CONSTRUCTION CARBON FOOTPRINT ANALYSIS OF BREAKWATERS AND SEA WALLS

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Construction carbon footprint analysis of breakwaters and sea walls

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ABSTRACT

With the ever-increasing emphasis on climate change and sustainability, there is growing interest in using environmentally friendly coastal structures. In addition to the engineering and cost factors, the construction Global Warming Potential (GWP) factor influences the selection and design of the structures. Therefore, analysis of constructions GWP facilitates informed decision-making in port and coastal projects to achieve climate goals. The Icelandic-type berm breakwaters (IceBB) constitute nearly half of the constructed berm breakwaters in the world. In this research project, the construction GWP of an IceBB is assessed and compared with concrete armor units conventional rubble mound breakwater (ConRMB). The assessment and comparison are made for the construction of a new breakwater at the port of Straumsvik and the extension of the existing breakwater at the port of Thorlakshofn in Iceland. The Life Cycle Assessment (LCA) method is applied to calculate the construction carbon footprint of the structures using GaBi software. Furthermore, the International Union for Conservation of Nature (IUCN) criteria for Nature-Based Solutions (NBS) are used to explore the IceBB characteristics. The results show that the construction of IceBB has a lower GWP than ConRMB. Moreover, the results indicate that IceBB characteristics meet the IUCN criteria for NBS, and thus can be granted as a (hard) NBS coastal structure. Considering the number of IceBB constructions worldwide, adopting this structure in coastal protection projects can considerably contribute to climate change mitigating policies.

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1. INTRODUCTION

Coastal communities benefit from proximity to coastal and marine resources as well as the economic advantages of ports (Eskafi et al. 2021; Eskafi et al. 2021). However, in this unstable world, ports as dynamic systems are developed under a high degree of uncertainty (Eskafi 2021). Furthermore, ports and coasts have been increasingly experiencing natural hazards and extreme events from the sea due to climate change (Sweeney and Becker 2020). To protect ports and coasts, hard structures such as breakwaters are commonly used. Nevertheless, the construction of these structures itself has a significant carbon footprint (CF) (Eskafi et al. 2024).

Carbon accounting has become a standard requirement for engineering option appraisal and investment justification (Gunnarsdottir et al. 2024). Decision making for the construction of coastal structures accounts for national and international climate change mitigating goals. For instance, Iceland aims to reduce greenhouse gas emissions from the construction industry by 43% compared to a reference year, which is 360,000 tons of CO_2-eq per year or 1 ton per capita, by 2030 and to achieve carbon neutrality by 2040 under the Paris Agreement (Icelandic Ministry for the Environment and Natural Resources 2020). In these numbers infrastructure, such as roads, bridges, and ports, is not considered although they are estimated to be responsible for around 30% of the emissions from the construction sector in Iceland. To achieve this, the Icelandic Building Regulations recommends a broad number of actions. The actions include Life Cycle Assessments (LCA) for new structures according to the international standards ISO 14040 and ISO14044 as well as reducing emissions from construction materials and reducing waste by implementing climate-friendly designs (Housing and Construction Agency, 2022). Control and quantification of emissions in projects are based on global-scale agreements such as Kyoto Protocol (United Nations 1998) and come into effect through measures such as the European Emissions Trading regulated by Directive 2003/87/CE (European Union 2003).

The Icelandic-type berm breakwater (IceBB) has been constructed worldwide for a wide range of wave climates, water depths, and tidal conditions. The design of IceBB is based on utilizing available rock sizes from an armorstone quarry and consists of several relatively narrow-graded stone classes. Structures of narrow-graded armorstone classes have a higher porosity than structures of wider-graded classes. This characteristic leads to a structure with 1- higher permeability and wave energy absorption, 2- more stability, 3- lower wave penetration into the ports, and less wave overtopping, and 4- lower wave reflection from the trunk and head of the structure (van der Meer and Sigurdarson

2016). These advantages are highly demanded by ports with narrow entrances, for instance, and ports exposed to severe wave conditions and high storm frequency.

Although Berm Breakwaters can be strengthened by concrete units, Sigurdarson, Smarason, and Viggosson (2000) pointed out that IceBB can achieve full utilization of the quarry run, and thus limit the fabrication of concrete unit armor. This could reduce the construction Global Warming Potential (GWP) of the structure.

However, there is limited knowledge about the GWP associated with the construction of coastal structures, particularly IceBB, in the literature. Therefore, in this paper, a Life Cycle Assessment (LCA) methodology is applied to assess the construction CF of IceBB and its potential contribution to climate change policies. This is in line with the goal of the Housing and Construction Agency on providing information regarding infrastructure for future assessments of the construction sector (Housing and Construction Agency, 2022).

Furthermore, (Eskafi et al. 2022) discussed the viability of Nature-Based Solutions (NBS) for coastal protection as well as climate change mitigation. NBS aims to address societal challenges effectively and adaptively (e.g., coastal protection, climate change mitigation) and sustainably add benefits to the ecosystems. Therefore, the characteristics of IceBB are explored whether this structure can meet the International Union for Conservation of Nature (IUCN) criteria for NBS and thus be granted a (hard) NBS coastal structure.

2. THE ICELANDIC-TYPE BERM BREAKWATER

The berm breakwater was introduced in the early eighties, and it was used for a porous mass of quarry stone. The design of the breakwater accounts for a horizontal berm with a steep seaward profile to allow the movement of stones under wave force. However, under design storm conditions, or even lower wave heights, the berm is reshaped. The reshaping process includes breaking, splitting, and abrasion of stones. Hence, degradation of the armor stone and plugging of the voids with smaller stones are expected. This decreases the permeability of the structure or reduces the dissipation of wave energy and thus increases runup and wave overtopping (van der Meer and Sigurdarson 2016).

In the early eighties, the Icelandic Harbour Authority (Hafnamalastofnun rikisins) recognized the suitability of the breakwater design for Icelandic conditions. The design of the breakwater was eventually developed into what is now known as the Icelandic-Type Berm Breakwater (IceBB), a higher-engineered berm breakwater that only allows for minor reshaping.

IceBB has been constructed worldwide for nearly 40 years. IceBB is designed to be statically stable with only limited stone movement and structural reshaping. The preliminary design of IceBB is based on initial size distribution estimates from potential quarries. The final design is tailored to fit the selected quarry, the design wave load, available construction equipment, and transport routes. IceBB is built with several stone classes of narrow-size gradation. This increases the stability of the structure, and thus, decreases armor stones' size.

The stability of the rubble mound breakwater can be investigated by physical modeling (Eskafi, Morovati, and Lari 2011). Using physical modeling tests the design of IceBB has been optimized to increase its structural stability and decrease the amount of overtopping (van der Meer and Sigurdarson 2016). They pointed out that structural behavior of berm breakwaters is described by the recession, Rec, and the damage, S_D, of the berm if the reshaping is not significant. Stability number of berm breakwater can be calculated by:

$$H_o = \frac{H_s}{\Delta D_{n50}} \quad (1)$$

where H_s is the significant wave height, D_{n50} is the nominal diameter of the stones, and Δ is the relative density of the stone (PIANC 2003). Using the stability number, Van der Meer and Sigurdarson (2016) classified berm breakwater as given in **TABLE 1**.

TABLE 1. Classification of berm breakwaters based on the stability parameters.

Type of breakwater	$\frac{H_s}{\Delta D_{n50}}$	S_d	$\frac{Res}{D_{n50}}$
Hardly reshaping berm breakwater (IceBB)	1.7 - 2.0	2 - 8	0.5 - 2
Partly reshaping berm IceBB	2.0 - 2.5	10 - 20	1 - 5
Partly reshaping mass-armored berm breakwater	2.0 - 2.5	10 - 20	1 - 5
Fully reshaping mass-armored berm breakwater	2.5 - 3.0	-	3 - 10

The design criteria of IceBB have been developed over the past 30 years, from 5% damage for a 25-50-year design return period to currently 0 – 2% damage for a 100-year design return period. Some IceBBs in Iceland have experienced the design wave conditions or even exceeded, but only minor profile changes have been observed. **TABLE 2** gives a complete list of IceBB structures in Icelandic ports.

TABLE 2. List of ports that are protected by IceBB in Iceland.

