main source of pollution in earthwork.

4-3- Geosynthetics

Using geosynthetics is often associated with carbon footprint reduction in construction projects. Such carbon savings stem from the reduction in base soil layers thicknesses, and possibility of using weak local soil when it is reinforced with geosynthetics, as illustrated in Fig. 11. As such, geosynthetics can reduce the volume of earthwork, and eradicate the need for transportation and discarding the local soil.

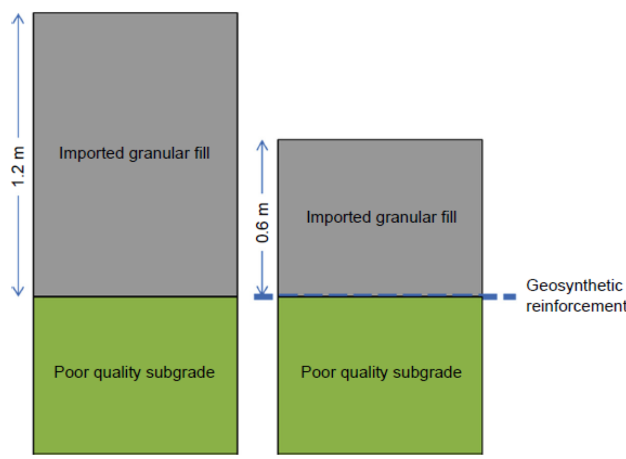


Fig. 11. The influence of geosynthetics on earthwork efficiency [37]

Using geosynthetics with a filtering function brings several clear advantages. Compared to the traditional drainage methods, they not only improve quality and cut costs but also allow for the use of less or lower-quality aggregate. This means fewer concerns about contamination or poor segregation of drainage materials during construction. However, geotextiles are still prone to clogging if exposed to a very large fine content. They also reduce the amount of excavation needed and help minimize material waste. In fact, installing geosynthetics can cost up to 50% less than using granular materials, all while improving drainage performance [38,39]

From an environmental standpoint, geosynthetics also come out ahead. For example, a geosynthetic filter layer has a significantly smaller footprint than gravel in terms of energy use, greenhouse gas emissions, acidification, eutrophication, and water consumption. That is largely because gravel has to be mined and hauled to site, which adds a substantial environmental burden [40].

A review of 25 geosynthetic applications presented at the GRI-24 conference demonstrated substantial reductions in carbon emissions compared to traditional construction techniques. On average, these geosynthetic solutions lowered the carbon footprint by 65%. Specific applications showed varying levels of reduction: retaining walls saw a 69% decrease, 65% for embankments and slopes, 76% for erosion protection, 75% in landfill covers, 30% in landfill liners, 61% for retention systems, and 40% for drainage pipes [41].

Embodied carbon (EC) refers to the total greenhouse gas emissions associated with the production of a material, expressed in tonnes of carbon dioxide equivalent per tonne of material (tCO_2e/t). These values can represent emissions from different life cycle stages. Most commonly, EC values are reported from cradle to gate, encompassing emissions from raw material extraction through to the point the product leaves the manufacturing facility. Less frequently, EC is reported from cradle to site, which includes emissions from transportation to the construction location (Fig. 12).

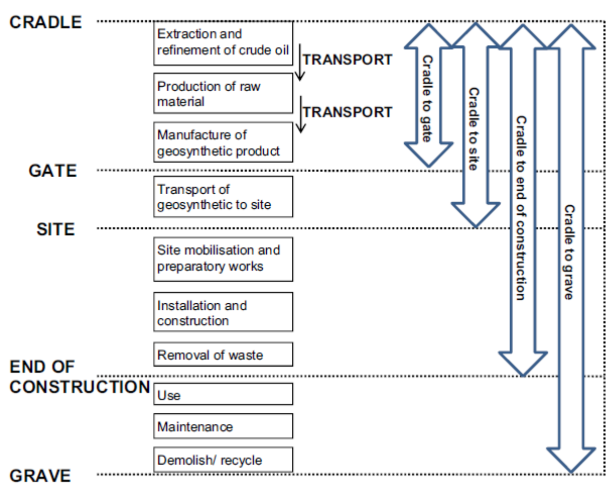


Fig. 12. Life cycle boundaries incorporated in geosynthetics carbon dioxide emission calculations [42]

One of the most widely used sources for EC data in construction is the Inventory of Carbon and Energy (ICE) database compiled by Hammond and Jones [43], which provides cradle-to-gate emission factors for a wide range of materials. Another commonly referenced source is EcoInvent v3.0 (EIC, 2013) [44], a comprehensive European life cycle analysis database. However, EC values can vary significantly between sources due to differing methodological assumptions, including boundary conditions, production technologies, and material specifications [45]. The base embodied carbon values for raw materials in geosynthetics are presented in **Table 16**.

Table. 16. Embodied carbon values for different types of plastics used in geosynthetics [42]

Material	Embodied carbon (kg CO_2e/kg)		
	ICE v2.0, 2011	ICE v1.6a, 2008	EcoInvent v2.2, 2010
General plastic	3.31	2.53	–
General polyethylene	2.54	1.94	–
High-density polyethylene (HDPE)	1.93	1.60	1.91
HDPE pipe	2.52	2.00	–
Low-density polyethylene (LDPE)	2.08	1.70	2.06
LDPE film	2.60	1.90	2.66
Polypropylene, orientated film	3.43	2.70	–
Polypropylene, injection moulding	4.49	3.90	–
Polypropylene, granules	–	–	1.98
Polyester, granules	–	–	2.70
Polyester, granules – bottle grade	–	–	2.90

Energy consumption by Raja et al. [42] was directly measured on the manufacturing lines of selected geosynthetic products. These energy inputs were converted into CO_2 emissions using fuel-specific emission factors, based on the UK's published conversion factors: 0.44548 kgCO_2e/kWh for electricity and 0.18404 kgCO_2e/kWh for natural gas [46]. This enabled calculation of cradle-to-gate embodied carbon, incorporating both material emissions and process-related emissions.

Additionally, because this study adopts cradle-to-gate boundaries, emissions associated with transporting raw materials to the manufacturing facility were also included. While the EC of polymer pellets used in geosynthetic production is generally reported on a cradle-to-gate basis, thus covering upstream emissions, the transport of these pellets from the polymer producer to the geosynthetic manufacturer required separate estimation and inclusion.

Four geosynthetic manufacturers participated in this study, two of which provided data on different types of nonwoven geotextiles, i.e., extruded geogrids and woven geogrids. Notably, the two nonwoven geotextile manufacturers used different production techniques. Manufacturer A utilized a needle-punching process, while Manufacturer B primarily relied on thermal bonding, though both processes may be used in combination on certain production lines. The CO_2 emissions due to the manufacturing phase of geosynthetics are tabulated in **Table 17**.

Table. 17. Emission breakdown due to the manufacturing phase of geosynthetics [42]

Manufacturer	Type	Product	Material	Mass (kg/m^2)	Energy (electricity)		Carbon emissions (tCO_2e/t)
					(kWh/t)	(kWh/m^2)	
A	Nonwoven geotextile (needle-punched)	1	PP	0.371	144.689		0.064
		2	PP	0.366	143.155		0.064
		3	PP	0.539	109.966		0.049
		4	PP	0.642	107.422		0.048
		5	PP	1.120	101.343		0.045
		6	PP	1.233	110.110		0.049
B	Nonwoven geotextile (thermally bonded/ needle-punched)	–	–	–	Electricity (kWh/t)	Gas (kWh/t)	–
		1	PP	0.07–0.15	222	620	0.213
		2	PP	0.135–1.2	240	315	0.165
C	Geogrid (extruded)	1	PP	0.232	–	–	–
		2	PP	0.290	–	–	–
		3	PP	0.320	–	–	–
D	Geogrid (woven)	1	PET	0.530	–	–	–

PET, polyester; PP, polypropylene.

By combining the recorded energy consumption with the appropriate emissions factors, the cradle-to-gate embodied carbon for each product type was calculated. For nonwoven geotextiles, the average embodied carbon value from Manufacturers A and B was determined to be approximately **2.35 tCO_2e/t** (Table 18).

Table. 18. Embodied carbon of manufactured geosynthetics [42]

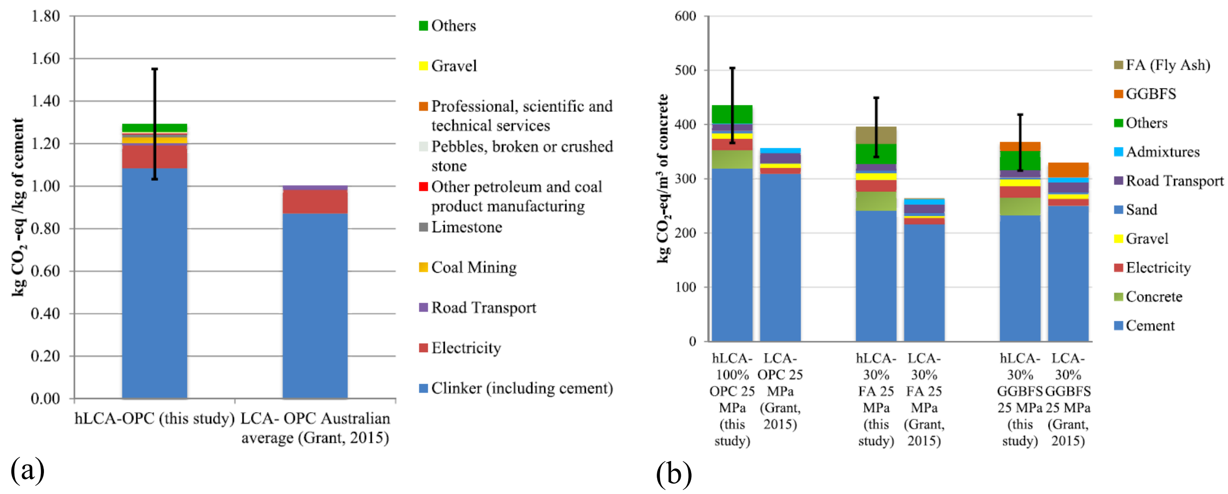
Manufacturer	Type	PP embodied carbon (tCO_2e/t)	Granules to fibre (tCO_2e/t)	Average manufacturing carbon emissions (tCO_2e/t)	Total embodied carbon (tCO_2e/t)
A	Nonwoven geotextile (needle-punched)	1.983	0.241	0.053	2.28
B	Nonwoven geotextile (thermally bonded/ needle-punched)			0.189	2.42
C	Geogrid (extruded)		–	0.987	2.97
D	Geogrid (woven)	–	–	–	2.36

4-4- Concrete

Concrete is a primary material used for sidewalks and infrastructures due to its durability and long service life, but it's also a major emitter of CO_2, primarily because of the cement content. Globally, cement production contributes approximately 8% of total CO_2 emissions, with 80% of a concrete mix's embodied emissions attributed to its cement component. Teh et al. [47] examined the amount of cement and concrete emissions in Australia through a hybrid LCA (hLCA), combining the process analysis with environmentally extended input-output analysis. As indicated in **Fig. 13a**, hLCA measurement shows 1.3 $kgCO_{2\,eq}$/kg of cement, compared to 1.0 $kgCO_{2\,eq}$/kg results from conventional LCA. The authors attribute the higher CFI in hLCA to the economy-wide system boundary, considering industry supply chains across the board. **Fig. 13b** shows the emissions for 25 MPa concrete with zero supplementary cementitious materials (SCMs), 30% fly ash (FA), and

30% ground granulated blast furnace slag (GGBFS). Accordingly, hLCA indicates around **430 kgCO$_{2\ eq}$/m^3**, while LCA yielded around 355 kgCO$_{2\ eq}$/m^3. Replacing **30% of cement with FA** and **GGBFS** reduces the emissions to **400** and **365 kgCO$_{2\ eq}$/m^3**, respectively. Notably, **Fig. 13c** shows **510 kgCO$_{2\ eq}$/m^3 for 50 MPa concrete**, which can be reduced by around 35% when switching to a geopolymer concrete of the same strength.

A study by Hottle et al. [48] delved into the emissions associated with the cement and concrete production and consumption in US based on a cradle-to-gate study. As shown in **Table. 19**, the results indicate 959 and **97.6 kgCO$_{2\ eq}$/t** for cement and concrete, respectively.



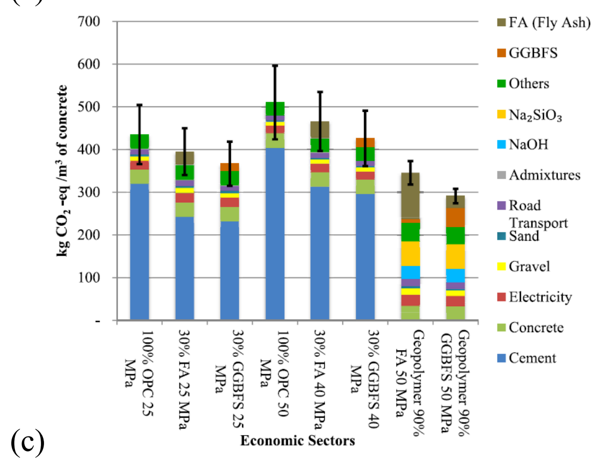


Fig. 13. Carbon footprint of a) cement, b) 25 MPa concrete, and c) alternative concretes in Australia [47]

Table. 19. National emissions of cement and concrete in the United States versus Portland Cement Association (PCA) measurements [48]

		Cement cradle-to-gate (tonne cement)			Concrete cradle-to-gate (tonne concrete)	
		Calculated National Average	PCA (2006)	PCA EPD (2016)	Calculated National Average	PCA (2007)
CO_2-eq.	kg	959	927	1040	97.6	88.0
CO_2	kg	938	927	-	95.3	87.9
CH_4	g	364	4.76	-	44.9	3.65
N_2O	g	6.93	-	-	0.748	-
SO_X	g	417	1,660	-	47.3	120
$PM_{2.5}$	g	128	0.0911	-	26.9	0.0153
PM_{10}	g	235	296	-	77.0	215
NO_X	g	1,360	2,500	-	168	237
CO	g	1,260	1,100	-	135	113
VOCs	g	109	50.2	-	81.5	6.33

Zhang et al. [49] studied the emissions associated with cement and concrete production in Hong Kong. According to the study, cement production emits 1.008 $kgCO_{2\ eq}$/kg cement, mainly caused by limestone calcination and coal combustion as indicated in Table. 20. Further, Zhang et al. [49] calculation shows 0.1808 $kgCO_{2\ eq}$/kg concrete, considering 2350 kg/m^3 density, as indicated in Table. 21. Finally, Table. 21 compares Zhang et al. [49] results with available dataset, indicating carbon footprint in the range of **424.89 $kgCO_{2\ eq}/m^3$ of concrete**.

Table. 20. Carbon footprint of cement production in Hong Kong [49]

	kg CO_2-e/kg clinker	kg CO_2-e/kg cement
Upstream material		
Limestone	3.699×10^{-3}	3.206×10^{-3}
Sand	2.800×10^{-4}	2.427×10^{-4}
Clay	2.075×10^{-4}	1.798×10^{-4}
Iron ore	8.751×10^{-5}	7.584×10^{-5}
Coal	1.644×10^{-2}	1.424×10^{-2}
Total CO_2-e	2.071×10^{-2}	1.795×10^{-2}
Cement manufacture		
Calcination	0.551	0.478
Coal combustion	0.348	0.302
Electricity consumption	0.051	0.080
Imported clinker	NA	0.058
Total CO_2-e	0.950	0.917
Transport		
Limestone	5.223×10^{-2}	4.527×10^{-2}
Sand	3.486×10^{-4}	3.021×10^{-4}
Clay	2.789×10^{-4}	2.417×10^{-4}
Iron ore	2.130×10^{-3}	1.846×10^{-3}
Imported clinker	4.472×10^{-3}	3.877×10^{-3}
Coal	2.163×10^{-2}	1.875×10^{-2}
Cement	3.770×10^{-3}	3.267×10^{-3}
Total CO_2-e	8.486×10^{-2}	7.355×10^{-2}
Overall total CO_2-e emission	1.056	1.008

Table. 21. Carbon footprint of ready-mix concrete production in Hong Kong [49]

	kg CO_2-e/m^3 concrete	kg CO_2-e/kg concrete
Upstream material		
Cement	409.73	0.1744
Aggregate	5.90	0.0025
Fly ash	0.30	0.0001
Total CO_2-e	415.94 [a]	0.1770[a]
Concrete batching		
Electricity supplier 1	1.47	6.2457×10^{-4} [b]
Electricity supplier 2	0.04	1.7499×10^{-5} [b]
Total CO_2-e	1.51	0.0006
Transport		
Raw materials within HK	0.94	3.9856×10^{-4}
Raw materials from mainland	5.89	2.5037×10^{-3}
Products transport	0.61	0.0003
Total CO_2-e	7.44	0.0032
Total CO_2-e emission	424.89	0.1808

Table. 22. Comparative carbon footprint of cement and ready-mix concrete production in Hong Kong and other available datasets [49]

Database	kg CO_2-e/kg cement	kg CO_2-e/kg concrete	kg CO_2-e/m^3 concrete	System boundary
ICE	0.950[a]	0.1810[b]	425.35[c]	Cradle to gate
CLCD	0.768[d]	ND	321.63[e]	Cradle to gate
Japan CFP database	0.882[f]	ND	346[g]	Cradle to gate
Korea LCI database	0.944[h]	ND	346[i]	Cradle to gate
This study	1.005	0.1805	424.28	Cradle to gate
This study	1.008	0.1808	424.89	Cradle to site

Values only represent CO_2 emission

[a] Average CEM I Portland cement

[b] 400 kg CEM I/m^3 concrete

[c] Back-calculated based on concrete density of 2,350 kg/m^3 (Hammond and Jones 2011)

[d] Chinese market average level of cement produced by large-scale (>4,000 t/day clinker) dry process technology (CLCD 2010)

[e] C30 concrete (CLCD 2008)

[f] Portland cement

[g] Ready mix concrete (JEMAI 2012)

[h] Portland cement type 1 (KEITI 2002)

[i] Ready mix concrete (KEITI 2008)

Arrigoni et al. [50] explored the concrete emissions in Ontario, while considering the influence of Supplementary Cementitious Materials (SCMs). The results of the study considering SCMs will be discussed later in the recommendations section. The amount of CO_2 emissions of non-air entrained concrete without SCMs with different compressive strength and slump values of 80 and 150 mm are reported in **Table. 23** [50]

Table. 23. Carbon footprint (kgCO_2 eq/m^3) of concrete with different slump and strength in Ontario [50]

	Compressive Strength (MPa)					
Slump (mm)	5	15	25	35	45	55
80	196	250	315	381	456	570
150	204	261	330	398	487	598

Arrigoni et al. [50] did not treat all SCMs as avoided waste (cut-off method) and took a substitution approach if there was more request to use a SCM than it's production amount. As such, they provided **Table. 24**, which shows the emissions associated with each SCM. Based on this table, GGBFS is not considered as a cut-off SCM due to the high demand, and therefore carries 0.825 kg$CO_{2\ eq}$/kg (versus 0.940 kg$CO_{2\ eq}$/kg for cement). It is therefore important to consider the difference between the cut-off and substitution methods when considering the emissions of the concrete commonly consumed in CoV GI projects.

Table. 24. Carbon footprint of different SCMs in Ontario [50]

Concrete material	Cut-off approach			Substitution approach					
	Processing	Transport	Total	Substitute material	Correction factor[e]	Processing	Transport	Avoided disposal	Total
	g CO_2e/kg	g CO_2e/kg	g CO_2e/kg			g CO_2e/kg	g CO_2e/kg	g CO_2e/kg	g CO_2e/kg
Portland cement	940 (Cement Association of Canada, 2016)	2	942	N.A.	N.A.	940	2	0	942
Fly ash	0	24	24	N.A.	N.A.	0	24	−86	−62
Ground bottom ash	24	24	48	N.A.	N.A.	24	24	−86	−38
Ground calcium carbide residue	44	36	80	N.A.	N.A.	44	36	−19	61
Ground granulated blast-furnace slag	44	9	54	PC	0.9	940	2	0	825
Ground rice husk ash	4	93	97	Ground wood ash	1	0	2	−21	−17
Metakaolin[f]	0	11	11	Metakaolin (non-by-product)	1	273[g]	191	0	464
Oil shale ash	0	116	116	N.A.	N.A.	0	116	−86	30
Silica fume	0	17	17	PC	2.9	940	2	0	2750
Volcanic ash	0	256	256	N.A.	N.A.	0	24	−13	240
Limestone filler	20 (Wernet et al., 2016)	0	20	N.A.	N.A.	20	0	0	20
Recycled concrete aggregate	1 (Ding et al., 2016)	2	3	N.A.	N.A.	1	2	−13	−10

[e] Correction factor (kg substitute material per kg of material substituted) indicates the average mass of unconstrained alternative (substitute) necessary to replace each kg of constrained SCM (substituted) to obtain the same required concrete properties. A sensitivity analysis on these factors is reported in Section S3.2 of the supplementary data.
[f] Metakaolin can be both a by-product and a reference product. Data for use refer to both, because detailed information was not available.
[g] The closest unconstrained supplier to Ontario uses natural gas for calcination (O'Neill, 2019).

Concrete mix RMXY1503 from Lafarge's (now Amrize) Kent Avenue Ready-Mix Plant, is a typical ready-mix product used in City of Vancouver sidewalk projects. This mix meets the specifications of CoV Mix 1503 for pavements, crossings, curb and gutter, and sidewalks as shown in **Table. 25**.

Table. 25. City of Vancouver Mix 1503 specifications

Property	Specification
Typical Use	Pavements, Crossings, Curb and Gutter, and Sidewalks
Cement Type	GUL (HE if required)
Maximum Aggregate Size	20mm
Slump	80mm ± 30mm
Air Content	5%-8%
Strength Accelerator	As needed
Hot Water	When required
Exposure Class	C2
Compressive Strength	Min. 20MPa for traffic loading unless otherwise allowed by the *City Engineer* and 32MPa at 28-day

Its cradle-to-gate emissions (life cycle stages A1–A3: raw material extraction, transport, and manufacturing) are summarized in the Environmental Product Declaration (EPD, **Fig. 14**) and leads to a GWP of 244 kgCO_2 eq/m^3 as follows:

• A1 (raw materials): 208 kg CO_2-eq/m^3

• A2 (transport): 10.1 kg CO_2-eq/m^3

• A3 (manufacturing): 5.42 kg CO_2-eq/m^3

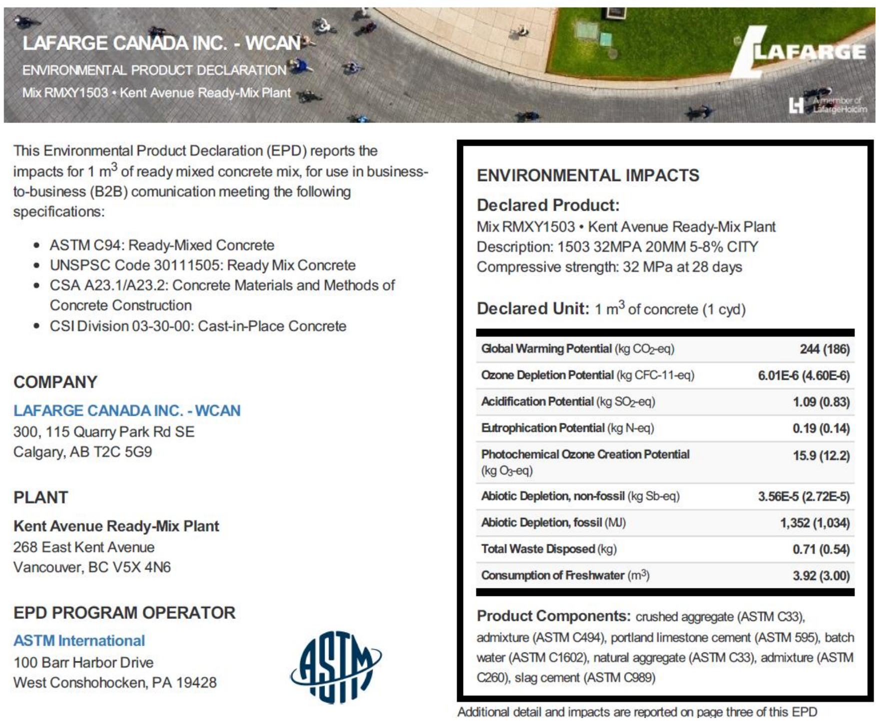
• Total: 224 kg CO_2-eq/m^3

Over 90% of concrete emissions occur during the cradle-to-gate phase, mainly due to cement production. Cement emissions arise from:

• Calcination (51%): Chemical decomposition of limestone

• Combustion (34%): Fossil fuels used to heat kilns

• Other factors (15%): Grinding, transport, handling



LAFARGE CANADA INC. - WCAN
ENVIRONMENTAL PRODUCT DECLARATION
Mix RMXY1503 • Kent Avenue Ready-Mix Plant

This Environmental Product Declaration (EPD) reports the impacts for 1 m^3 of ready mixed concrete mix, for use in business-to-business (B2B) comunication meeting the following specifications:

- ASTM C94: Ready-Mixed Concrete
- UNSPSC Code 30111505: Ready Mix Concrete
- CSA A23.1/A23.2: Concrete Materials and Methods of Concrete Construction
- CSI Division 03-30-00: Cast-in-Place Concrete

COMPANY

LAFARGE CANADA INC. - WCAN
300, 115 Quarry Park Rd SE
Calgary, AB T2C 5G9

PLANT

Kent Avenue Ready-Mix Plant
268 East Kent Avenue
Vancouver, BC V5X 4N6

EPD PROGRAM OPERATOR

ASTM International
100 Barr Harbor Drive
West Conshohocken, PA 19428

ENVIRONMENTAL IMPACTS

Declared Product:
Mix RMXY1503 • Kent Avenue Ready-Mix Plant
Description: 1503 32MPA 20MM 5-8% CITY
Compressive strength: 32 MPa at 28 days

Declared Unit: 1 m^3 of concrete (1 cyd)

Global Warming Potential (kg CO_2-eq)	244 (186)
Ozone Depletion Potential (kg CFC-11-eq)	6.01E-6 (4.60E-6)
Acidification Potential (kg SO_2-eq)	1.09 (0.83)
Eutrophication Potential (kg N-eq)	0.19 (0.14)
Photochemical Ozone Creation Potential (kg O_3-eq)	15.9 (12.2)
Abiotic Depletion, non-fossil (kg Sb-eq)	3.56E-5 (2.72E-5)
Abiotic Depletion, fossil (MJ)	1,352 (1,034)
Total Waste Disposed (kg)	0.71 (0.54)
Consumption of Freshwater (m^3)	3.92 (3.00)

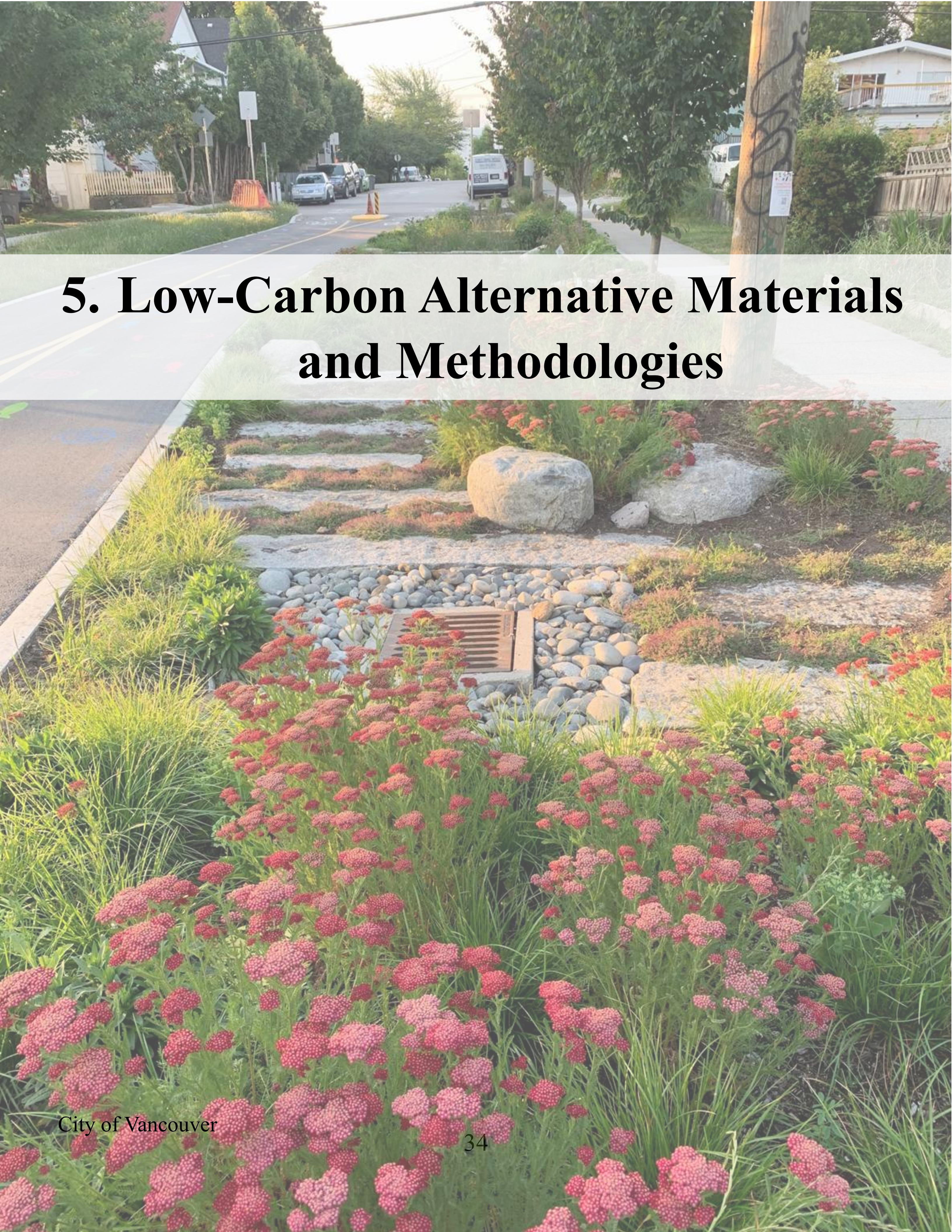
Product Components: crushed aggregate (ASTM C33), admixture (ASTM C494), portland limestone cement (ASTM 595), batch water (ASTM C1602), natural aggregate (ASTM C33), admixture (ASTM C260), slag cement (ASTM C989)

Additional detail and impacts are reported on page three of this EPD

Fig. 14. Environmental Product Declaration (EPD) for Lafarge RMXY1503 mix as provided by Amrize Ltd.