		Year of construction	Volume	Design wave on trunk		Class I on top of berm on trunk	
				H_s	T_p	M_{50}	$H_s/\Delta D_{n50}$
			(Km^3)	(m)	(s)	(t)	(-)
1	Akranes	1991	25	3.8	19	4-8	1.71
2	Arnarstapi	1984	15	4.1	17	0,9-5	2.71
3	Arnarstapi	2002	15	4.1	17	4-10	1.85
4	Olafsvik	1995	31	4.4	10	4-8	2.06
5	Olafsvik	2021	36	4.0	10	4-10	1.80
6	Grundarfjordur	2001	40	2.2	6.5	0.5-2	1.80
7	Grundarfjordur	2019	48	2.2	6.5	2-5	1.33
8	Brjanslaekur	1987	44	2.2	5	1-2.5	1.57
9	Bolungarvik	1993	200	5.5	17	4-10	2.42
10	Nordurfjordur	1984	60	2.0	19	0.6-1.5	1.69
11	Blonduos	1994	95	4.8	12	1-6	2.82
12	Skagastrond	1991	25	3.5	15	5-8	1.58
13	Skagastrond	1997	8	3.5	15	4-10	1.58
14	Saudarkrokur	1988	20	3.5	8	2-5	1.98
15	Saudarkrokur	1998	17	2.8	10	2-5	1.59
16	Saudarkrokur	2021	13	2.8	10	2-5	1.59
17	Hofsos	1983	32	4.2	12	3-6	2.16
18	Dalvik	1995	104	2.5	8	1.5-4	1.55
19	Arskogssandur	1987	24	2.7	6	1-2.5	1.93
20	Arskogssandur	2000	28	2.7	6	3-10	1.24
21	Grenivik	1995	40	3.1	8	3.5-8	1.52
22	Husavik	1988	83	4.0	16	1-5	2.37
23	Husavik	2001	270	6.8	16	16-30	1.94
24	Husavik	2016	65	5.5	16	10-20	1.86
25	Thorshofn	1985	9	2.6	14	0.6-3.0	1.86

Continued

TABLE 2. (Continued) List of ports that are protected by IceBB in Iceland.

		Year of construction	Volume	Design wave on trunk		Class I on top of berm on trunk	
				H_s	T_p	M_{50}	$H_s/\Delta Dn_{50}$
			(Km^3)	(m)	(s)	(t)	(-)
26	Thorshofn	1999	24	4.5	14	5-10	1.91
27	Thorshofn	2007	41	4.5	14	3-7	2.21
28	Bakkafjordur	1983	105	4.8	12	0.5-6	3.35
29	Vopnafjordur	2003	124	5.0	16	8-25	1.67
30	Djupivogur	1995	33	3.0	14	2-6	1.61
31	Hornafjordur	1995	100	3.8	15	5-10	1.52
32	Landeyjahofn	2008	600	6.1	17	12-30	1.86
33	Thorlakshofn	2004	230	5.5	15	8-25	1.84
34	Thorlakshofn	2022	445	6.1	15	8-15	2.24
35	Grindavik	2001	170	5.1	18	6-15	1.96
36	Helguvik	1986	900	5.0	10	1.7-7.0	2.77
37	Helguvik	2008	350	5.0	10	5-15	1.95
38	Keflavik	1996	150	3.7	10	5-8	1.67
39	Hafnarfjordur	1985	8	2.7	9	0.8-2.5	1.97
40	Hafnarfjordur	1998	550	3.0	14	3-6	1.51

A wide range of precast concrete armor units has been developed for breakwaters and coastal protection. These units come in various shapes and designs, ranging from simple cubes to more complex forms (Smith, 2016). The concrete armor type chosen for this research project is called Cubipod, which is a cube that features protrusions on each face. This prevents face-to-face fitting and increases friction between units and underlying layers (Medina and Gómez-Martín, 2012).

3. METHODS

3.1. Life cycle assessment and system boundaries

The carbon footprint calculations in this research project follow the Life Cycle Assessment (LCA) methodology outlined in ISO standard 14044:2006 Environmental management, Life cycle assessment, Requirements and guidelines (International Organization for Standardization 2006). LCA is a methodology that allows the calculation, evaluation, and interpretation of the generated emissions during the lifetime of the infrastructure. **TABLE 3** gives a concise description of CF associated with the construction of concrete armor unit conventional rubble mound berm breakwater (ConRMB) and Icelandic-type berm breakwaters (IceBB).

TABLE 3 Sources of CO_2 emission in the construction of IceBB and ConRMB.

	Cradle-to-Grave[1]				
	Cradle-to-Site[2]				
	Cradle-to-Gate[3]				
	Procurement/production of materials	Transport to site	Construction on site	Operation/maintenance	Disposal
IceBB	Quarry operation of armor stone including drilling, blasting, sorting, internal transport on site, and production of stone waste[4]	Barges[4], and trucks for the transport of rock and quarry run from the quarry	Excavators, front loaders[4] and barges[4]	Excavators and barges, for the repair of armor layers[4]	_
ConRMB	Cement, aggregate, steel reinforcement[4], quarry operation of armor stone including drilling, blasting, sorting, internal transport on site, and production of stone waste[4]	Barges[4] and trucks for the transport of armor units, rock, and quarry run from yard and quarry	Excavators, cranes[4], front loaders[4] and barges[4]	Excavators, cranes, and barges for the repair of armor layers[4]	_

System Boundaries:
[1] carbon released from the extraction of raw material until the end of the product lifetime.
[2] carbon is released until the product has reached the point of use.
[3] carbon releases until the product leaves the factory.
[4] sources not used in this research project

This paper focuses on the system boundaries, including the procurement of raw materials, transport to the construction site, and construction activities. CF of operation and maintenance of the breakwater is much smaller than its construction CF. Measurement of CF beyond the long design lifetime (i.e., decommissioning and disposal, if carried out) has uncertain results and requires a detailed options appraisal exercise (Bruce and Chick 2010). Their assessment is not expected to have a significant effect on the outcome of the present appraisal.

A simplified version of the equation used to calculate the total CF for this research project is shown below. The first and second line represents the production of the materials, the third line represents the transport of the materials, and the fourth line represents the construction of the berm breakwater. The overall CF is expressed in weight:

$$CF = \sum_{i=1}^{n}\left(\left(ANFO_i \times e_{ANFO,i} + f_{drill,i} \times e_{f,drill,i} + f_{q,exc,i} \times e_{f,exc,i}\right) \times V_i\right) + \sum_{i=1}^{n}\left(\left(e_{concrete,i} + f_{q,exc,i} \times e_{f,exc,i} + f_{c,exc,i} \times e_{f,exc,i}\right) \times V_i\right)^{*} + \sum_{i=1}^{n}\left(\left(f_{truck,i} \times e_{f,truck,i}\right) \times d_i\right) + \sum_{i=1}^{n}\left(\left(f_{cs,exc,i} \times e_{f,exc,i}\right) \times V_i\right)$$

$ANFO_i$: The amount of explosives needed per m^3 of quarry material $\left[\frac{g}{m^3}\right]$
$e_{ANFO,i}$: CO_2-eq emissions per gram of the specific ANFO $\left[\frac{\text{kg CO}_2-\text{eq}}{\text{g}}\right]$
$f_{drill,i}$: Fuel consumption of a specific drill needed to extract 1 m^3 of quarry material $\left[\frac{\text{l}}{\text{m}^3}\right]$
$e_{f,drill,i}$: CO_2-eq emissions per liter of the specific fuel for a specific drill $\left[\frac{\text{kg CO}_2-\text{eq}}{\text{l}}\right]$
$f_{q,exc,i}$: Fuel consumption of a specific excavator needed to excavate 1 m^3 of quarry material $\left[\frac{\text{l}}{\text{m}^3}\right]$
$e_{f,exc,i}$: CO_2-eq emissions per liter of the specific fuel for a specific excavator $\left[\frac{\text{kg CO}_2-\text{eq}}{\text{l}}\right]$
V_i: Volume $[m^3]$
$f_{c,exc,i}$: Fuel consumption of a specific excavator needed to excavate 1 m^3 of concrete armor units $\left[\frac{\text{l}}{\text{m}^3}\right]$
$e_{concrete,i}$: CO_2-eq emissions per m^3 of ready mix concrete for Cubipod $\left[\frac{\text{kg CO}_2-\text{eq}}{\text{m}^3}\right]$
$f_{truck,i}$: Fuel consumption of a specific truck needed to transport specific amount of material 1 km $\left[\frac{\text{l}}{\text{km}}\right]$
$e_{f,truck,i}$: CO_2-eq emissions per liter of the specific fuel a specific truck $\left[\frac{\text{kg CO}_2-\text{eq}}{\text{l}}\right]$
d_i: Distance $[km]$
$f_{cs,exc,i}$: Fuel consumption of a specific excavator needed to excavate 1 m^3 of material at construction site $\left[\frac{\text{l}}{\text{m}^3}\right]$
*Only for ConRMB

In this research project, the GaBi software from Sphera was used for LCA, and calculations were conducted using the background data from the GaBi professional and construction databases (Sphera 2022b; 2022a). GaBi is a leading tool for LCAs, with many advantages over other calculation tools.

3.2. Procurement/production of materials

Carbon emissions for the production of rock are based on the type of quarry, including aggregate, dimension stone, and dedicated armor stone quarries (CIRIA, CUR, CETMEF 2007). The armor stone should meet the quality requirements, for instance, durability, specific gravity, and water absorption (Sigurdarson, Smarason, and Viggosson 2000).

On the other hand, the CF of concrete depends on the compressive strength class of concrete, the amount of cement additions, such as fly ash or ground granulated blast furnace slag, and the amount of steel reinforcement (Hammond and Jones 2008). In this paper, armor units are not reinforced, and thus no additional EC component for steel reinforcement is added.

Excavators were used to load the rocks and concrete armor onto trucks for transport to the construction site. The carbon emissions resulting from machinery are directly linked to fuel consumption, which is influenced by various factors, including the distance traveled, the type of machinery used, the fuel type, and the degree of cargo capacity utilization, among other considerations. In this research project, the machinery was fueled by fossil fuels.

3.3. Transport to site

In this research project, machinery equipment is classified into two groups (European Environment Agency 2019):

1. Transport machinery to transport the material to the site,
2. Construction machinery to carry out the construction activity.

3.4. Construction on site

Rocks and quarry run are transported from the quarry to the construction site, and Cubipod armor units from an on-site concrete casting plant to the breakwater at the site, using trucks. Carbon emissions due to transportation are directly related to fuel consumption, which depends on transportation distance, type of vehicle and fuel used, and cargo capacity utilization, among other factors.

3.5. Nature-Based Solution

NBS has been a common practice in soft coastal protection projects. Coastal habitats, such as dunes, biogenic reefs, mangroves, and wetlands can provide soft coastal protection. However, Sutton-Grier, Wowk, and Bamford (2015) highlighted the weaknesses of soft coastal protection. They stated that to ensure the successful establishment and functioning of NBS in coastal protection projects, their design requires consideration of a range of biological, chemical, and physical parameters, and land availability.

Keesstra et al (2018) highlighted that coastal management is well advanced in using soft solutions as NBS. However, research on hard coastal protection is scant in the literature.

IUCN has introduced global standards for verifying NBS that yield the desired outcome, in solving social challenges. Using these standards implementation of NBS can be measured and monitored to ensure its credibility (IUCN 2020). Furthermore, the standard can be used as a means of communication with stakeholders to discuss NBS trade-offs, just as this research project examines IceBB with IUCN criteria and presents the results. The Standard consists of 8 criteria and 28 indicators (IUCN 2020).

4. STUDY AREA

In this research project, the assessments and comparisons are made for different scenarios in two Icelandic port projects, as follows:

1. Protection of the port of Thorlakshofn
   a) Extend the existing breakwater with an IceBB,
   b) Extend the existing breakwater with a ConRMB,
2. Protection of the port of Straumsvik
   a) Construct a new IceBB,
   b) Construct a new ConRMB.

Coda Terminal is the world's first large-scale transport and storage of CO_2. An 800 m breakwater is planned to be constructed to protect a new landfill at the port as well as the port basin. The main function of the port will be to receive ships to unload CO_2 that will be stored temporarily in onshore tanks and then transported in pipes to a network of wells to be injected into the fresh basaltic bedrock and transform into solid minerals.

The Port of Thorlakshofn is in the south of Iceland. The port has a competitive advantage, due to its geographical location, infrastructure, and services among the other ports in the south of the country. Coastal shipping and road transportation are the only two transport modes that connect the port to its hinterland, which is the whole country.

The main functions of the port:

- Transfer and storage of the vehicle, containerized cargo, and noncontainerized cargo.
- Industrial value-added activities, including fisheries and aquaculture.
- Recreational activities, such as rendering services to expedition vessels and cruise ships.

FIGURE 1 shows the port of Thorlakshofn and the port of Straumsvik as well as the Icelandic ports that are protected by IceBB.

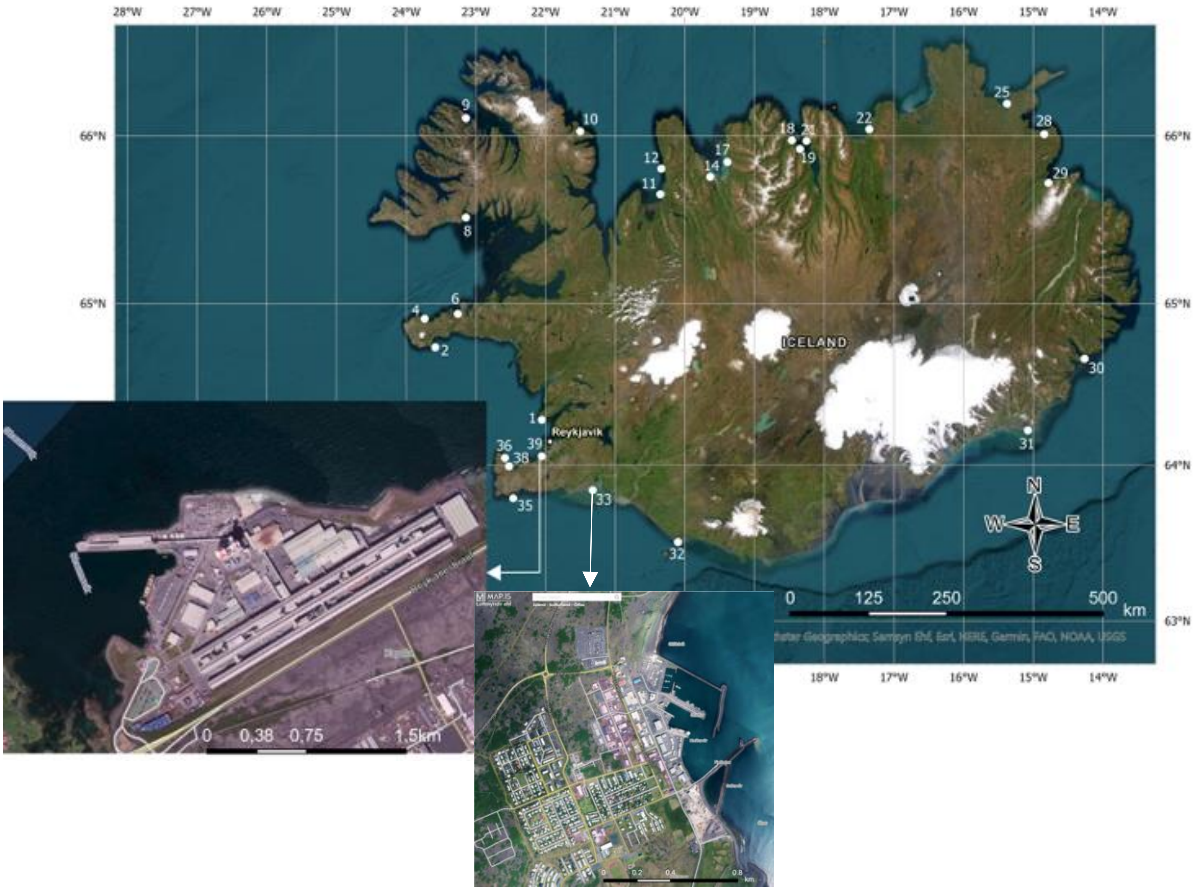

FIGURE 1 Locations of IceBB in Iceland; numbers refer to the ports in **TABLE 2**. The port of Straumsvik and the port of Thorlakshofn are magnified in the figure.