Replacing clinker with low-carbon SCMs offers the most effective and deployable solution. This approach is widely followed by the industry. While EPD for RMXY1503 does mention SCM consumption, it is not clear how much cement has been replaced by such materials. On the other hand, the EPD states that a cut-off method has been used for GGBFS, which may have added up to lower emissions than when a substitution method is used as suggested earlier in Arrigoni et al. [50]. Therefore, it is suggested that this point is discussed further with any concrete provider to CoV projects.

5. Low-Carbon Alternative Materials and Methodologies



This section discusses recommendations across the four materials previously introduced in order to reduce the emissions of GI assets during their construction phase. Relevant literature studies are also presented wherever available.

5-1- Crushed Aggregates Alternatives

As discussed earlier by de Bortoli [32], the type of rock can majorly influence the amount of emissions in the crushed aggregates production process. Based on **Table. 4**, limestone requires the least amount of explosive, followed by dolomitic rocks, and hard rocks such as volcanic rocks and sandstones which consumed the highest amount of rocks in the study. As a result, adding the type of rocks for crushed aggregates in CoV specifications can help to reduce the unnecessary emissions. Furthermore, transportation is another key player in emissions from crushed aggregates, which can vary widely on a project basis. Therefore, the interaction between rock type and transportation distance should be considered, i.e., sourcing a soft rock from further distance may increase the emissions.

Another option for emission reduction in aggregates can be full (or partial) replacement with Recycled Concrete Aggregates (RCA). RCA is produced from end-of-life concrete structures and elements and has recently gained attention due to the circular economy benefits that it offers. Using RCA can reduce emissions in multiple ways, i.e., avoiding natural materials consumption that require blasting [51], avoiding landfilling the waste concrete [52], and long-term carbonation of RCA [53] (this will be further explored in suggestions for concrete). On the other hand, RCA can reduce the costs of materials up to 60% [54]. Ghanbari et al. [55] compared three scenarios for aggregates consumption, i.e., natural aggregates, recycled aggregates from construction and demolition waste, and a hybrid method (50% replacement), as described in **Fig. 15**.

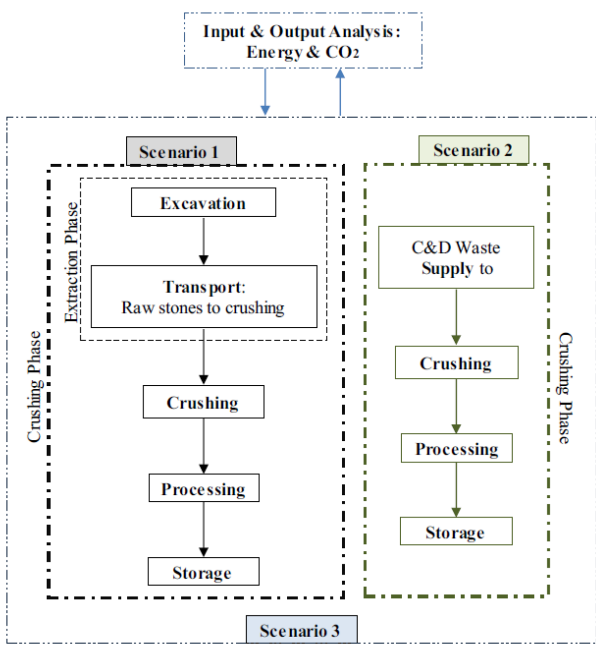


Fig. 15. Life cycle assessment procedures studied by Ghanbari et al. [55]

According to the results shown in Table. 26 and Fig. 16, consuming recycled aggregates can lead to significant emission abatement and lower energy consumption. GHG emissions in natural aggregates are mostly related to the extraction phase, where more diesel is consumed, which is different from the recycled aggregate case. Based on Ghanbari et al. [53], emissions more than tripled between the recycled and natural aggregate cases.

Table. 26. Energy consumption and CO_2 emissions of aggregates in the scenarios studied by Ghanbari et al. [55]

Aggregate obtaining type	Processing step (parameter)	Primary specific energy demand (toe/year) and contribution (%)	Specific CO_2eq emissions (ton CO_2eq/year) and contribution (%)
Scenario 1	Extraction and mining	444.31 and 40.2	1347.16 and 63
	Crushing and screening	660.50 and 59.8	792.60 and 37
	Total	1104.82	2139.76
Scenario 2	Pre crushing	42.43 and 9.7	128.65 and 21.4
	Crushing and screening	393.94 and 90.3	472.72 and 78.6
	Total	436.37	601.37
Scenario 3	Extraction and mining	243.37 and 31.6	737.90 and 53.8
	Crushing and screening	527.22 and 68.4	632.66 and 46.2
	Total	770.59	1370.57

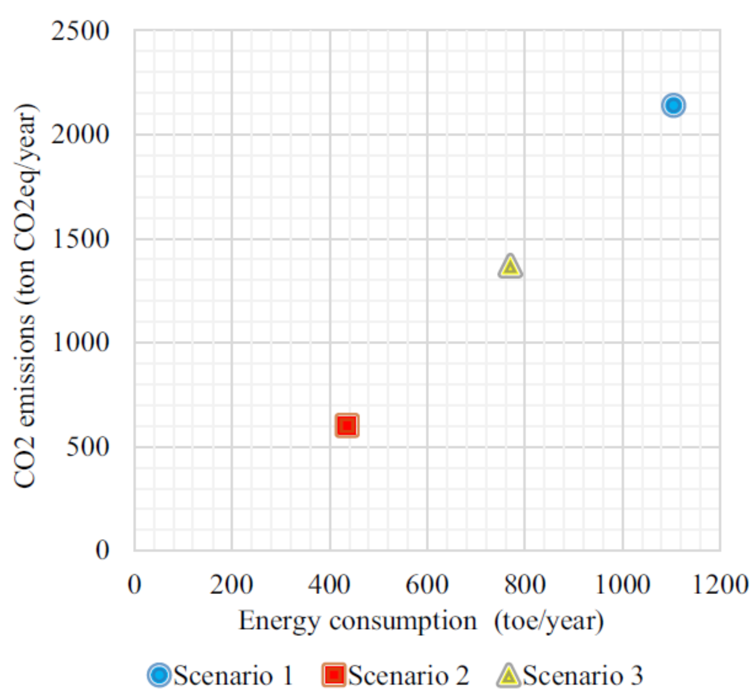


Fig. 16. Comparative chart of energy consumption and emissions by Ghanbari et al. [55]

Another option for reducing the emissions from aggregate consumption is using recycled glass formed as aggregates. There is an existing body of knowledge regarding the emission comparison of natural aggregates and recycled glass. Tushar et al. [56] investigated the environmental impacts of using recycled glass aggregates (RGA) in road pavements and pipeline bedding. The study included the influence of both washing and crushing of the waste glass and considers one ton of RGA as functional unit and compares it to one ton of sand from quarry extraction. Most of the glass is recycled (90%) and 5% is deleterious and toxic waste while the other 5% contain bricks, plaster, etc. Tushar et al. [56] study considers RGA as a replacement for 150 mm sand backfill compacted to a minimum of 95% of the standard proctor density (**Fig. 17**). The environmental impact scores of washing and crushing glass are shown in **Table. 27**.

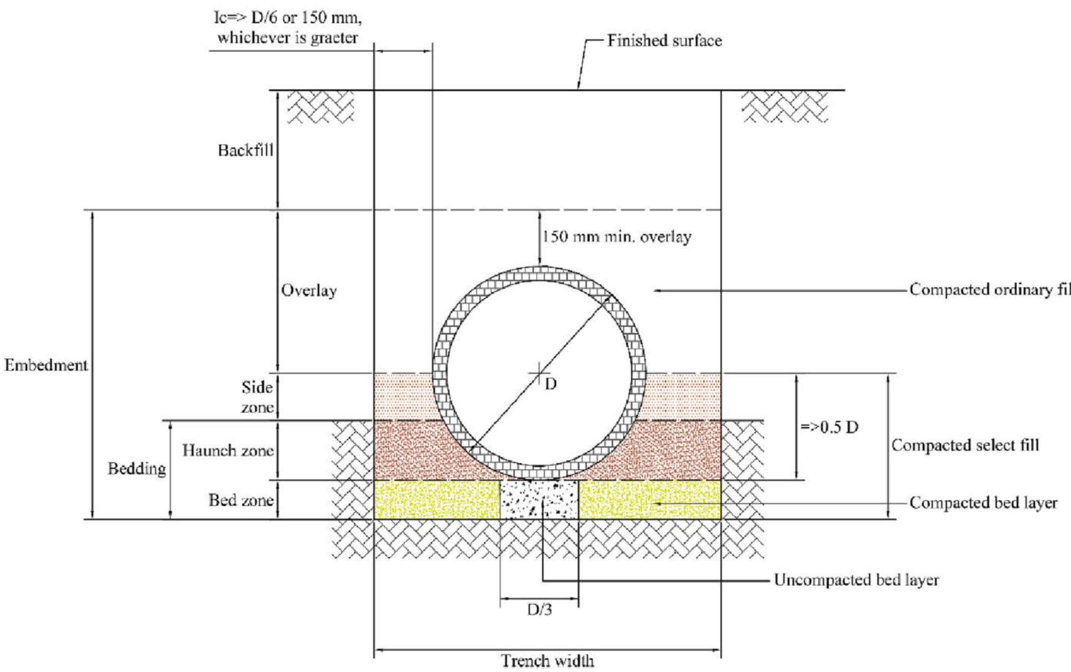


Fig. 17. Pipeline cross section with backfilling media [56]

Table. 27. Environmental impact scores of glass washing and crushing [56]

Impact categories and their unit	Impact per ton RCG		Landfill of by-products from washing and crushing operations		Recycling of by-product from crushing	Natural Sand	Benefit over landfill of waste glass
	Washing	Crushing	Washing	Crushing			
Climate change (kg CO_2 eq)	1.92	2.15	5.25	4.15	2.64	4.95	−10.62
Ozone depletion (kg CFC-11 eq)	4.06E-09	4.12E-09	2.76E-07	1.67E-07	8.14E-08	2.26E-07	−1.19E-06
Terrestrial acidification (kg SO_2 eq)	0.011	0.013	0.032	0.025	0.016	0.030	−0.06
Freshwater eutrophication (kg P eq)	2.21E-06	1.68E-06	4.13E-05	2.51E-05	4.01E-06	8.6E-05	−1.68E-04
Marine eutrophication (kg N eq)	4.78E-04	5.53E-04	1.31E-03	1.05E-03	7.09E-04	1.08E-03	−2.65E-03
Human toxicity (kg 1,4-DB eq)	0.50	0.59	0.97	0.87	0.65	0.24	−0.97
Abiotic depletion (kg Sb eq)	1.05E-07	2.45E-06	1.38E-05	1.06E-05	5.40E-06	9.23E-06	−5.75E-05
Abiotic depletion (fossil fuels) MJ	25.02	34.67	74.93	64.62	43.53	61.89	−159.91

The environmental benefits of replacing sand with RCG for a 150 mm backfilling that spans for 1 km and width of 3.5 m is shown in Table. 28, based on which sand backfilling emits 4162 $kgCO_{2eq}$ (**7.93 $kgCO_{2\ eq}/m^3$**) which is reduced by partial and full replacement with RCG to -8924 $kgCO_{2eq}$ (**-16.99 $kgCO_{2\ eq}/m^3$**).

Table. 28. Environmental impact assessment of crushed glass as backfilling material [56]

Impact categories	150 mm thick backfill of drainage conduits for 1 km pavement lane with a width of 3.5 m				
	Unit	100 % Sand	20 % RCG	50 % RCG	100 % RCG
Climate change	kg CO_2 eq	4162.14	1544.90	−2380.95	−8924.05
Ozone depletion	kg CFC-11 eq	1.90E-04	−4.72E-05	−4.03E-04	−9.96E-04
Terrestrial acidification	kg SO_2 eq	25.31	9.34	−14.62	−54.56
Freshwater eutrophication	kg P eq	7.23E-02	2.96E-02	−3.44E-02	−1.41E-01
Marine eutrophication	kg N eq	0.91	0.28	−0.66	−2.22
Human toxicity	kg 1,4-DB eq	201.26	−2.34	−307.75	−816.75
Abiotic depletion	kg Sb eq	7.02E-03	−3.14E-03	−1.84E-02	−4.38E-02
Abiotic depletion (fossil fuels)	MJ	47,110	13,342	−37,309	−121,728

In a case study for Hong Kong, Hossain et al. [57] studied the environmental impacts of using construction and demolition (C&D) waste aggregates in sub-base materials and lower grade concrete aggregates. The study measured and compared crushed C&D consumption as both fine and coarse aggregates, and the results are shown in Table. 29 and Table. 30, respectively. Accordingly, natural fines from river sand and crushed stone emit **23 and 33 $kgCO_{2\ eq}/t$**, respectively. The emissions shrink to **12 and 9 $kgCO_{2\ eq}/t$**, when recycled construction and demolition waste and waste glass are used, respectively. In the case of coarse aggregates, the emissions for crushed stone and recycled C&D are **32 and 11 $kgCO_{2\ eq}/t$**, respectively.

Table. 29. Environmental impact assessment of natural and recycled fine aggregates [57]

Impact category	Impact symbol	Unit	Natural fine (RS)	Natural fine (CS)	Recycled fine (C&D waste)	Recycled fine (WG)
Carcinogens	CG	kg C_2H_3Cl eq	0.23	0.05	0.05	−0.27
Non-carcinogens	N–CG	kg C_2H_3Cl eq	0.02	0.03	0.02	−0.49
Respiratory in-organics	RIn	kg PM 2.5 eq	0.03	0.05	0.03	0.02
Ionizing radiation	IR	Bq C-14 eq	40	82	51	−75
Ozone layer depletion	OL	kg CFC-11 eq	8.99E − 07	9.91E − 07	4.43E − 07	−1.35E − 05
Respiratory organics	ROg	kg C_2H_4 eq	0.02	0.02	0.006	−0.02
Aquatic ecotoxicity	AEco	kg TEG water	462	879	282	−3032
Terrestrial ecotoxicity	TEco	kg TEG soil	43	44	25	−1079
Terrestrial acid/nutri	TAci	kg SO_2 eq	0.98	1.29	0.98	0.54
Land occupation	LOc	m^2org.arable	0.01	0.01	0.008	−0.13
Aquatic acidification	AAci	kg SO_2 eq	0.14	0.19	0.13	0.06
Aquatic eutrophication	AEu	kg PO_4 P-lim	0.0006	0.0007	0.0003	−0.27
Global warming potential	GWP	kg CO_2 eq	23	33	12	9
Non-renewable energy	N–Re	MJ primary	341	518	235	156
Mineral extraction	MEx	MJ surplus	0.14	0.10	0.11	−0.21

Note: RS, River sand; CS, Crushed stone; C&D waste, Construction & demolition waste; WG, waste glass.

Table. 30. Environmental impact assessment of natural and recycled coarse aggregates [57]

Impact category	Impact symbol	Unit	Natural coarse (CS)	Recycled coarse (C&D waste)
Carcinogens	CG	kg C_2H_3Cl eq	0.05	0.05
Non-carcinogens	N–CG	kg C_2H_3Cl eq	0.03	0.01
Respiratory in-organics	RIn	kg PM 2.5 eq	0.05	0.03
Ionizing radiation	IR	Bq C-14 eq	72	38
Ozone layer depletion	OL	kg CFC-11 eq	9.88E – 07	4.38E – 07
Respiratory organics	ROg	kg C_2H_4 eq	0.02	0.005
Aquatic ecotoxicity	AEco	kg TEG water	821	204
Terrestrial ecotoxicity	TEco	kg TEG soil	44	25
Terrestrial acid/nutria	TAci	kg SO_2 eq	1.27	0.95
Land occupation	LOc	m^2org.arable	0.01	0.008
Aquatic acidification	AAci	kg SO_2 eq	0.19	0.13
Aquatic eutrophication	AEu	kg PO_4 P-lim	0.0007	0.0003
Global warming potential	GWP	kg CO_2 eq	32	11
Non-renewable energy	N–Re	MJ primary	496	211
Mineral extraction	MEx	MJ surplus	0.10	0.11

Hossain et al. [57] then compare their results to the literature as indicated in **Table. 31**, which shows an emission range of **10-103 kg$CO_{2\ eq}$/t** for natural aggregates and **-14 to 16 kg$CO_{2\ eq}$/t** for recycled aggregates in different studies.