The knowledge of construction CF is of importance to the port authorities for informed decision-making aimed at addressing the Icelandic climate change policies.

5. NUMERICAL DATA AND ASSUMPTIONS

To compare the construction CF of the two breakwaters, a full design needed to be carried out for both scenarios, i.e., IceBB and ConRMB.

The construction assumptions and numerical values used in this research project had been derived from similar projects undertaken in Iceland. The designed IceBB and ConRMB can be seen in **FIGURE 2** and **FIGURE 3**, showcasing their respective cross-sections.

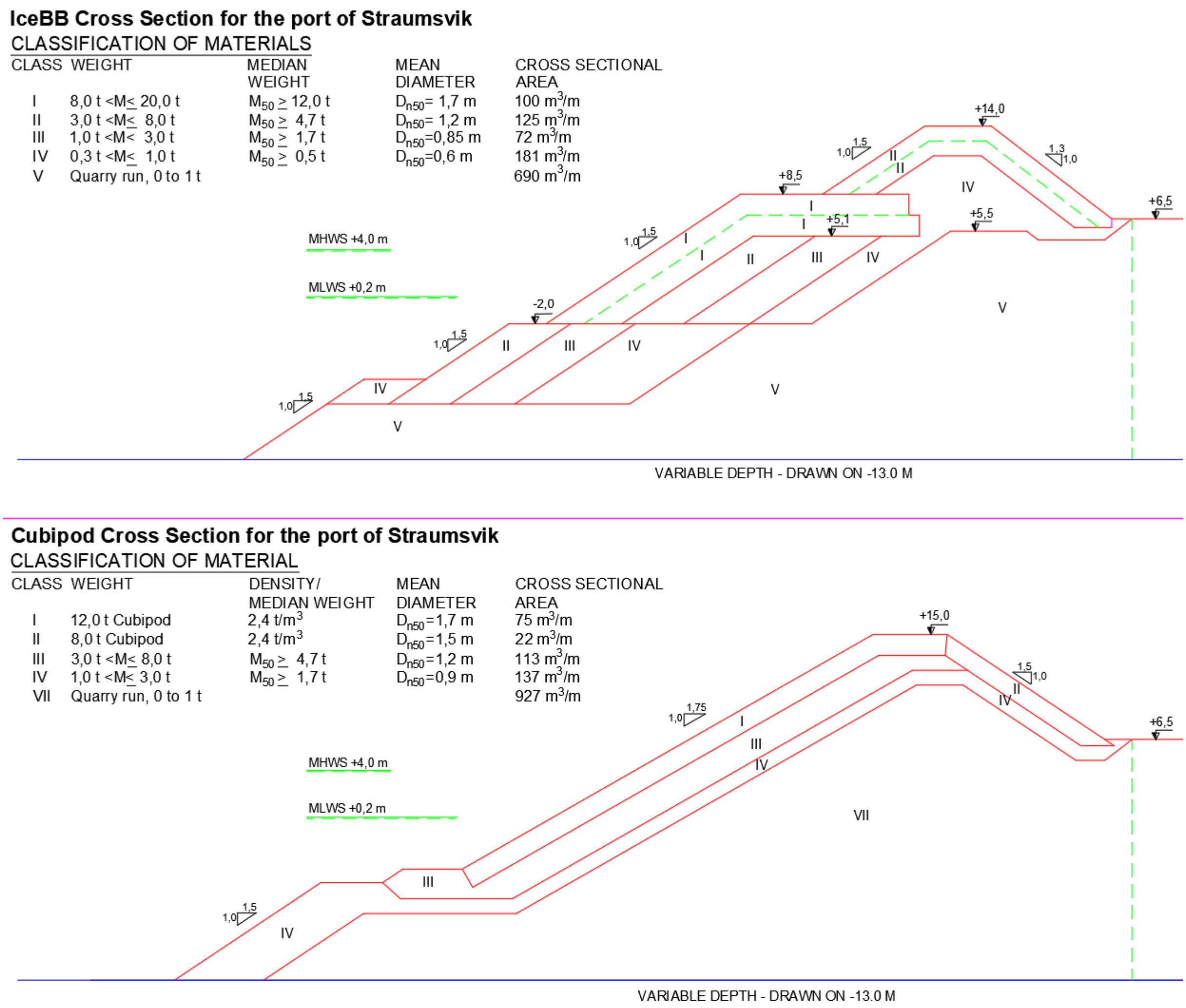

FIGURE 2. The cross section of IceBB (top row) and ConRMB (bottom row) for the protection of the Straumsvik port.

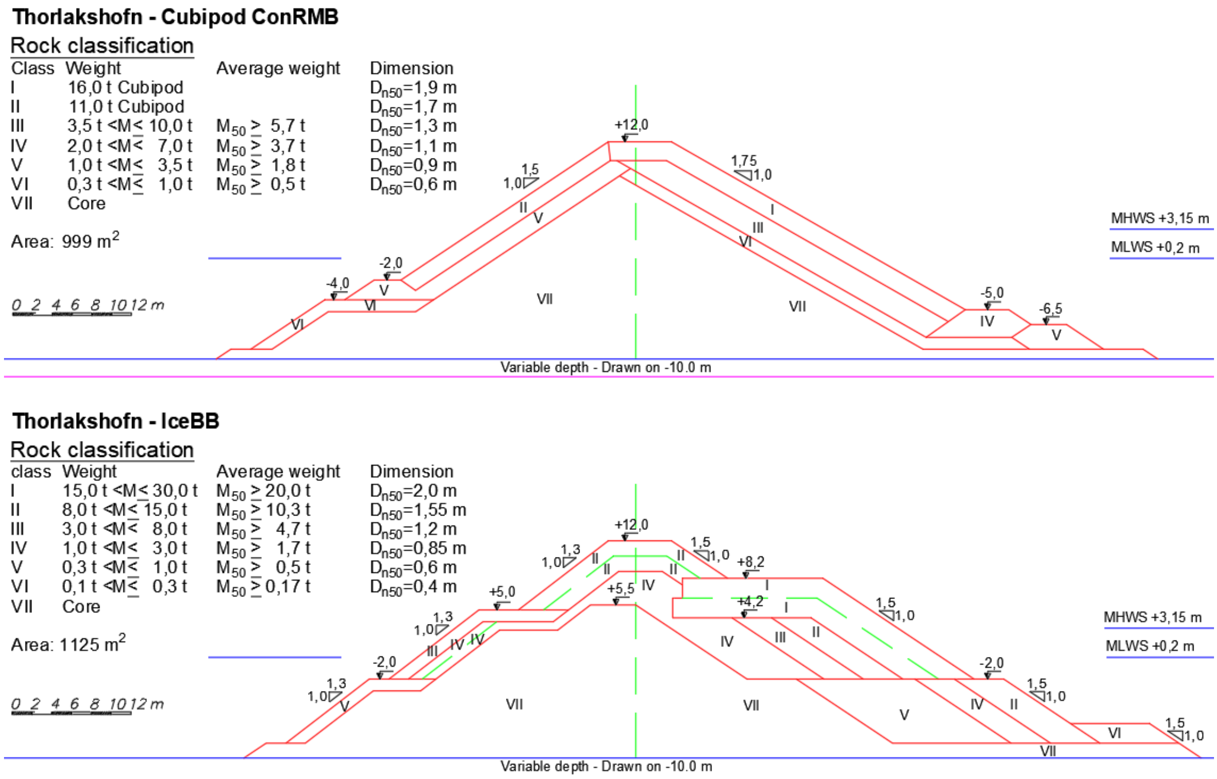

FIGURE 3. The cross section of IceBB (bottom row) and ConRMB (top row) for the protection of the Thorlakshofn port.

5.1. Procurement/production of materials

In this comparative LCA research project, the environmental impact of constructing one linear meter of the breakwater was evaluated.

The construction process involved sourcing rocks of various sizes and quarry run from a quarry located 8 km and 4 km away from the construction site for the port of Straumsvik and the port of Thorlakshofn, respectively. To extract the rocks, a drilling rig was used to create holes in the bedrock, followed by the insertion and detonation of ANFO explosives at a rate of 250 grams per cubic meter of rock and quarry run.

Two excavators, weighing 70 and 50 tons for the port of Straumsvik, and 90 and 45 tons for the port of Thorlakshofn were used to sort and load the rocks and quarry run onto trucks for transport. For the port of Straumsvik port project the 70-ton excavator handled rocks weighing over 1.0 tons, while the 50-ton excavator dealt with rocks lighter than 3.0 tons. However, for the port of Thorlakshofn project the 90-ton excavator is used to sort and load rocks that are heavier than 3 t onto trucks, and the 45-t excavator is used to sort and load rocks lighter than 8 t. It was assumed that the two excavators evenly sort rocks based on the total volume of rocks.

In terms of carbon emission calculations related to the excavators, the focus was on the total volume without differentiating between rock sizes and quarry run. This approach simplified the analysis while still providing meaningful results.

It is important to note that during the calculations, a density adjustment for the rock was made considering approximately 40% porosity of the breakwater (van der Meer & Sigurdarson, 2016). The density of basalt was considered $2850\frac{kg}{m^3}$. Thus, the density of the rock material used in the breakwater was calculated as $2850\frac{kg}{m^3} \times 0.6 = 1710\frac{kg}{m^3}$ reflecting the presence of air pockets within the breakwater. The same porosity assumption was made for the ConRMB.

TABLE 4 and **TABLE 5** give the volume of each rock size class used in the IceBB and the total volume of rocks and quarry run each excavator sorts and loads onto trucks. For the calculations of carbon emissions from the excavators, only the total volume is used as an input, i.e., no distinction is made between different rock sizes and quarry runs.

The excavators' and drilling rig's fuel consumption is estimated based on their power output. For diesel engines, fuel consumption under full-rated power ranges from 0.21-0.26 kg/(kW·h) (Klanfar, Korman, and Kujundžić 2016). Therefore, fuel use of 0.235 kg/(kW·h) diesel fuel (0.85 kg/L), and a load factor of 0.56 (Klanfar, Korman, and Kujundžić 2016) accounted for the excavators. The drilling rig is assumed to have the same fuel consumption as an excavator (0.235 kg/(kW·h)), but with a load factor of 0.61 (Klanfar, Korman, and Kujundžić 2016). Generic excavator background data from the Gabi professional and construction databases was used to model the excavators and drilling rig, but with adjusted hourly fuel consumption and load factors. Other modeling parameters were kept as default values, such as the number of cycles per minute and bucket volume.

In the ConRMB scenario, the same quarry and methods were used for the rocks as in the IceBB scenario. Furthermore, the same excavator and drilling rig activities used for the IceBB scenario were applied in the ConRMB scenario.

In addition to rocks and quarry run, the construction of the ConRMB involved the use of Cubipod concrete armor units. Two sizes of these units were used, as follows:

- 12.0 tons and 8.0 tons for the port of Straumsvik project.
- 16.0 tons and 11.0 tons for the port of Thorlakshofn project.

They were produced using C35/45 concrete, with CEM I 32 cement and 77% clinker content. The manufacturing of concrete units took place 1 km from the construction site. 50-ton and 60-ton excavators loaded them onto trucks for the port of Straumsvik port project and the port of Thorlakshofn project, respectively. **TABLE 4** and **TABLE 5** provide detailed information on the weight range of each of the two rock size classes and concrete armor units used in the ConRMB scenario, as well as the volume sorted and loaded onto trucks by excavators.

TABLE 4 The needs for the construction of IceBB and ConRMB (numbers in brackets) at the Straumsvik port in Iceland. All data is per linear meter of the breakwater.

class		Volume in breakwater (m^3/m)	Volume concrete 40% porosity (m^3/m)	Sorted and loaded by each excavator (m^3/m)		
				70 t excavator	50 t excavator	50 t excavator
I	8.0 t < M < 20.0 t, M_{50} > 12.0 t (12.0 t Cubipod, 2400 kg/m^3)	100 (75)	(45)	100 (0)	0 (0)	(75)
II	3.0 t < M < 8.0 t, M_{50} > 4.7 t (8.0 t Cubipod, 2400 kg/m^3)	125 (22)	(13)	125 (0)	0 (0)	(22)
III	1.0 t < M < 3,0 t, M_{50} > 1.7 t (3.0 t < M < 8.0 t, M_{50} > 4.7 t)	72 (113)		14 (113)	58 (0)	(0)
IV	0.3 t < M < 1.0 t, M_{50} > 0.5 t (1.0 t < M < 3.0 t, M_{50} > 1.7 t)	181 (137)		0 (12)	181 (125)	(0)
VII	Quarry run	690 (927)		584 (464)	584 (463)	(0)
Total	IceBB (ConRMB)	1168 (1274)	(58)	584 (589)	584 (588)	(97)

TABLE 5. The needs for the construction of IceBB and ConRMB (numbers in brackets) at the port of Thorlakshofn in Iceland. All data is per linear meter of the breakwater.

class		Volume in breakwater (m^3/m)	Volume concrete 40% porosity (m^3/m)	Sorted and loaded by each excavator (m^3/m)		
				90 t excavator	60 t excavator	45 t excavator
I	15 t < M < 30 t, M_{50} > 20 t (16 t Cubipod, 2400 kg/m^3)	116 (75)	0 (45)	116 (0)	0 (75)	0
II	8,0 t < M < 15 t, M50 > 10.3 t (11 t Cubipod, 2400 kg/m^3)	115 (42)	0 (25)	115 (0)	0 (42)	0
III	3.0 t < M < 8,0 t, M_{50} > 4.7 t (3.5 t < M < 10 t, M_{50} > 5.7 t)	47 (86)	0	24 (86)	0	23 (0)
IV	1,0 t < M < 3,0 t, M_{50} > 1.7 t (2,0 t < M < 7,0 t, M_{50} > 3.7 t)	129 (21)	0	0 (11)	0	129 (10)
V	0.3 t < M < 1 t, M_{50} > 0.5 t (1.0 t < M < 3,5 t, M_{50} > 1.8 t)	97 (71)	0	0	0	97 (71)
VI	0.1 t < M < 0,3 t, M_{50} > 0.17 t (0.3 t < M < 1 t, M_{50} > 0.5 t)	16 (75)	0	0	0	16 (75)
VII	Quarry run	606 (628)	0	303 (314)	0	303 (314)
Total	IceBB (ConRMB)	1,125 (998)	0 (70)	557 (411)	0 (117)	568 (470)

5.2. Transport to site

For the IceBB and ConRMB in the port of Straumsvik project, the transport of rocks and quarry run to the construction site was carried out by three mining trucks and four regular trucks. Each trip carried approximately 11 m^3 of rock or 14 m^3 of quarry run, covering a distance of about 8 km from the quarry to the construction site at the port. However, in the port of Thorlakshofn, three mining trucks are used to transport rocks and quarry run to the construction site, yielding approximately 18 m^3 of rock or 22 m^3 of quarry run per trip. The transportation distance is about 4 km from the construction site at the port.

The return trip is with an empty truck, so the total utilization or load factor of 0.5 per trip is used. Emissions due to transport were calculated assuming the use of trucks that weigh more than 32 t and meet EU emission standards ranging from Euro I to Euro VI.

In the ConRMB construction, in addition to rocks and quarry run, Cubipod concrete armor units were utilized. They are assumed to be manufactured 1 km away from the construction site and loaded onto a mining truck using a 50-ton excavator.

5.3. Construction on site

At the construction site, a 95-t excavator, or a bulldozer, is used to arrange the quarry run and rock to construct the breakwaters, i.e., IceBB and ConRMB. Fuel use of 0.235 kg/(kW·h) diesel fuel (0.85 kg/L) and a load factor of 0.56 is accounted for the construction machinery. This excavator's activity was modeled in the same way as the ones working at the quarry. Generic excavator background data from the Gabi professional and construction databases was used to model the excavator, but with adjusted hourly fuel consumption and load factors. Other modeling parameters were kept as default values, such as the number of cycles per minute and bucket volume.

TABLE 6 and TABLE 7 summarize the inputs and parameters used for the modeling of the construction of the IceBB and ConRMB at the port of Straumsvik and the port of Thorlakshofn.

TABLE 6 Inputs and parameters used for the modeling of the construction of IceBB and ConRMB in the port of Straumsvik. All data is per linear meter of the breakwater.