Table. 31. Comparative emission results for natural and recycled aggregates [57]

Study	Energy consumption, MJ/t	GHG emissions, kg CO_2 eq/t	System boundary
Natural aggregates			
Simion et al. (2013) (Natural inert)	1664	103	Cradle-to-gate
Estanqueiro (2011) (Limestone)	232	14	Cradle-to-site
Blengini et al. (2007) (Sand)	152	10	Cradle-to-gate
This study (Crushed stone)	496–518	32–33	Cradle-to-site
This study (River sand)	341	23	Cradle-to-site
Recycled aggregates			
Lamb et al. (2011) (Misc. aggregates)	–	6	Cradle-to-gate
Simion et al. (2013) (Recycled aggregates from C&D waste)	246	16	Cradle-to-gate
Blengini and Garbarino (2010) (Recycled aggregates from C&D waste)	−250	−14	Cradle-to-site
Butera et al. (2015) (Recycled aggregates from C&D waste)	145	9	Cradle-to-site
This study (Recycled aggregates from C&D waste)	211–235	11–12	Cradle-to-site
This study (Recycled aggregates from waste glass)	156	9	Cradle-to-site

5-2- Soil and Geotechnical Systems Alternatives

As shown in the previous section, part of the crushed C&D and glass waste recommendations for crushed aggregates are useful for the case of earthwork as well. However, other measures and materials are also discussed in this part. As shown earlier, the largest part of emissions for earthwork is attributed to the materials transportation. In most of the CoV GI projects, the in-situ soil is initially excavated and transported out of the area to be landfilled. Depending on the logistics, the transportation usually includes a number of empty truck travels, adding more to the emissions of the project. More transportation is required to bring the soil from a quarry to site, which again includes empty truck travels as well. As a result, it is highly advisable to take every measure possible to reuse the in-situ soil for the project using a cut and fill approach. In cases where the in-situ soil does not show the required engineering properties, different remediation methods are widely studied and available to be assimilated by the CoV projects. Filho et al. [58] conducted a pilot project on a 700 m unpaved road section, which was divided into 7 sections of 100 m. Each section was then constructed using different techniques and the mechanical as well as the LCA of the sections were measured and compared. The construction techniques and soil improvement methodologies were described as below and shown in **Fig. 18**. The system boundary for LCA analysis is presented in **Fig. 19**.

1- This section was chemically improved by adding 1% Portland cement (MPC1%)
2- The section was stabilized by incorporating 20% sand and 10% clayey gravel into the primary coating (65%) (MSC)
3- This section was chemically improved by adding 2% Portland cement (MPC2%)
4- Control section, which included mechanical improvement and compaction of the primary coating (CS)
5- The section was stabilized by incorporating 25% reclaimed asphalt pavement (RAP) and 10% clayey gravel into the primary coating (65%) (MRAP)
6- This section was chemically improved by adding 1% hydrated lime (MHL1%)
7- The section was stabilized by incorporating 25% graded crushed stone (GCS) into the primary coating (75%) (MGCS)

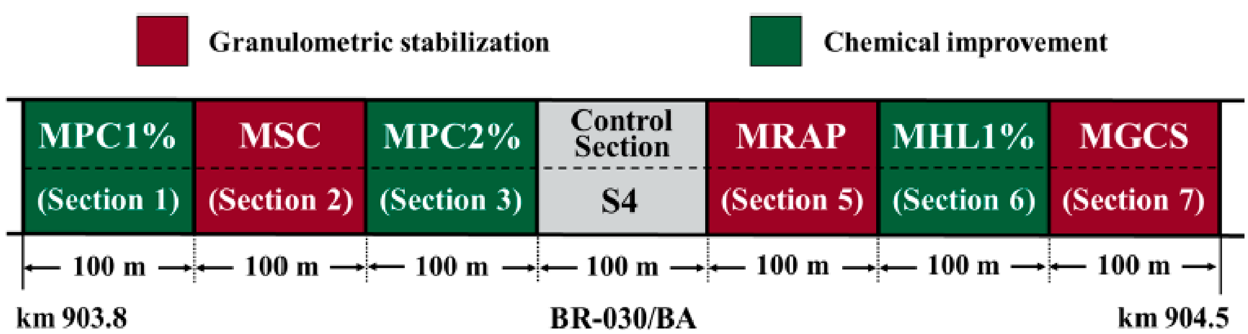


Fig. 18. Soil treatment methods studied by Filho et al. over 700 m road [58]

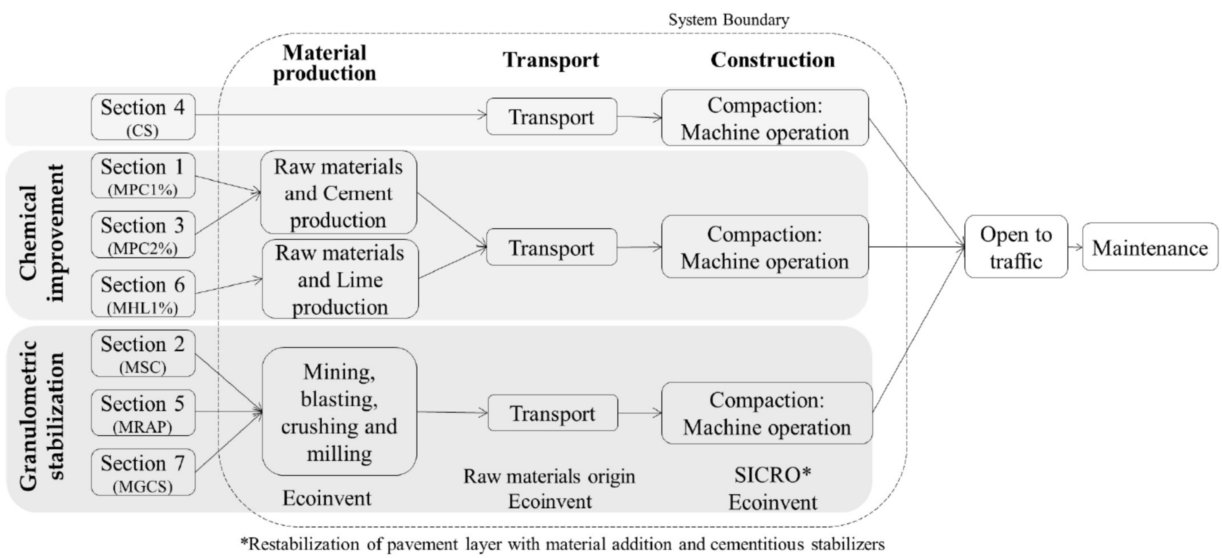


Fig. 19. System boundary and scope of LCA analysis of soil improvement by Filho et al. [58]

The influence of each construction method on the mechanical properties was studied through California bearing ration (CBR) test, which is indicated in **Fig. 20**. Based on the results, 2% cement yields the highest improvement in CBR.

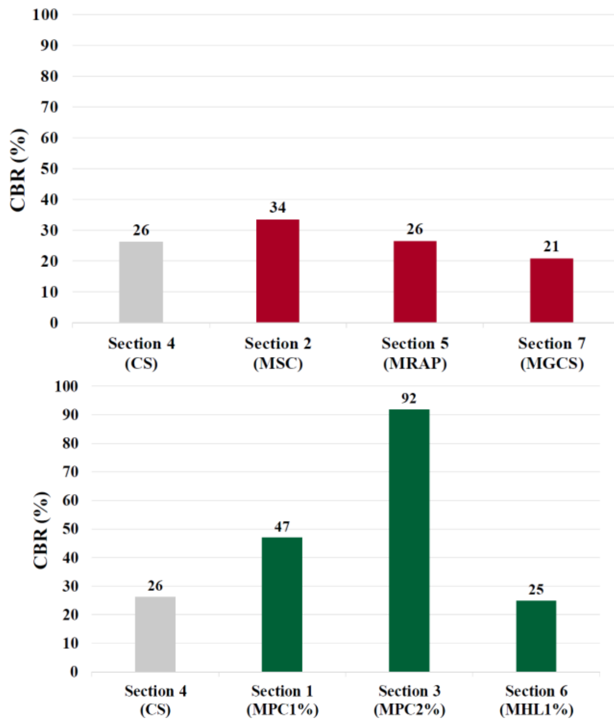


Fig. 20. California Bearing Ratio (CBR) results for different soil improvement methods [58]

The LCA results are shown in **Table. 32**. The authors concluded that Granulometric stabilization using 25% sand and 10% clayey gravel into the primary coating leads to the highest impacts in most of the categories, and therefore should be rejected. On the other hand, compacting the in-situ soil inherently causes the least amount of emissions. Despite the highest CBR value, MPC2% section with 2% Portland cement yields the highest emissions. Therefore, the engineers should take into account the required mechanical properties, and the environmental impacts of the construction methods at the same time.

Table. 32. Life cycle assessment results of different soil improvement methods [58]

Impact Categories	Unit	S1 MPC1%	S2 MSC	S3 MPC2%	S4 CS	S5 MRAP	S6 MHL1%	S7 MGCS
Acidification	kg SO_2 eq	66.4	122.9	119.0	13.9	68.2	52.5	89.2
Carcinogenics	CTUh	0.0004	0.0029	0.0007	0.0001	0.0004	0.0002	0.0010
Ecotoxicity	CTUe	36,306.4	216,994.0	70,217.3	3,439.0	56,277.8	29,282.8	92,935.9
Eutrophication	kg N eq	19.5	47.4	38.2	2.5	14.1	13.3	33.6
Fossil fuel depletion	MJ surplus	15,101.4	33,957.5	24,299.5	5,906.0	25,355.4	24,283.9	25,375.7
Global warming	kg CO_2 eq	25,593.7	18,432.6	48,693.4	2,784.0	11,933.1	26,562.4	15,795.7
Non-carcinogenics	CTUh	0.002	0.010	0.004	0.000	0.002	0.001	0.004
Ozone depletion	kg CFC-11 eq	0.002	0.004	0.002	0.001	0.003	0.003	0.003
Respiratory effects	kg $PM_{2.5}$ eq	8.2	17.1	15.2	1.2	7.2	6.7	14.5
Smog	kg O_3 eq	1343.1	2,787.6	2,310.0	376.4	1795.3	1,009.0	1,906.1

While lime and cement stabilization are the most common and familiar soil remediation methods, they require highly emitting materials. A cleaner approach to avoid emissions, reduce the cost of the project, and uphold circular economy is using fine aggregates from recycled concrete aggregates (RCA). While the larger aggregates are normally used as aggregate replacement in concrete (further discussed in a later section), the fine particles are usually not as interesting to the concrete industry and are used for backfilling and sub-base. Although no study was found to study emissions of RCA fines for soil improvement, the synergy between using the coarse particles in concrete and fine particles for in-situ soil improvement can lead to full consumption of the old concrete, avoid lime and cement consumption, and evade soil transportation, all of which contribute to a positive environmental impact. A few studies have shown the remarkable potential of these aggregates for soil improvement. Henzinger and Heyer [59] showed that RCA fines can substantially improve CBR for clayey soils. According to the results provided in **Fig. 21**, RCA fines work best with soils with lower liquid limit (generally below LL = 40%).

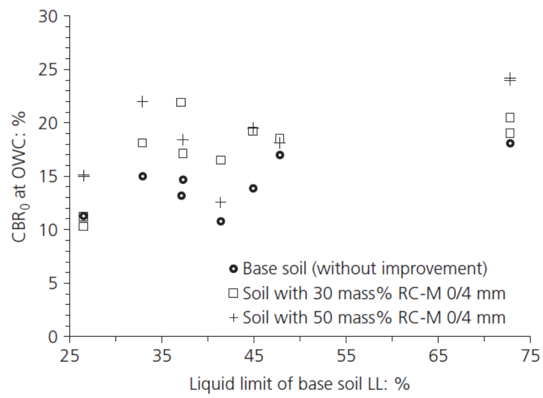


Fig. 21. California Bearing Ratio (CBR) for clay with various liquid limit stabilized by recycled concrete fines [59]

In another study, Kianimehr et al. [60] used RCA up to 15% by dry weight of the soil. The standard compaction curves in **Fig. 22** prove that the optimum moisture content increases with RCA percentage, which implies the beneficial use of RCA for soils with high natural moisture content.

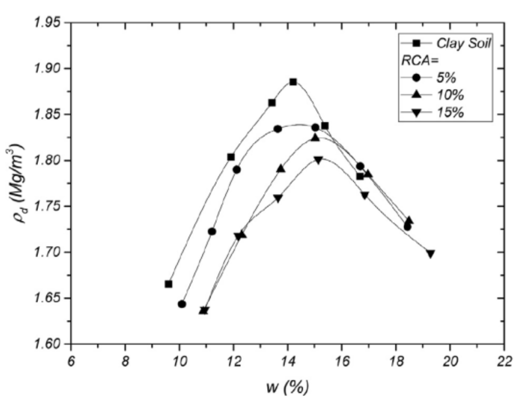


Fig. 22. Standard compaction curves of clay with recycled concrete fines stabilization [60]

As indicated in **Fig. 23**, RCA can substantially enhance the unconfined compressive strength (UCS) of soils, with values extending higher than 1400 kPa after 28 days of curing with 15% RCA content. Moreover, the results of direct shear tests in **Fig. 24**, indicate an increase in both cohesion and internal friction angle of the soil with RCA addition, proving that the shear strength of soil is enhanced remarkably with RCA content.