Procurement of raw materials				
Explosives	**Quantity [g/m^3 excavated material]**			
ANFO	250			
Machinery	**Power [kW]**	**Fuel consumption [l/h]**	**Load factor**	**Excavated material [m^3]**
Drilling rig	209	58	0.61	1168, 1177*
70 T excavator	339	93	0.56	584, 589*
50 T excavator	268	74	0.56	584, 588*
50 T excavator for loading Cubipod	268*	74*	0.56*	97*
Cubipod production	**Volume [m^3]**			
Ready-Mix Concrete	58*			
Transport to construction site				

Trucks	Payload [m^3] ([t])	Distance [km]	Utilization	Volume transport [m^3]
Truck for rock transport	11(19.8)	8	0.5	478, 250*
Truck for quarry run transport	14 (25.2)	8	0.5	690, 927*
Truck for Cubipod transport	(27)*	1*	0.5*	97*
Construction site activities				
Excavator	**Power [kW]**	**Fuel consumption [L/h]**	**Load factor**	**Excavated material [m^3]**
95 T excavator	522	144	0.56	1168, 1274*
* For ConRMB				

TABLE 7. Inputs and parameters used for the modeling of the construction of IceBB and ConRMB in Thorlakshofn. All data is per linear meter of the breakwater.

Assumptions, parameters, and inputs				
Procurement of raw materials				
Explosives	**Quantity [g/m^3 excavated material]**			
ANFO	250			
Machinery	**power [kW]**	**Fuel consumption [l/h]**	**Load factor**	**Excavated material [m^3]**
Drilling rig	206	57	0.61	1125, 882*
90 T excavator	600	166	0.56	557, 411*
45 T excavator	240	66	0.56	568, 471*
60 T excavator for loading Cubipod	420*	116*	0.56*	70*
Cubipod production	**Volume [m^3]**			
Ready-Mix Concrete	70*			
Transport to construction site				
Trucks	**Payload [m^3] ([t])**	**Distance [km]**	**Utilization**	**Volume transport [m^3]**
Truck for rock transport	18 (32.5)	4	0.5	519, 254*
Truck for Quarry run transport	22 (39.6)	4	0.5	606, 628*
Truck for Cubipod transport	(27)*	1*	0.5*	70*
Construction site activities				
Excavator	**Power [kW]**	**Fuel consumption [L/h]**	**Load factor**	**Excavated material [m^3]**
95 T excavator	514	142	0.56	1125, 952*
* For ConRMB				

6. RESULTS AND DISCUSSION

The comparison of the CF from the two construction types, IceBB and ConRMB, for the Straumsvik port project and the port of Thorlakshofn is interpreted and discussed in this section.

The calculated results of the construction CF for the port of Straumsvik project reveal that the total GWP for the construction of IceBB is 4.44 t CO_2-eq/m, while for ConRMB, it is 22.1 t CO_2-eq/m. The significant difference in GWP between IceBB and ConRMB is a direct consequence of the production of concrete used for the Cubipod armor units, which contributes to approximately 77% of the total emissions, accounting for 17.1 t CO_2-eq/m.

Furthermore, the results of calculations of construction CF show that the total GWP for the construction of ConRMB is 24.0 t CO_2-eq per linear meter of the breakwater, compared to 3.68 t CO_2-eq/m for the IceBB. The difference in GWP between IceBB and ConRMB is mainly due to the production of the concrete used for the Cubipod armor units, which account for 20.7 t CO_2-eq/m, or about 86% of total emissions.

FIGURE 4 and **FIGURE 5** provide an overview of the carbon emissions associated with each phase of the construction process, ranging from raw material procurement to breakwater construction at the port.

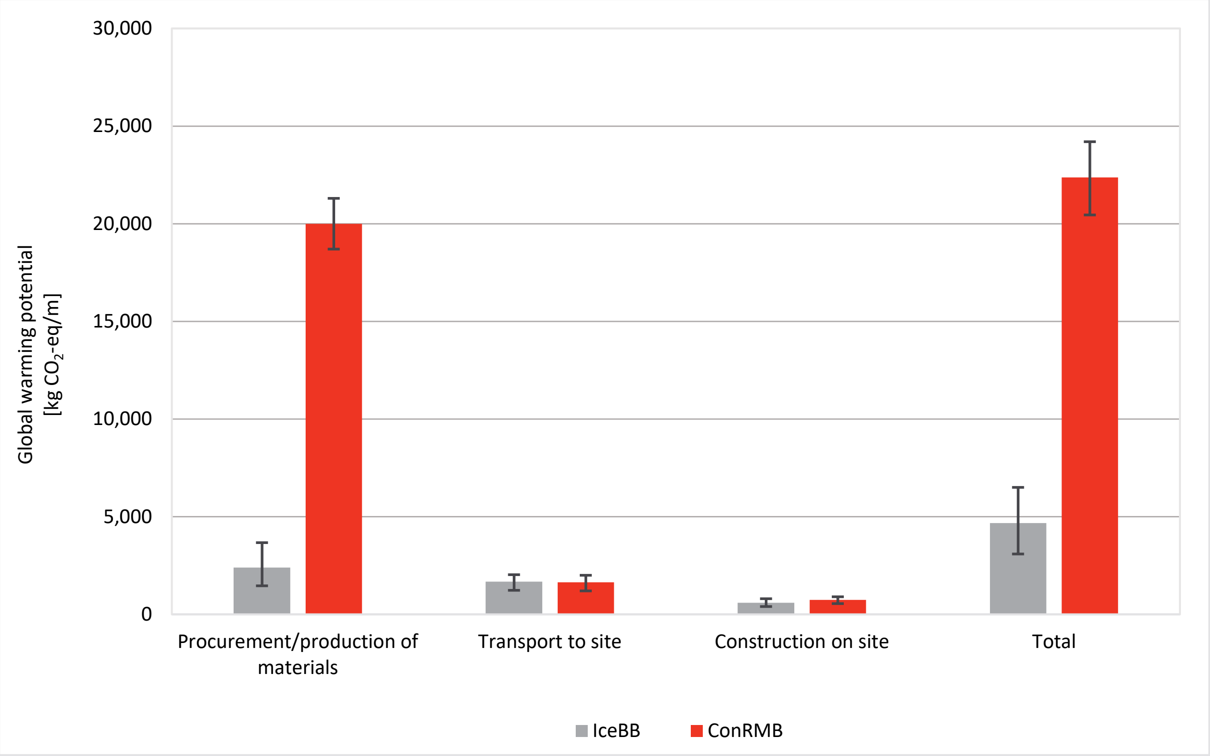

FIGURE 4 Comparative results of the calculation of the CF of IceBB and ConRMB for the port of Straumsvik project.

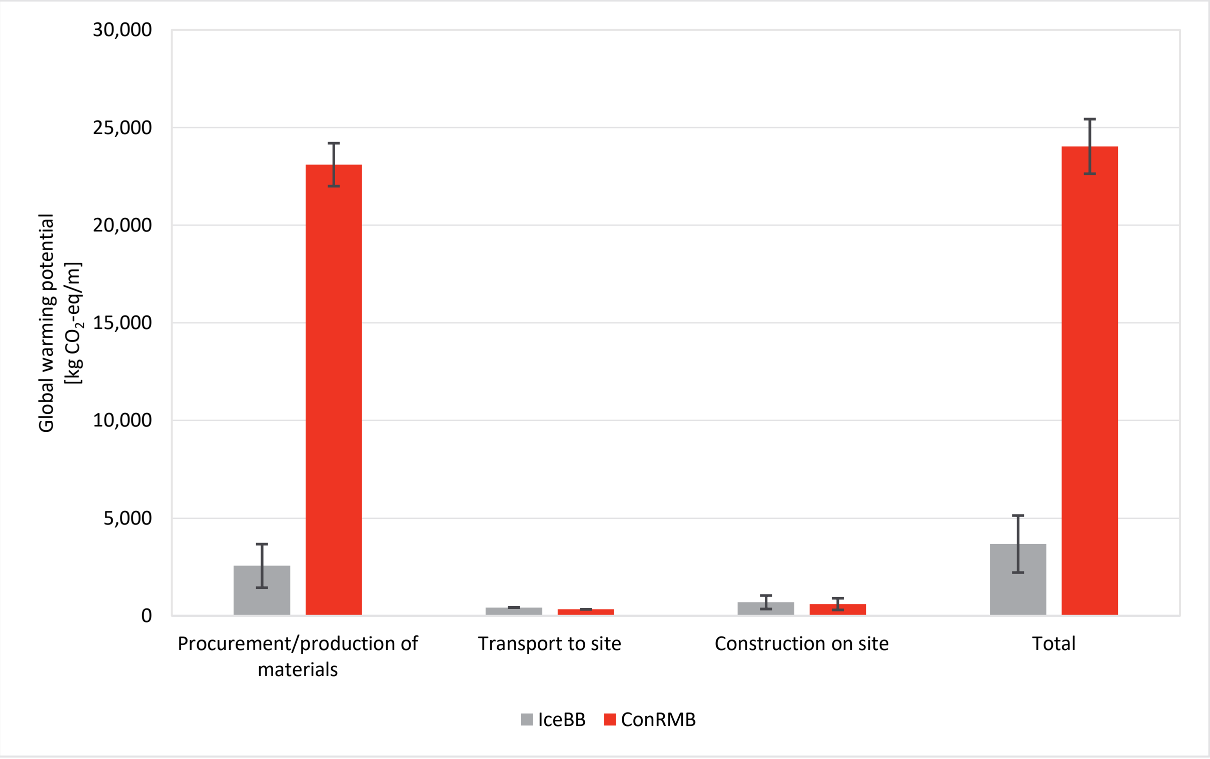

FIGURE 5 Comparative results of the calculation of the CF of IceBB and ConRMB for the port of Thorlakshofn project.

This finding shows that coastal protection solutions utilizing natural rocks may have lower CF compared to concrete-based armor units. This is in line with the literature as Labrujere and Verhagen (2012) stated that hard solutions for coastal protection using natural rocks, may have lower CF in comparison to concrete units armor.

It is important to mention that various measures can be implemented to reduce the CF of concrete. By using concrete of a lower strength class or with a higher ratio of pozzolanic materials, natural or artificial, such as pumice, silica fume, or fly ash, the total CF of the concrete may be decreased (Hammond & Jones, 2008). To reach near-zero-carbon cement production CO_2 emissions need to be captured and stored permanently (De Brito & Kurda, 2021).

The emission factor used in this research project for ready-mix concrete production is 296 kg CO_2-eq/m^3 concrete. Even with the assumption of using low-carbon concrete with an emission factor of, for instance, 150 kg CO_2-eq/m^3, the climate benefit of IceBB construction is still evident. Using the emission factor of 150 kg CO_2-eq/m^3 decreases the total ConRMB construction CF to 13.8 t CO_2-eq/m which is still considerably high in comparison to construction CF from IceBB.

The CF of a breakwater can be reduced by optimizing the design and construction processes, maximizing the use of quarry run, and minimizing the use of materials and heavy machinery/equipment (Broekens et al. 2011), just as IceBB is designed and constructed. Indeed, the lower GWP of IceBB could significantly contribute to climate change mitigation when considering the number of IceBB constructions worldwide.

In **FIGURE 4** and **FIGURE 5** the error bars represent uncertainty in diesel-fueled equipment's (i.e., excavators and drilling rigs) fuel consumption. The positive and negative errors represent scenarios in which equipment uses 50% more or 50% less fuel than estimated, respectively. The results show that the uncertainty in fuel consumption has a negligible effect on the results.

It is important to note that the present research project considered a relatively short transport distance of 8 km and 4 km from the quarry to the construction site at the port of Straumsvik and the port of Thorlakshofn, respectively. However, in the global context of constructing coastal structures such as IceBB and ConRMB, the distances between quarries and construction sites can vary significantly. Therefore, to assess the climate impacts of IceBB and ConRMB constructions under different transport distances, a sensitivity analysis is conducted. **FIGURE 6** and **FIGURE 7** illustrate the sensitivity of the construction CF to varying transport distances from the quarry to the construction site.

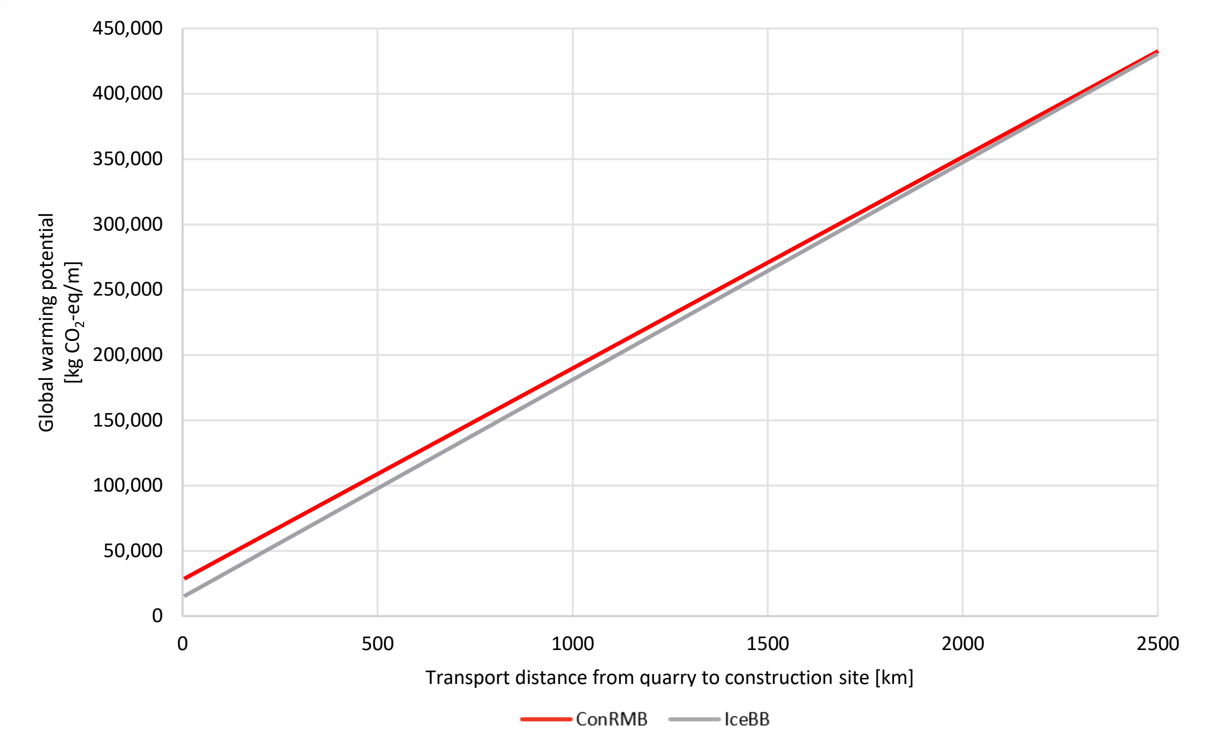

FIGURE 6 Comparison of the CF of the construction of IceBB and ConRMB, with increased transportation distance from the quarry to the construction site at the port, the port of Straumsvik project.