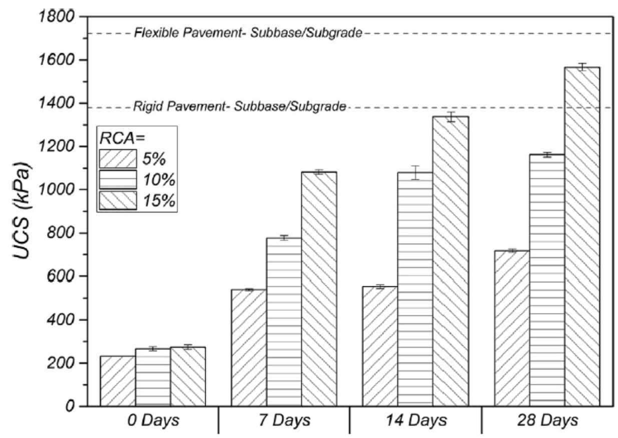


Fig. 23. UCS results of clay soil with recycled concrete fines stabilization [60]

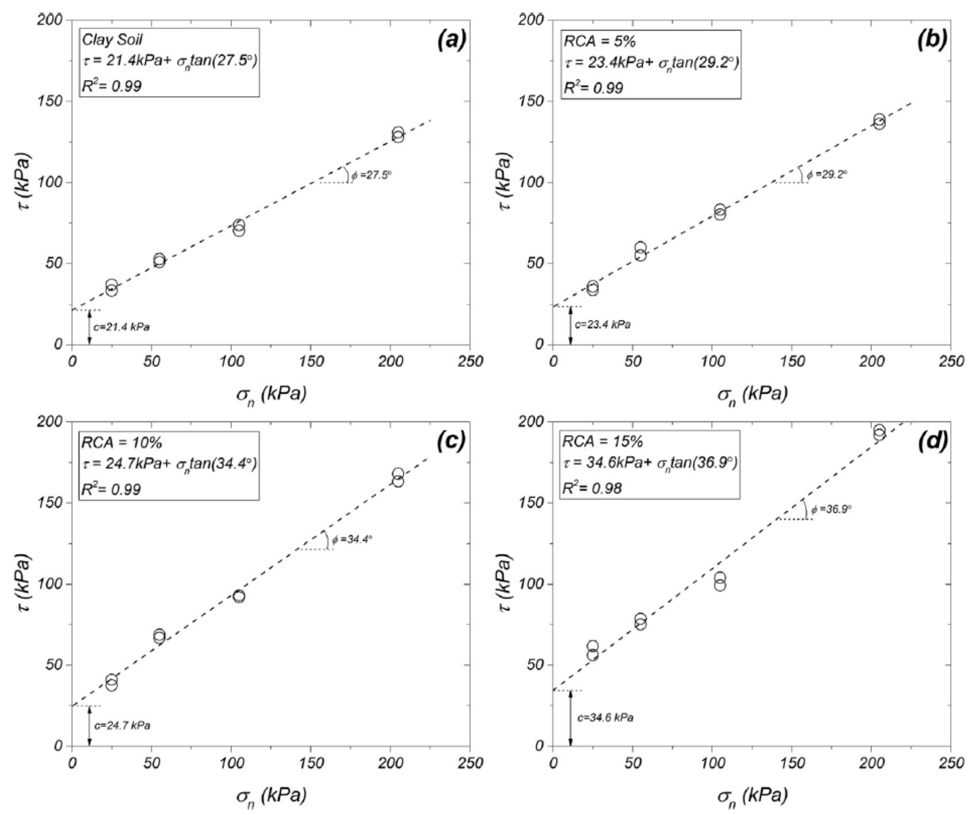


Fig. 24. Internal friction angle and cohesion of clay soil with recycled concrete fines stabilization [60]

5-3- Geosynthetics Alternatives

Geosynthetics may be the hardest GI material to decarbonize due to the lack of options in the market. In general, the bottom geotextile may be replaced by crushed aggregates to maintain permeability. Another greener approach may be using recycled geotextiles. A few vendors such as Wallbarn and Procotex offer geotextiles out of recycled materials. Attarchian et al. [61] compared recycled PET and virgin PET geotextiles, and estimated a 30% service life reduction in the case of the recycled geotextile. As indicated in **Fig. 25**, the tensile strength of virgin PET geotextile (V370-W) is higher than the recycled material (R420-G), and the 50% combination of both (RV420-W) yields the average strength.

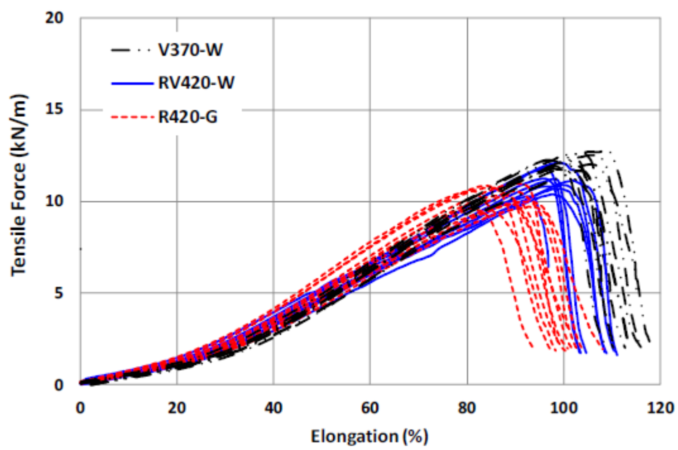


Fig. 25. Tensile strength of virgin and recycled PET geotextiles [61]

Besides replacing geosynthetics with crushed aggregates and recycled geotextiles, using natural and biodegradable geotextiles is the third option for reducing emissions of this material. For instance, two coconut coir geotextile samples of different unit weight were studied by Ravikumar et al. [62], who reported a reduced vertical strain and enhanced modulus based on plate loading tests. The literature on LCA and emission assessments of biodegradable geotextiles is not yet developed. In one of the few studies that was conducted in Morocco on palm fiber-based geotextile by Lassri and Naim [63], the system boundary indicated in **Fig. 26** was considered. As indicated in **Fig. 27**, CO_2 emissions are mainly attributed to transportation (i.e., 0.470 kgCO_2 eq/m^2) followed by manufacturing (i.e., 0.255 kgCO_2 eq/m^2), leading to a total emission of **0.725 kgCO_2 eq/m^2** and no emission was attributed to the material. The authors compared the emission values with two commercial geosynthetics as indicated in **Table. 33**, which shows that on average the biodegradable geotextile emits less than half the commercial geotextiles. Some natural geotextile vendors such as Naue, Cascade, and Coirngrow offer a wide range of materials that can reduce the embodied carbon of GI assets. Special care and due diligence are needed when switching to natural and biodegradable geotextiles to ensure strength, durability, and longevity.

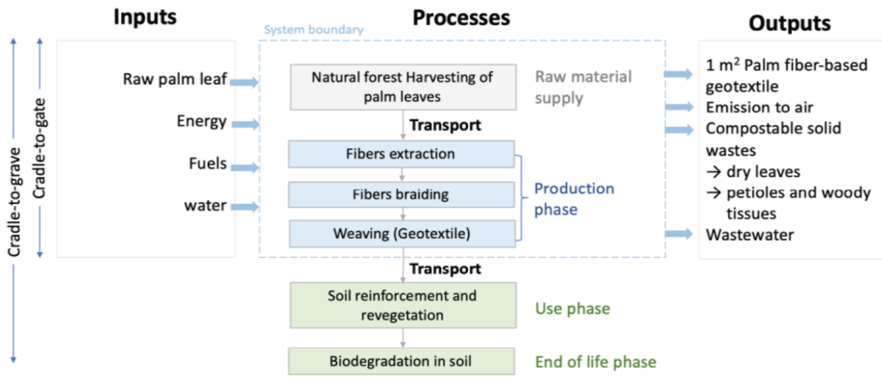


Fig. 26. LCA system boundary considered for palm fiber geotextile [63]

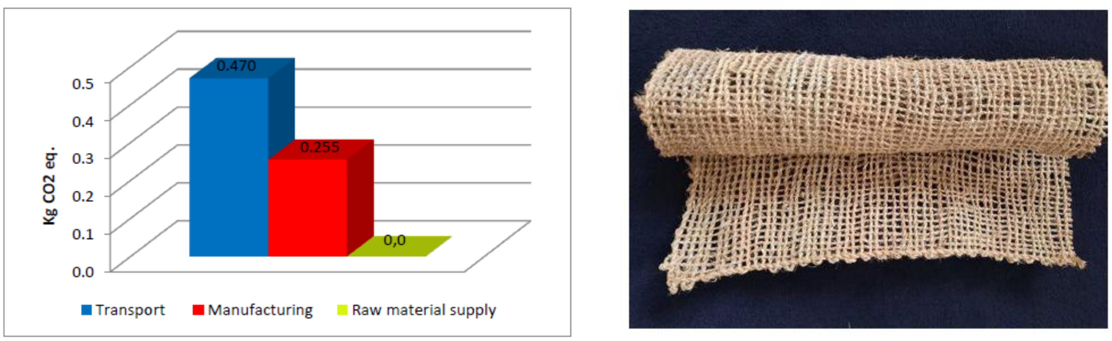


Fig. 27. Carbon dioxide emissions of palm fiber geotextile [63]

Table. 33. Comparative LCA of palm fiber geotextile and commercial geosynthetics [63]

Environmental Impacts		Secugrid® PET (Polyester) [15]	Geogrid TriAx TX190 G (Polypropylene) [16]	Palm-fiber based geotextile (This study)
	Unit	580 [g/m^2]	434 [g/m^2]	1250 [g/m^2]
ADP(e)	[kg Sb$^-$eq.]	8.78E-06	2.70E-07	2.67E-06
ADP(f)	[MJ]	43.57	35.1	8.38
GWP	[kg CO_2 eq.]	1.901	1.23	0.7249
ODP	[kg CFC11 eq.]	6.43E-08	7.82E-11	9.91E-08
POCP	[kg Ethen eq.]	3.81E-04	4.14E-04	2.70E-04
AP	[kg SO^{2-}eq.]	6.10E-03	3.04E-03	3.78E-03
EP	[kg $(PO_4)^{3-}$eq.]	7.85E-04	2.91E-04	1.10E-03

Global warming potential

5-4- Concrete Alternatives

Concrete is the second most consumed material in earth after water. Given the amounts of the concrete and cement consumption, it is calculated to contribute to around 8% of global CO_2 emissions. The polluting nature of cement and the increasing demand for the material has prompted numerous attempts and innovations to lower the CO_2 emissions. Although companies like Sublime Systems, Brimstone, and Fortera are working on re-engineering the production process of cement, such innovations are yet far from mass commercialization.

5-4-1- Concrete Specifications

As indicated in **Table. 25**, CoV requires a minimum 32 MPa strength after 28 days of curing for pavements and sidewalks. The study that was presented before in **Table. 23**, showed that CO_2 emissions for concrete with 80 mm slump grows from 315 $kgCO_2$ eq/m^3 at 25 MPa to 381 $kgCO_2$ eq/m^3 at 35 MPa when no SCM is used. Therefore, it is safe to assume that reducing the CoV strength requirement from 32 MPa to 25 MPa can remarkably reduce the emissions. On the other hand, the specifications do not specify a maximum strength requirement, which as indicated in **Table. 34** leads to excess emissions and cement consumption. The results show an average strength of 38 MPa after 28 days of curing, which further increases to 44 MPa after 56 days of curing, which is 37.5% higher than the 32 MPa requirement. As such, including a maximum strength requirement to the specifications can help to avoid unnecessary cement consumption. On the other hand, adding a 56-day strength requirement can help to promote green concrete consumption, which often require longer curing period to develop strength.

Table. 34. Test results for CoV 1503 concrete mix as provided by Amrize Ltd.

LAFARGE

SAMPLES SUMMARY BY DATE

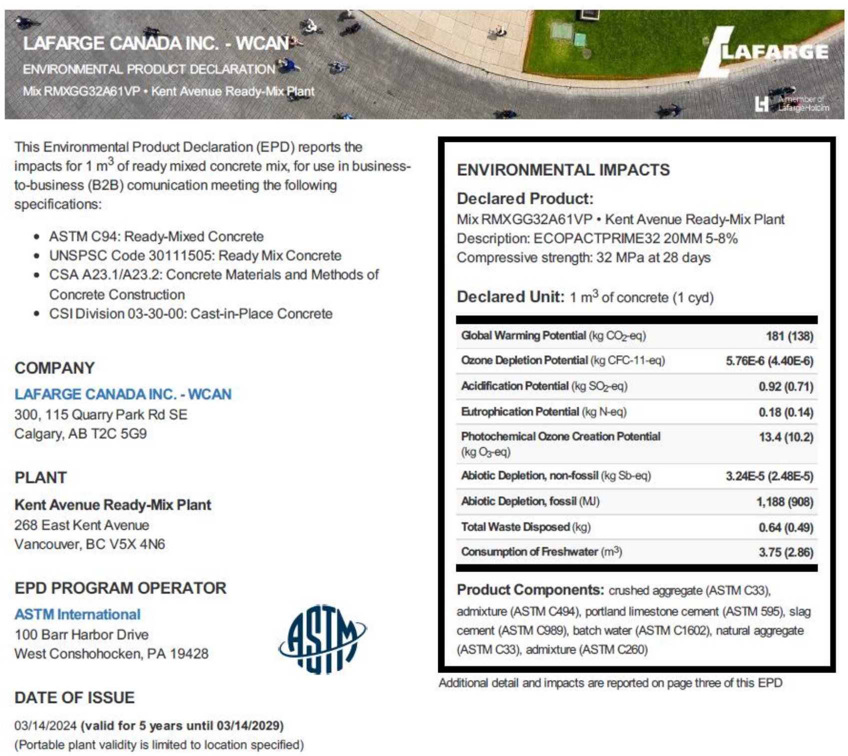
Batches from: 01/16/2019 To: 09/03/2024 Period selected: 1/1/2019 to 11/1/2024

Plant Selection: **Multiple Plants**

Date	Ticket Number	Mix	f'c (MPa)	Plant		Load Time	Sample Time	Slump Bef.	Slump Aft.	Air	Unit Wt.	Temperature Air	Temperature Conc	Avg Strength 1 d	2 d	3 d	7 d	28a	28b	28 avg	56 d	90 d	% f'c	Mov 3 Avg 28 d
1/16/19	82369370	RMXY1503	32	B05		9:28	09:28		120	5.6		4	15				30.5	39.3	39.2	39.2			122.5	
3/26/19	82373651	RMXY1503	32	B05		8:54	08:54	95		5.4		15	13				24.2	41.6		41.6	44.6		130.0	
4/4/19	82374393	RMXY1503	32	B05		8:17	08:17	90		5.3		10	17				34.7	45.1	45.5	45.3	50.1		141.6	42.0
4/9/19	82374697	RMXY1503	32	B05		9:16	09:16	80		6.0		9	17				23.8	37.3	37.4	37.4			116.9	41.4
4/26/19	83260159	RMXY1503	32	B04		9:05	09:05	100		4.5		11	20				36.3	51.8	50.7	51.3	46.7		160.3	44.7
6/20/19	83262829	RMXY1503	32	B04		8:41	08:41	65		6.4		14	24				26.2	39.1	37.8	38.4	41.4		120.0	42.4
6/25/19	82380727	RMXY1503	32	B05		8:19	08:19		115	6.7		16	22				26.2	35.2	37.3	36.2	38.7		113.1	42.0
4/27/20	82400603	RMXY1503	32	B05		8:44	08:44	110		6.2		11	19				25.9	36.1	36.8	36.4	40.2		113.8	37.0
5/27/20	82402561	RMXY1503	32	B05		8:38	08:38	110		6.0		12	19				27.5	38.5	38.3	38.4	41.7		120.0	37.0
8/19/20	83280728	RMXY1503	32	B04		7:51	07:51	120		4.9		19	26				29.8	42.8	41.9	42.3	45.2		132.2	39.0
3/16/21	83289088	RMXY1503	32	B04		8:13	08:13	75		6.4		1	15				25.8	36.3	37.1	36.7	42.8		114.7	39.1
3/18/21	82418665	RMXY1503	32	B05		8:29	08:29	90		5.2		8	21				25.8	39.3	38.7	39.0	42.7		121.9	39.3
3/22/21	82418838	RMXY1503	32	B05		8:47	08:47	100		5.9		6	17				24.9	36.7	37.4	37.0	38.7		115.6	37.6
6/10/21	83292498	RMXY1503	32	B04		13:44	13:44	100		6.2		19	22				25.9	36.9	36.8	36.8			115.0	37.6
6/29/21	83293238	RMXY1503	32	B04		10:53	10:53	60		5.0		27	30				24.8	36.4	35.9	36.1			112.8	36.6
8/18/21	83295043	RMXY1503	32	B04		8:11	08:11	100		5.7		15	26				23.4	31.2		31.2	34.6		97.5	34.7
8/26/21	82426458	RMXY1503	32	B05		9:05	09:05	90		5.5		16	24				28.4	34.3	32.9	33.6			105.0	33.6
8/1/23	83332468	RMXY1503	32	B04		8:55	08:55	100		5.5		23	21				25.8	34.7	35.4	35.1			109.7	33.3
10/5/23	83335698	RMXY1503	32	B04		12:44	12:44	100		5.2		19	23				20.7	33.6	32.7	33.1			103.4	33.9
11/15/23	82482593	RMXY1503	32	B05		8:51	08:51	90		5.3		6	18				25.7	41.1	39.2	40.2			125.6	36.1
11/15/23	82482636	RMXY1503	32	B05		12:17	12:17	80		5.9		7	21				24.1	38.4	38.0	38.2			119.4	37.2
12/6/23	82483877	RMXY1503	32	B05		10:20	10:20	100		6.0		9	16				17.9	37.0	37.9	37.5			117.2	38.6
12/15/23	82484466	RMXY1503	32	B05				60		5.6		7	19				26.8	38.4	37.4	37.9			118.4	37.9
2/16/24	82486946	RMXY1503	32	B05		7:40	07:40	100		5.4		5	17				27.0	36.1	36.8	36.4			113.8	37.3
6/19/24	82494269	RMXY1503	32	B05		6:46	06:46		80	3.6		13	21				35.6	47.5	47.9	47.7	55.2		149.1	51.2
8/22/24	82497370	RMXY1503	32	B05		9:09	09:09	140		2.2		20	24				22.9	37.2		37.2	46.6		116.3	51.5
9/3/24	83348535	RMXY1503	32	B04		7:16	07:16	90		6.0		16	24				24.6	39.3	38.2	38.7	49.8		120.9	41.2
Total Average:								94	105	5		13	20				26	39	39	38	44		120	