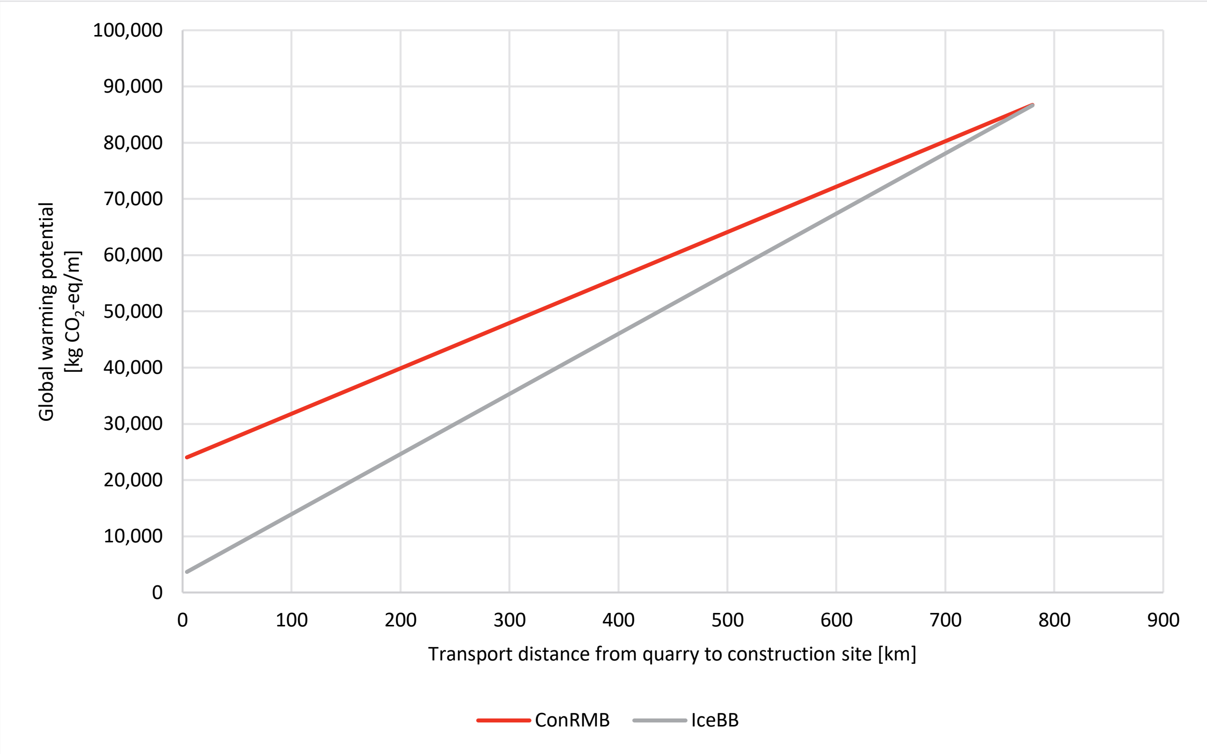

FIGURE 7 Comparison of the CF of the construction of IceBB and ConRMB, with increased transportation distance from the quarry to the construction site at the port, the port of Thorlakshofn project.

As depicted in **FIGURE 6** and **FIGURE 7**, the total emissions increase linearly with transport distance. Notably, IceBB exhibits a steeper slope, indicating higher sensitivity to distance due to the slightly larger volume of material that needs to be transported. At a transport distance of approximately 2488 km in the port of Straumsvik project and 800 km in the port of Thorlakshofn project, the climate benefit of using natural stone instead of concrete armor units is negligible.

In this research project, moreover, the IUCN criteria for NBS are used to explore the characteristics of IceBB. This helps to identify whether the IceBB meets the standards of IUCN and thus can be granted as a (hard) NBS coastal structure. **TABLE 8** shows the IUCN criteria and the corresponding IceBB characteristics.

TABLE 8. IUCN criteria and the corresponding IceBB characteristics

IUCN criteria	IceBB Characteristics
1. NBS effectively address societal challenges.	On one hand, ports have always been developing to satisfy the new or changing demands of stakeholders (e.g., (Eskafi et al. 2020)). Increase in port activities (Eskafi et al. 2021; Eskafi, Taneja, and Ulfarsson 2022) leads to brown- and green field port development project.
2. Design of NBS is informed by scale.	The design of IceBB accounts for the demands of stakeholders. The technical quality of IceBB to protect the ports and coasts has been well documented in the literature, for instance (van der Meer and Sigurdarson 2016), which indicates its success in many countries through years.
3. NBS results in a net gain to biodiversity and ecosystem integrity	IceBB design and implementation are based on matching the quarry run which helps to utilize all size grades from the predicted quarry. IceBB requires about 25% less volume of rock than dynamic berm breakwaters. Therefore, the construction of IceBB minimizes environmental disturbances in the quarry and surrounding ecosystem (Sigurdarson et al. 1997). Furthermore, as discussed in this paper, the construction of IceBB is with a relatively low construction CF which is in line with climate change policies.
4. NBS are economically viable.	IceBB is designed to match the quarry run. This helps to utilize all size grades from the predicted quarry (Sigurdarson et al. 2001). Furthermore, this reduces the quantity of blasted rock material and hence, the relevant cost. The construction cost of IceBB ranges between 67-86% of the cost for the conventional rubble mound breakwater (Sigurdarson et al. 1998). Quarry prediction is used in the design process of IceBB which can minimize transport costs. IceBB is constructed with relatively smaller stones compared to a conventional rubble mound breakwater. Thus, commonly smaller and less specialized (and thus cheaper) construction equipment/machinery can be used.
	Continued

5. NBS is based on inclusive, transparent, and empowering governance processes	Ports planning and development are highly affected by spatial and temporal influences and concerns of multiple stakeholders (Eskafi et al. 2019; Eskafi and Ulfarsson 2023). The construction of IceBB requires an effective engagement of stakeholders throughout the planning, design, and construction processes. The engagement increases the success of the design and construction processes. Through the years, the design process of IceBB in Iceland has been improved in close collaboration with stakeholders such as designers, geologists, supervisors, contractors, and local governments. The collaboration has helped to fully utilize all rock classes from the quarry (Sigurdarson et al. 1998).
6. NBS equitably balance trade-offs between the achievement of their primary goal(s) and the continued provision of multiple benefits.	IceBB addresses social and environmental challenges by protecting coastal communities, for instance, against floods, erosion, and storms. Furthermore, an active port promotes economic development and strengthens the economy of the surrounding community. Coastal communities highly rely on port activities, for instance, sea trade, and supply their food from the sea (Niemeyer et al. 2016).
7. NBS has managed adaptively, based on evidence.	Adaptive management is required to deal with uncertainty in port planning and development (Eskafi et al. 2021; Eskafi, Taneja, and Ulfarsson 2022). IceBB is adapted according to needs (i.e., sedimentation in a port, the effect of the storm, waves, and sea-level rise). Furthermore, the design of IceBB is adapted based on the size of rocks available in the quarry run.
8. NBS are sustainable and mainstreamed within an appropriate jurisdictional context.	The adaptive development of IceBB increases the lifecycle of the structure and minimizes the risk of redundancy, ensuring the return on investments and thus its sustainability. The implementation process of IceBB and lessons learned are available (e.g., (van der Meer and Sigurdarson 2016)) to individuals and stakeholders who are interested in replicating the design and construction of IceBB to protect their ports and coasts.

As indicated in Table 8, the IceBB characteristics meet the IUCN criteria for NBS. IUCN (2020) does not clearly state to what extent a solution, for instance, IceBB in this paper, should fulfill the criteria to be labeled as an NBS. Nevertheless, IceBB is a solution that addresses social challenges, i.e., coastal protection, while at the same time contributing to national and international climate change policies. These co-benefits offered by IceBB, therefore, can potentially make this coastal structure a hard NBS.

7. CONCLUSION

In this research project, using GaBi software a LCA method was applied to assess the CF associated with the construction of two types of breakwaters, namely the IceBB and the concrete armor unit ConRMB. The goal was to evaluate the environmental impact, specifically focusing on CO_2-eq emissions from these coastal engineering solutions.

The results of the LCA analysis provided valuable insights into the CF associated with the construction phase of IceBB and ConRMB. The system boundaries of the research project encompassed procurement/production of materials, transport to site, and construction on site.

The assessment and comparison were made for the construction of a new breakwater at the port of Straumsvik and the extension of the existing breakwater at the port of Thorlakshofn in Iceland.

Furthermore, the IceBB characteristics were examined using the IUCN criteria for NBS.

The results indicated that the IceBB demonstrated several advantages in terms of its CF compared to ConRMB. IceBB, being made entirely from natural rock significantly reduced the GWP associated with the construction. The LCA analysis of IceBB and ConRMB highlighted the potential of IceBB as a coastal engineering solution with a lower CF compared to ConRMB.

Furthermore, there are opportunities to reduce emissions in the construction phase including the use of greener fuels or electricity for machinery and optimizing transport logistics to minimize distance and increase cargo capacity utilization.

With a relatively low construction GWP as well as fulfilling the IUCN criteria for NBS, IceBB can be considered as an example of a hard NBS coastal structure.

The assessment of CF in breakwater construction provides valuable information for stakeholders involved in coastal development projects. By considering the CF during decision-making processes such as planning, design, and construction, it is possible to account for more sustainable and climate-friendly solutions.

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