5-4-2- Recycled Concrete Aggregates

Using recycled concrete aggregates (RCA) has been proposed as a viable method to reduce the emissions in concrete. Coarse aggregates in RCA are fully or partially replaced with crushed concrete from construction and demolition waste. The environmental product declaration (EPD) for Lafarge's RMXGG32A61VP mix is shown in **Fig. 28**. The GWP for the proposed RCA mix measured 181 kgCO_2 eq/m^3. Compared to the conventional CoV 1503 EPD (**Fig. 14**) with an estimated emission of 244 kgCO_2 eq/m^3, the RCA concrete mix shows around 25% GHG savings. The reduced emissions mainly stem from avoided concrete landfilling. However, there is still a significant debate around emission calculations of RCA concrete. For instance, Marinkovic et al. [64] highlighted the significance of transportation means and distance on the environmental benefits of RCA. Their results show that when the transportation distance of recycled aggregates is shorter than natural river aggregates, the environmental impact of the two aggregates is approximately the same and the recycling benefits in terms of natural mineral resources depletion is obtained. However, the environmental impacts of RCA is higher than natural aggregate concrete when equal transportation distance is considered.



LAFARGE CANADA INC. - WCAN
ENVIRONMENTAL PRODUCT DECLARATION
Mix RMXGG32A61VP • Kent Avenue Ready-Mix Plant

LAFARGE

This Environmental Product Declaration (EPD) reports the impacts for 1 m^3 of ready mixed concrete mix, for use in business-to-business (B2B) comunication meeting the following specifications:

- ASTM C94: Ready-Mixed Concrete
- UNSPSC Code 30111505: Ready Mix Concrete
- CSA A23.1/A23.2: Concrete Materials and Methods of Concrete Construction
- CSI Division 03-30-00: Cast-in-Place Concrete

COMPANY
LAFARGE CANADA INC. - WCAN
300, 115 Quarry Park Rd SE
Calgary, AB T2C 5G9

PLANT
Kent Avenue Ready-Mix Plant
268 East Kent Avenue
Vancouver, BC V5X 4N6

EPD PROGRAM OPERATOR
ASTM International
100 Barr Harbor Drive
West Conshohocken, PA 19428

DATE OF ISSUE
03/14/2024 **(valid for 5 years until 03/14/2029)**
(Portable plant validity is limited to location specified)

ENVIRONMENTAL IMPACTS

Declared Product:
Mix RMXGG32A61VP • Kent Avenue Ready-Mix Plant
Description: ECOPACTPRIME32 20MM 5-8%
Compressive strength: 32 MPa at 28 days

Declared Unit: 1 m^3 of concrete (1 cyd)

Global Warming Potential (kg CO_2-eq)	181 (138)
Ozone Depletion Potential (kg CFC-11-eq)	5.76E-6 (4.40E-6)
Acidification Potential (kg SO_2-eq)	0.92 (0.71)
Eutrophication Potential (kg N-eq)	0.18 (0.14)
Photochemical Ozone Creation Potential (kg O_3-eq)	13.4 (10.2)
Abiotic Depletion, non-fossil (kg Sb-eq)	3.24E-5 (2.48E-5)
Abiotic Depletion, fossil (MJ)	1,188 (908)
Total Waste Disposed (kg)	0.64 (0.49)
Consumption of Freshwater (m^3)	3.75 (2.86)

Product Components: crushed aggregate (ASTM C33), admixture (ASTM C494), portland limestone cement (ASTM 595), slag cement (ASTM C989), batch water (ASTM C1602), natural aggregate (ASTM C33), admixture (ASTM C260)

Additional detail and impacts are reported on page three of this EPD

Fig. 28. Environmental Product Declaration (EPD) for Lafarge RMXGG32A61VP mix as provided by Amrize Ltd.

A study conducted by Yazdanbakhsh et al. [65] on LCA of natural and recycled aggregates concrete in New York did not show as remarkable environmental benefits. The literature shows that cement content should be slightly increased to obtain the same strength with RCA. Yazdanbakhsh et al. [65] considered a 40 MPa strength for both natural aggregate and RCA. Moreover, RCA concrete often requires more superplasticizer to reach the same workability as natural aggregates. The life cycle inventory presented in **Table. 35** was used to measure the emissions in the study, based on which natural aggregates concrete and RCA concrete emit **300 and 310 kgCO_2 eq/m^3**, respectively. The normalized LCA results for 5 million m^3 of concrete produced annually in New York is presented in **Fig. 29**, which confirms that RCA concrete leads to a slight increase in CO_2 emissions. In order for RCA to emit lower CO_2 emissions, the increased cement consumption should be confined to **4.4%**.

Table. 35. Life cycle inventory for recycled concrete aggregate (RCA) and natural Aggregate (NA) concrete in New York [65]

Category	Climate change		Acidification		Smog formation		Eutrophication		Human health		Ozone depletion	
Unit	kg CO_2 eqv.		kg SO_2 eqv.		kg O_3 eqv.		kg N eqv.		kg PM2.5 eqv.		kg CFC 11 eqv.	
Concrete type	NA	RCA	NA	RCA	NA	RCA	NA	RCA	NA	RCA	NA	RCA
Cem. prod.	2.7E+02	2.9E+02	5.3E−01	5.7E−01	9.7E+00	1.1E+01	3.3E−01	3.6E−01	1.1E−01	1.2E−01	1.0E−05	1.1E−05
Trans, truck	1.5E+01	7.7E+00	6.8E−02	3.5E−02	1.6E+00	8.3E−01	1.7E−02	8.6E−03	1.1E−02	6.0E−03	3.6E−06	1.9E−06
Trans, water	1.4E+01	1.0E+01	1.3E−01	9.3E−02	3.9E+00	2.7E+00	2.4E−02	1.7E−02	9.9E−03	7.0E−03	2.9E−06	2.0E−06
NA/RCA prod	4.6E+00	4.2E+00	2.6E−02	2.4E−02	2.8E−01	2.6E−01	6.5E−04	6.0E−04	6.3E−02	5.8E−02	8.5E−11	7.9E−11
Sand. prod	3.2E+00	2.8E+00	2.1E−02	1.9E−02	4.1E−01	3.6E−01	1.0E−02	9.1E−03	5.3E−03	4.8E−03	3.9E−07	3.5E−07
Total	3.0E+02	3.1E+02	7.7E−01	7.4E−01	1.6E+01	1.5E+01	3.8E−01	3.9E−01	2.0E−01	2.0E−01	1.7E−05	1.6E−05
Normalized total, pt	1.25E−02	1.30E−02	8.51E−03	8.17E−03	1.14E−02	1.06E−02	1.76E−02	1.82E−02	8.25E−03	8.12E−03	1.06E−04	9.83E−05
Avoided landfilling	–	1.2E+01	–	9.4E−02	–	1.6E+00	–	2.9E−02	–	1.3E−02	–	8.0E−06
Normalized avoided landfilling, pt.	–	4.83E−04	–	1.03E−03	–	1.16E−03	–	1.32E−03	–	5.44E−04	–	4.93E−05

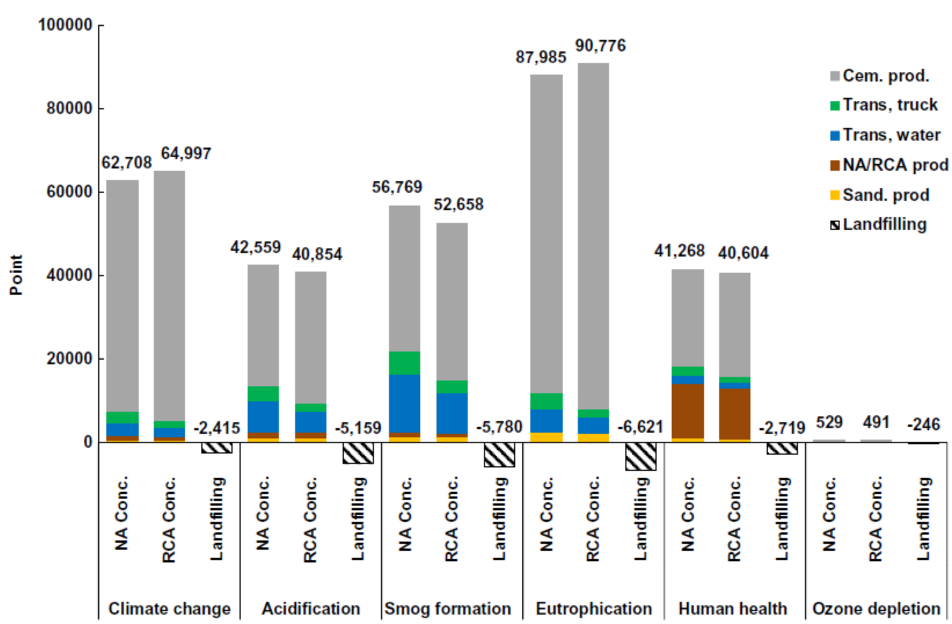


Fig. 29. LCA results for 5 million m^3 RCA and natural aggregate concrete produced annually in New York [65]

Shi et al. [66] studied the LCA for concrete pavements with RCA. The hypothetical pavements were 12.8 km long, 14.4 m wide and 25 cm thick. The study considered a lower service life for

RCA pavement to reflect its relatively poorer performance. To do so, Shi et al. [66] considered a 27-year service life for RCA and 32-year service life for conventional concrete. They limited the analysis period to 27 years and considered the remaining 5 years of conventional concrete service life as salvage value. The LCA results are provided in Table. 36, which shows negligible reduction in GHG emissions (0.07% reduction) when RCA is consumed. However, RCA pavement has other societal benefits such as improved human health.

Table. 36. Life cycle inventory for RCA and NA concrete pavement studied by Shi et al. [66]

TRACI category indicator	Explanation and interpretation	Values		% Change
		Plain PCC pavement	RCA-PCC pavement	
Global warming potential (ton CO_2 eq)	An average increase in the temperature of the atmosphere near the Earth's surface and in the troposphere, which can contribute to changes in global climate patterns.	1319708	1318834	−0.07%
Acidification air (ton SO_2 eq)	Lead to acid rain, fog, or snow or dry deposition; cause damage to building materials, paints, and other human-built structures, lakes, streams, rivers, and various plants and animals.	4538	4536	−0.05%
Human health particulate air (ton PM_{10} eq)	A collection of small particles in ambient air which have the ability to cause negative human health effects including respiratory illness and death.	1198	1174	−2.05%
Eutrophication air (ton N eq)	Enrichment of an aquatic ecosystem; accelerate biological productivity and an undesirable	136	136	0.33%
Eutrophication water (ton N eq)	accumulation of algal biomass.	0.470	0.471	0.14%
Ozone depletion air (ton CFC-11 eq)	Lead to increased frequency of skin cancers and cataracts in the human population; also has effects on crops, other plants, marine life, and human-built materials.	0.401	0.402	0.14%
Smog air (ton O_3 eq)	Lead to a variety of respiratory issues including increasing symptoms of bronchitis, asthma, and emphysema; Permeant lung damage may result from prolonged exposure to ozone. Ecological impacts include damage to various ecosystems and crop damage.	80385	80280	−0.13%
Ecotoxicity (low) (ton 2,4D)	Characterize potential adverse effect that a chemical causes to an aquatic or terrestrial receptor	67	52	−22.30%
Ecotoxicity (high) (ton 2,4D)		68	53	−21.90%
Human health cancer (low) (ton benzene eq)	Characterize potential cancer human health hazards	99	90	−9.93%
Human health cancer (high) (ton benzene eq)		506	458	−9.51%
Human health non-cancer (low) (ton toluene eq)	Characterize potential non-cancer human health hazards	63266	56300	−11.01%
Human health non-cancer (high) (ton benzene eq)		1345530	1061000	−21.15%

5-4-3- Pre-Carbonated Recycled Concrete Aggregates

The literature almost unanimously shows that RCA consumption entails specific environmental benefits but does not necessarily lead to lower emissions. However, RCA has great potential to reduce emissions if it is subjected to pre-carbonation in a controlled environment. RCA has large amounts of uncarbonated calcium in the form of calcium silicate hydrate (C-S-H) or calcium hydroxide that can potentially react with carbon dioxide and precipitate calcium carbonates. The carbonated phases are then safely stored in RCA unless the RCA is heated up to 800°C. For RCA carbonation to happen quickly and efficiently, the reaction environment should be engineered to control the relative humidity and temperature and increase the CO_2 content. Studies have shown that the carbonated RCA improve the properties of concrete by reducing the water absorption of RCA (i.e., enhancing the workability of concrete) and increasing the strength of RCA through densification. Leemann et al. [67] showed that RCA particles finer that 16 mm can potentially **absorb around 21 kg CO_2/tonne** after only 70 minutes of carbonation. Their results show that on average, RCA concrete can hold 8 kg CO_2/m^3 of concrete. Leemann et al. [67] detected minor reduction in water absorption of RCA after carbonation, a reduced workability of the concrete and improved strength values. Leemann et al. [67] measured a **10-14% reduction in CO_2 emissions** by using carbonated RCA, emanating from the absorbed carbon dioxide and cement content reduction due to strength improvement. Ang et al. [68] conducted experimental carbonation of RCA using an ammonia solution, and measured the LCA of the process. As indicated in **Fig. 30**, Ang et al. [68] proved that RCA carbonation leads to a net **21.42 kg CO_2/tonne** in CO_2 abatement.

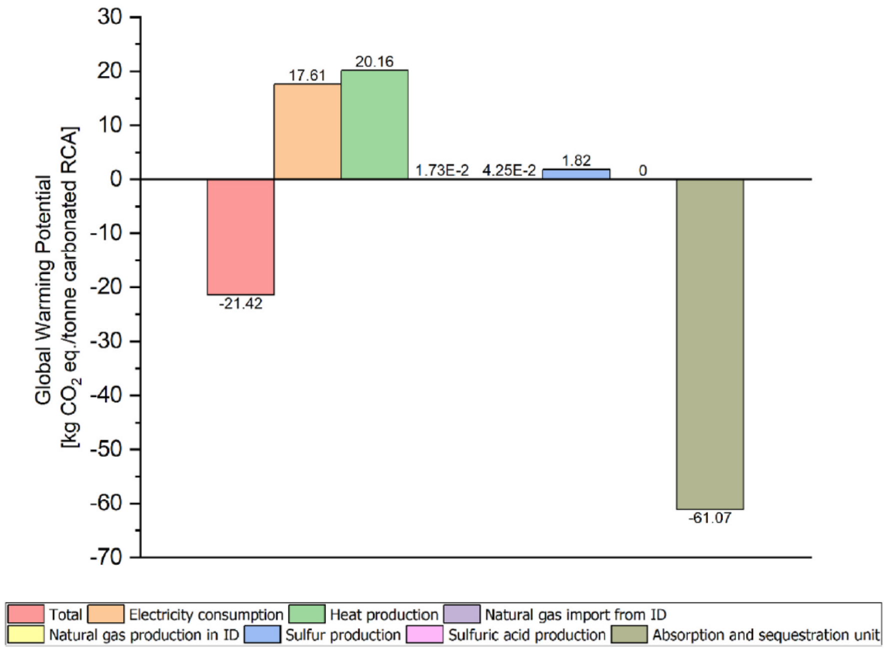


Fig. 30. Global warming potential results for one tonne of RCA carbonation [68]

5-4-4- Supplementary cementitious materials

Despite the current advancements in concrete technology, supplementary cementitious materials (SCMs) remain the main avenue for decarbonisation in the concrete industry. SCMs include a wide range of materials such as pozzolanic materials (e.g., coal fly ash, metakaolin, calcined clay) and latent hydraulic materials (e.g., ground granulated blast furnace slag (GGBFS)). SCMs are not cementitious alone, but react over time in the highly alkaline environment of concrete to develop strength and durability. As a result, using high SCM content in concrete to replace cement up to 50% offers the most viable short-term method for cutting the emissions in GI assets. For a high SCM concrete to meet the requirements, CoV may need to switch its 28-day strength requirement to 56 days. The common 28-day strength specification is based on the curing properties of hydraulic cement, which almost fully develops strength within the first 28 days of placing, with minor improvements thereafter. However, as stated before, SCMs react at a much slower pace and keep developing strength up to 90 days of curing and beyond. Knight et al. [69] explored the optimum SCM/ cement (s/c) ratio to minimize the environmental impacts of concrete while maintaining the compressive strength by modeling the concrete consumption in San Francisco Bay Area, California. The SCMs considered by Knight et al. [69] included lime stone (LS), natural pozzolans (NP), shale ash (SA), Metakaolin (MK), silica fume (SF), coal flu ash (FA), and GGBS.

Knight et al. [69] first measured the CO_2 abatement by 20% cement replacement by each SCM without considering the influence on compressive strength. As indicated in **Fig. 31a**, this approach shows an average 16% CO_2 reduction. On the other hand, **Fig. 31b**, shows the GHG emissions with 20% cement replacement by SCMs and varying cementitious content to maintain 30 MPa strength. This graph shows emissions reduction in the range of 6-28% with the lowest reductions from GGBFS consumption and highest reduction by LS and SF. Knight et al. [69] presented **Fig. 32**, which shows the optimum s/c ratio for each type of SCM and a wide range of compressive strength from 15-45 MPa.

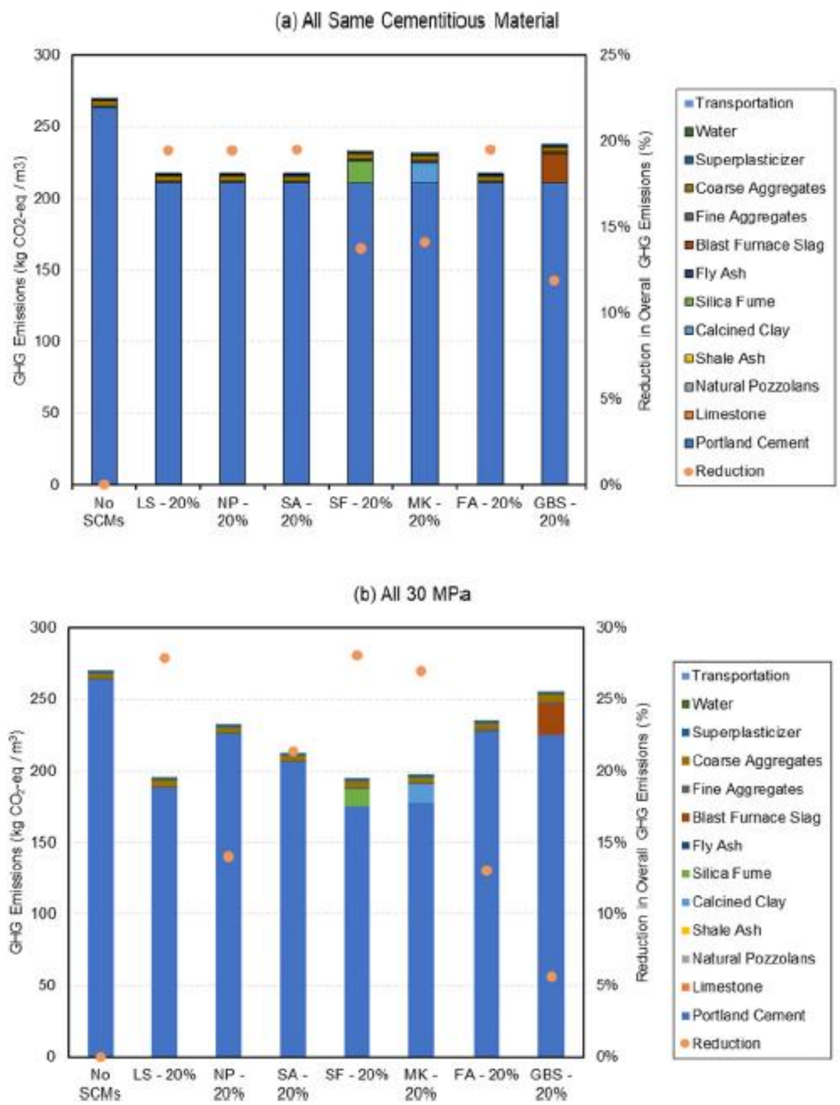


Fig. 31. GHG emissions per 1 m^3 concrete for a) same cementitious content, and b) same strength concrete mixtures 30 MPa [69]

		28 days						
		15 MPa	20 MPa	25 MPa	30 MPa	35 MPa	40 MPa	45 MPa
LS	GHG/NOX/SOX/VOC/CO/Pb/Energy Demand	0.21	0.21	0.21	0.21	0.20	0.20	0.20
	PM10	0.18	0.18	0.18	0.17	0.17	0.17	0.17
	PM2.5	0.17	0.17	0.16	0.16	0.16	0.16	0.16
	Water Consumption	0.18	0.18	0.18	0.18	0.18	0.18	0.18
	Water Withdrawal	0.19	0.19	0.19	0.19	0.18	0.18	0.18
NP	GHG/NOX/SOX/VOC/CO/Pb/Energy Demand	0.82	0.82	0.82	0.82	0.82	0.82	0.82
	PM10	0.00	0.13	0.18	0.21	0.23	0.24	0.25
	PM2.5	0.00	0.07	0.12	0.16	0.18	0.20	0.22
	Water Consumption	0.08	0.18	0.22	0.24	0.25	0.27	0.27
	Water Withdrawal	0.17	0.23	0.25	0.27	0.28	0.28	0.29
SA	GHG/NOX/SOX/PM10/PM2.5/VOC/CO/Pb/Enery Demand	0.67	0.67	0.67	0.67	0.67	0.67	0.67
	Water Consumption	0.04	0.04	0.05	0.06	0.06	0.06	0.07
	Water Withdrawal	0.67	0.67	0.67	0.30	0.28	0.26	0.24
MK	GHG/SOX/NOX/VOC/CO/Pb/Water Consumption/Water Withdrawal/Enery Demand	0.33	0.33	0.33	0.33	0.33	0.33	0.33
	PM10	0.00	0.00	0.04	0.09	0.12	0.15	0.17
	PM2.5	0.00	0.00	0.00	0.03	0.06	0.09	0.11
SF	GHG/SOX/PM10/PM2.5/VOC/CO/Pb/Water Consumption/Energy Demand	0.25	0.25	0.25	0.25	0.25	0.25	0.25
	NOX	0.06	0.07	0.09	0.10	0.25	0.25	0.25
	Water Withdrawal	0.00	0.00	0.01	0.02	0.03	0.03	0.04
FA	GHG/NOX/SOX	0.40	0.42	0.43	0.44	0.45	0.46	0.47
	PM10	0.42	0.44	0.45	0.46	0.46	0.47	0.48
	PM2.5	0.43	0.44	0.45	0.46	0.47	0.48	0.48
	VOC/CO/Pb	0.40	0.42	0.43	0.44	0.45	0.46	0.47
	Water Consumption	0.19	0.20	0.21	0.23	0.24	0.26	0.28
	Water Withdrawal	0.31	0.32	0.34	0.36	0.38	0.39	0.40
	Energy Demand	0.35	0.37	0.39	0.40	0.42	0.43	0.44
GGBS	GHG	0.42	0.46	0.50	0.57	0.68	0.81	0.90
	NOX	0.05	0.04	0.00	0.00	0.00	0.00	0.00
	SOX	0.44	0.48	0.54	0.63	0.76	0.88	0.96
	PM10/PM2.5	1.57	1.57	1.57	1.57	1.57	1.57	1.57
	VOC	0.32	0.35	0.37	0.41	0.45	0.51	0.60
	CO	0.69	0.94	1.04	1.10	1.13	1.16	1.18
	Pb	1.41	1.40	1.39	1.38	1.38	1.38	1.37
	Water Consumption	0.31	0.33	0.36	0.39	0.43	0.48	0.56
	Water Withdrawal	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Energy Demand	0.30	0.32	0.34	0.37	0.41	0.46	0.53

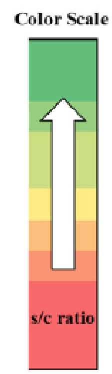


Fig. 32. Heatmap of calculated optimum SMC/Cement (s/c) ratio to reduce the environmental impacts based on 28-day strength [69]

As the demand for SCM is soaring to decarbonize the built environment, and given the depleting sources of coal fly ash and GGBFS, new startups are establishing novel methods and materials for producing engineered SCMs. A novel SCM produced by biomass fly ash treatment from BC's pulp and paper and bioenergy industry is currently under development at UBC Okanagan. Given the biogenic source of biomass fly ash, reusing this material in concrete provides numerous environmental advantages such as reducing CO_2 emissions, promoting bioenergy as a renewable source of energy, and preserving land. Conducting a pilot project with the group to test and scale up biomass fly ash consumption can help CoV projects with emission reduction, and contribute to BC and Canada forestry products management.

5-4-5- Biochar Concrete

Biochar is produced through the pyrolysis process of biomass (mainly wood waste) to lock the carbon of the material. Although biochar is majorly used for soil enhancement, it has recently garnered interest as an additive material in concrete to produce sustainable construction materials. The locked carbon in concrete turns this construction material into a carbon sink and safely stores carbon dioxide. Biochar is used in concrete in different forms, including finer particles that act as a filler or coarse particles that are intended to partially replace the aggregates in concrete. While biochar enables internal curing and reduces concrete shrinkage, its high moisture uptake poses serious challenges in concrete workability and strength. Mekky et al. [70] calculated 32.2% lower GHG emissions after replacing 5% of cement with a sludge-based biochar. The compressive strength, slump, and LCA results are shown in **Fig. 33**.

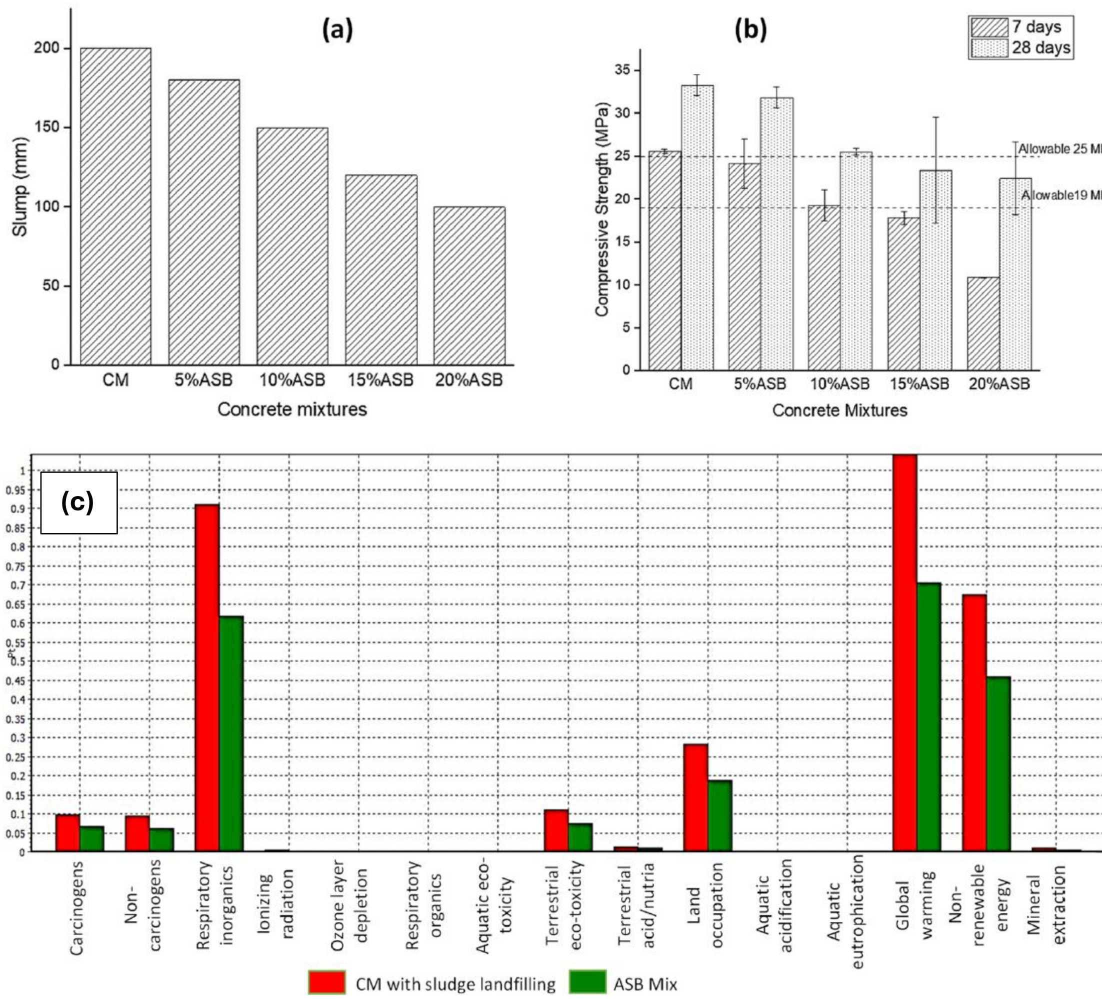


Fig. 33. The influence of biochar on a) slump, b) compressive strength, and c) life cycle analysis of concrete [70]

In a study conducted at UBC, Onuaguluchi et al. [71] used sewage sludge biochar by 0.5-2% content and measured improved compressive strength at such small dosages (i.e., **Fig. 34a**). Onuaguluchi et al. calculation shows GWP reduction from 505 to 478 kgCO_2 eq/m^3 with 2% biochar incorporation in mortar (i.e., **Fig. 34b**). On the other hand, further GHG saving can be achieved by reducing cement content to reach the desired strength.

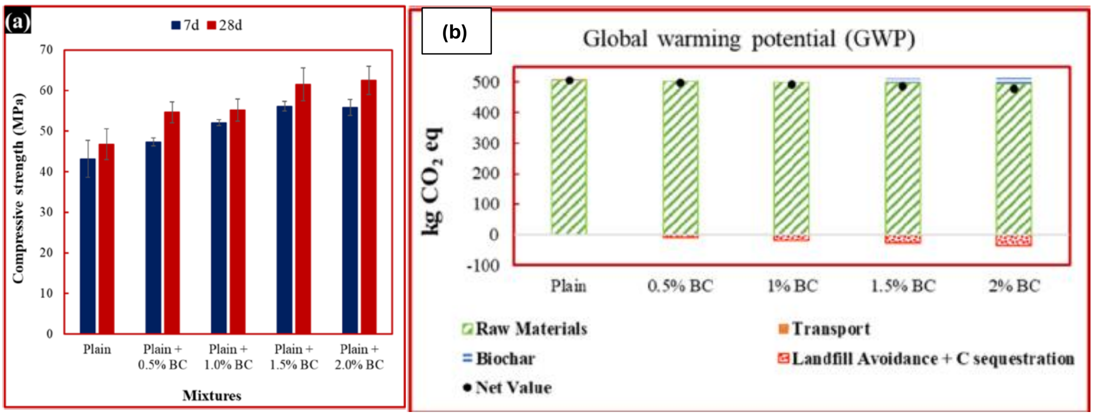


Fig. 34. The influence of sludge biochar on a) compressive strength, and b) CO_2 footprint [71]

Currently, Dr. Sumi Siddiqua's research group at UBC Okanagan is working on biochar treatment to minimize moisture uptake and enhance workability of concrete. Pilot projects can be coordinated to test the green concrete for CoV, and specifically GI projects.

5-5- Summary of Emissions and Recommendations

While green infrastructure and bioretention cells play a crucial role in sustainable development and stormwater management in urban areas, our knowledge about the environmental and carbon footprint of these assets during construction is limited. The CO_2 emissions of four main construction materials employed in GI construction, i.e., crushed aggregates, soil and geotechnical systems, geotextiles, and concrete are broken down and listed in **Table. 37**. The readers are referred to the source publications for an in-depth description of the materials, methodologies, assumptions, limitations, and results.

Table. 37. Summary of reviewed literature on CO_2 footprint of GI construction materials

Material	Main influential factors	Emissions	Unit	Locations of Study	References
Crushed aggregates	Type of rock, explosives, crushing, transportation	2.28-3.59	$kgCO_{2\ eq}/t$	Quebec, Canada	[32]
		3.44	$kgCO_{2\ eq}/t$	Switzerland	[32]
		4.86	$kgCO_{2\ eq}/t$	Brazil	[32]
		7.29	$kgCO_{2\ eq}/t$	India	[32]
Soil and geotechnical systems	Slope, type of soil, transportation, cut and fill, mode of operation	10.4-145.6	$kgCO_{2\ eq}/m^2$	Australia	[35]
		0.186	$kgCO_{2\ eq}/m^3$	Norway	[36]
		15.92-20.35	$kgCO_{2\ eq}/m^3$	India	[34]
Geotextile	Raw materials, electricity grid	2,350	$kgCO_{2\ eq}/t$	UK	[42]
Concrete	Portland cement content, type of fuel in cement kiln, type and content of SCM, SCM transportation, slump, type of aggregates	430 (25 MPa concrete), 510 (50 MPa concrete)	$kgCO_{2\ eq}/m^3$	Australia	[47]
		97.6	$kgCO_{2\ eq}/t$	USA	[48]
		424.89	$kgCO_{2\ eq}/m^3$	Hong Kong	[49]
		381-398	$kgCO_{2\ eq}/m^3$	Ontario, Canada	[50]
		244	$kgCO_{2\ eq}/m^3$	Vancouver, BC	Amrize RMXY1503 EPD

The scholar recommends the following materials and measures to reduce emissions:

Crushed aggregates:

- Specify softer types of rock, such as limestone, wherever possible.
- Minimize aggregates transportation.
- Use recycled concrete as aggregates.
- Use construction and demolition waste as aggregates.
- Use recycled glass aggregates.

Soil and geotechnical systems:

- Minimize soil transportation.
- Reuse the in-situ soil.
- Use fine recycled concrete aggregates to improve soil engineering properties.

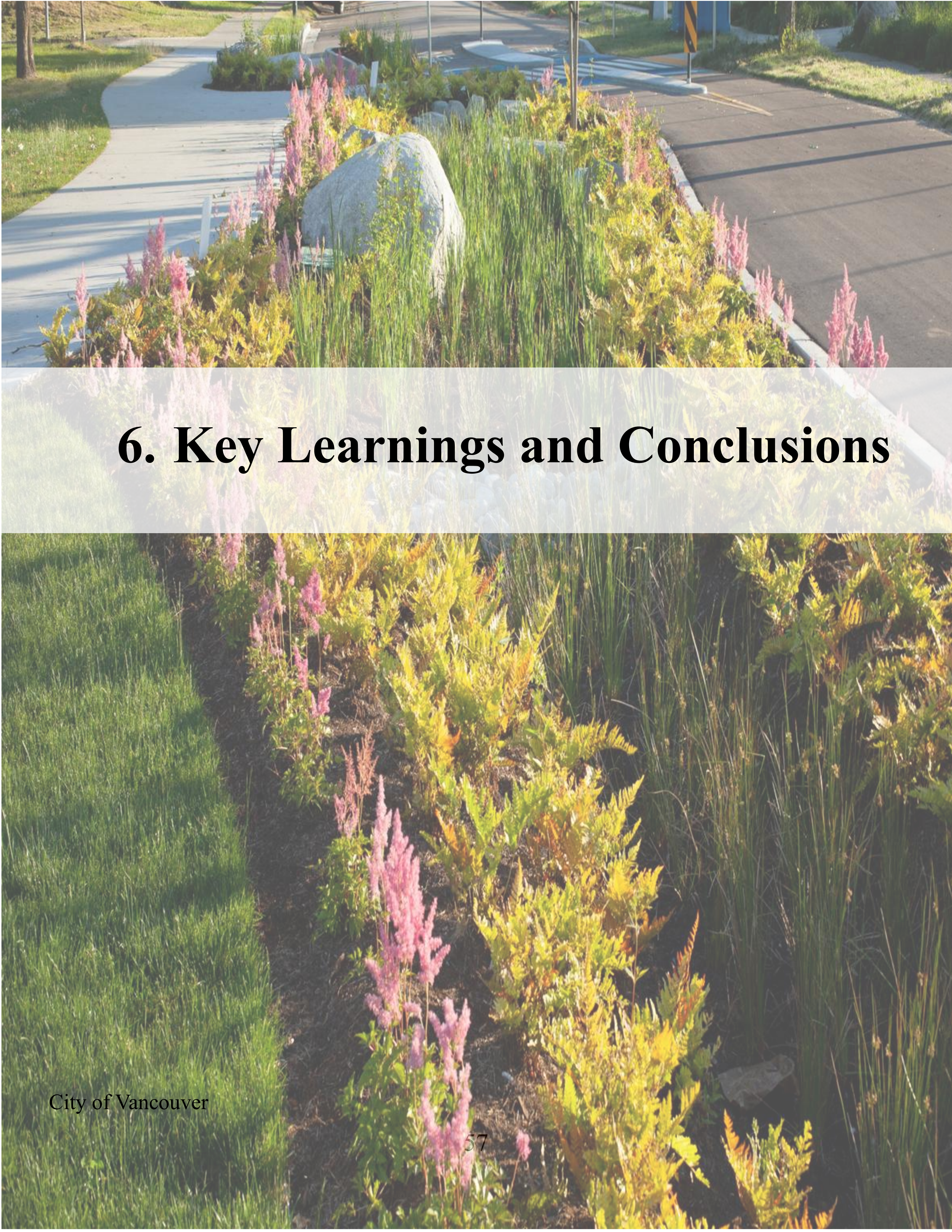
Geotextile:

- Use crushed aggregates instead of the lower geotextile layer.
- Use geotextiles fabricated out of recycled plastic.
- Use biodegradable geotextiles.

Concrete:

- Reduce the required strength from 32 MPa to 25 MPa.
- Cap the maximum strength after 56 days of curing.
- Change the curing date from 28 days to 56 days to allow for more low-cement concrete.
- Incorporate recycled concrete aggregates.
- Pre-carbonate the recycled concrete aggregates to strengthen the concrete while storing CO_2.
- Use high dosages of novel SCMs, such as upgraded wood fly ash.
- Use biochar concrete to safely and permanently store CO_2.

This study did not address the constructability issues, which need to be further investigated. Each recommendation may offer blind spots that need to be explored, such as geotextile puncture due to glass aggregates, leaching possibility from recycled aggregates, soil storage issues on site, longevity of recycled and biodegradable geotextiles, chloride accumulation in recycled concrete aggregates, etc.



6. Key Learnings and Conclusions

Green Infrastructure (GI) is a relatively new urban development method to enhance stormwater management and optimize sewage system utilization. Despite the advantages of GI such as minimizing runoff water, improving water quality, urban heat island mitigation, air quality improvement, biodiversity enhancement, improving public health and other socioeconomic benefits, the structures still emit greenhouse gases (GHG), mainly during the construction and maintenance phases. This report explored the available knowledge about the life cycle assessment (LCA) of GI, with a focus on carbon dioxide emissions by the materials and methods employed to build the GI assets. The studied materials include crushed aggregates, soil and geotechnical systems, geotextiles, and concrete. The most comprehensive and scientific peer-reviewed publications were studied to set the baseline for the emissions. It should be noted that the emissions and LCA can vary remarkably as the assumptions of the study change. As a result, the data may not be directly used to measure the emissions of GI assets in the city of Vancouver but rather used as a starting point to get a grasp of the collective knowledge on the matter and prioritize next steps to precisely measure emissions on a project basis and minimize emissions accordingly. After studying the emission values, recommendations were made to reduce emissions for each material. In any case, the available literature on emissions saved by the recommended methods were discussed. Given the novelty of the recommended methods, the body of knowledge regarding the environmental benefits is limited. The following key findings were learned from this study:

1. **Concrete holds the second largest amount of CO_2 footprint after geotextile per ton of material.** However, given the large quantity of concrete consumption, it is safe to conclude that **concrete contributes the most to the carbon footprint of GI units**. However, concrete industry and research are also delivering innovative solutions to reduce the emissions. From novel SCMs and biochar to recycled aggregates, cement and concrete research is testing and introducing the new generation of concrete that avoid natural resources exploitation, uphold circular economy, and drive sustainability. For such innovations to succeed, the public sector should collaborate with producers to test, procure, and promote these materials, demonstrating meaningful support. It is worth noting that the main role of GI is to increase the permeable surface area in urban locations. Therefore, GI generally reduces the concrete and asphalt consumption compared to the other typical urban development systems.

2. **Geotextile is the most carbon-emitting GI material per ton of material.** Geotextile is a necessary part of GI designs. The high CO_2 emissions from geotextiles stem from the raw synthetic materials. As a result, using recycled geotextiles can effectively reduce the embodied carbon of GI assets. The lower geotextile layer may be replaced by other permeable systems such as crushed aggregates. Biodegradable geotextiles fabricated out of materials such as hemp, coir, etc. are finding their ways into the market and can be considered for GI purposes. The biodegradable materials can be treated to increase their service life.

3. **The type of the source rock and transportation show a remarkable influence on CO_2 emissions of crushed aggregates.** Stronger rocks require more explosives, more energy-intensive grinding, and more frequent maintenance of the crushing units, which may ultimately add up to increase the GI carbon footprint. However, sourcing crushed aggregates from a softer rock that is too far from the location of a project may also not reduce the emissions due to the transportation.

4. **Transportation is the main contributor to GHG emissions of soil and earthwork.** This phase may include empty trucks moving between the construction and quarry, adding to the unnecessary emissions. To minimize the emissions, every attempt should be made to reuse the local soil on site. In cases where the local soil does not inherently have the required engineering properties, soil improvement by using waste or low-emitting materials can be considered. One such example is the fine portion of recycled concrete aggregates. On the other hand, the excavation and compaction machines should be managed to minimize the idling operation condition.

5. **Regulations need to change to facilitate more sustainable designs and materials.** The unnecessary overdesign and large safety factors, such as the high strength requirement for concrete pose a great threat against sustainability. Moreover, regulations should be revisited to incorporate the learnings from LCA, for instance the influence of type of rocks on CO_2 emissions from the aggregates. The regulations around material procurement should be updated to allow for novel materials consumption and support startups or research working towards GHG reduction in construction materials. The procurement regulations should also consider distance and means of transportation as a main source of emissions.

6. **The generic life cycle assessment of GI proves the extensive environmental benefits of the assets.** Most of the CO_2 emissions of GIs are attributed to the construction phase, i.e., materials, transportation, and construction, whereas the GI units can potentially absorb large amounts of CO_2 during their service life. The environmental impacts of GIs can be reduced by planning to recycle the materials after decommissioning. Moreover, the engineering design can play a crucial role in the CO_2 emissions reduction. Attempts must be made to minimize concrete consumption, with the service life period in mind. Since the literature proves that CO_2 emissions of GI units mainly are attributed to the construction materials and transportation, every effort must be made to select greener construction materials, optimize the engineering design, and plan for the minimum materials transportation.

7. **A wide array of the positive environmental impacts of GI are not included in the current emission assessments due to the difficulty of measurement.** GIs help avoid flooding the streets, mitigate heat islands in cities, optimize sewage system utilization, and improve water quality, which are often neglected in the LCA studies. Moreover, CO_2

uptake properties of bioretention system and soil are also neglected when trees are not planted.

8. **GI projects can put the innovative low-carbon construction materials to test at a lower risk for the city.** Once the constructability and performance of the materials are verified through pilot projects, the materials can be adopted by other branches, which will position the GI office as the leader in green construction materials and properties. City of Vancouver as a whole will benefit from the pioneering role of the GI branch as the other branches follow by assimilating the materials and know-how from the GI office.

According to the results derived from this research, GI assets are indeed sustainable means of construction in urban development. However, there is space for improvement, especially during the construction phase of the units. Such parameters as design, materials selection, transportation, and machinery are major players in reducing the environmental footprint of GI. Moreover, LCA calls for a well-established decommissioning plan for GI, which significantly affects the associated emissions.

Based on this report, a few potentially useful research topics are as below:

- Collaboration for employing wood ash-based SCM in concrete as a low-carbon construction material in GI construction.
- Collaboration for pre-carbonation of recycled concrete aggregates to produce superior and low-carbon concrete for GI units.
- Collaboration for understanding the influence of recycled concrete fine aggregates to enhance local soils in City of Vancouver and the possibility of contamination leaching.
- Reviewing the current GI designs in City of Vancouver and revising the designs to reduce emissions.
- Reviewing the design and construction regulations in City of Vancouver and other cities with comparable climate situation to understand the obstacles against sustainability.
- Reviewing and revising the procurement procedure to consider the environmental impacts and life cycle assessment of the materials.
- Reviewing the current decommissioning and maintenance procedure and ratifying regulations to include recycling strategies in designing GI.
- Exploring the material transportation distances and the associated CO_2 emissions to recommend minimization strategies.

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