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Life Cycle Assessment of Icelandic-Type Berm Breakwater

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Ágrip

Með vaxandi nauðsyn til takast á við loftslagsbreytingar og draga úr umhverfisáhrifum frá byggingu mannvirkja er mikilvægt að rannsaka og innleiða umhverfisvænni kosti. Þessi rannsókn fjallar um að meta kolefnisspor frá byggingu brimvarnargarða. Rannsóknin skoðar samanburð á kolefnisspori frá byggingu íslenska bermugarðsins og hefðbundins brimvarnargarðs (ConRMB) með steyptum einingum með ýtarlegri lífsferilsgreiningu. Lífsferilsgreiningunni er skipt niður í nokkra hluta: öflun/framleiðsla á byggingarefnum, flutningur á byggingarstað og samsetning á byggingarstað.

Íslenskur bermugarður býður upp á hönnun sem nýtir náttúrulegt berg sem gefur tækifæri til að draga verulega úr hnatthlýnunarmætti frá byggingu brimvarnargarða.

Niðurstöður rannsóknarinnar leiða í ljós að íslenskur bermugarður hefur þó nokkra kosti fram yfir ConRMB þegar kemur að kolefnisspori byggingar brimvarnargarðs í Straumsvíkurshöfn á Íslandi. Umfram allt er íslenski bermugaðurinn með verulega lægri hnatthlýnunarmátt samanborið við hefðbundinn brimvarnargarð. Sú innsýn sem fæst með þessari rannsókn veitir mikilvægar upplýsingar fyrir ákvarðanatöku hagsmunaaðila.

Lykilorð: *Íslenskur bermugarður, Coda Terminal, hnattræn hlýnun, kolefnisspor, lífsferilsgreining.*

Abstract

With the growing urgency to address climate change and reduce the environmental impacts of construction, there is an increasing necessity to explore and implement environmentally friendly solutions. This study focuses on evaluating the Carbon Footprint (CF) associated with the construction of breakwaters. The study compares the CF of Icelandic-type berm breakwater (IceBB) and concrete armor unit conventional rubble mound berm breakwater (ConRMB) through a comprehensive Life Cycle Assessment (LCA). The LCA analysis encompasses various stages, including procurement/production of raw materials, transport to site, and construction on site. IceBB offers a design that utilizes natural rock which reduces the Global Warming Potential (GWP) associated with breakwater construction.

The findings of the study indicate several advantages of IceBB over ConRMB in terms of its CF for the case study of the Straumsvik port in Iceland. Above all, IceBB has a significantly lower GWP compared to ConRMB.

The insights gained from this study provide valuable information for stakeholders involved in coastal projects.

Keywords: *Icelandic-type Berm Breakwater, Coda Terminal, Global Warming Potential, Carbon Footprint, Life Cycle Assessment.*

1. Introduction

Roughly 40% of the global population, lives within 100 km of coastlines, (Kummu et al., 2016), and benefits economically from domestic and international supply chains of coastal resources and ports (Eskafi, 2021; Eskafi et al., 2021). Coastal areas and ports, however, are exposed to environmental forces that are becoming more severe due to climate change (Sweeney & Becker, 2020). Therefore, it is essential to protect coasts and ports by implementing coastal engineering solutions, such as breakwaters, (Schoonees et al., 2019), while at the same time accounting for environmentally friendly solutions.

With increased environmental regulations and awareness, carbon accounting has become a standard requirement for engineering design and development as well as investment justification (Merschak et al., 2020). In coastal and port projects, stakeholders demand different objectives, for instance, effectively reducing emissions (Eskafi et al., 2019, 2020).

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. 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).

The Icelandic-type berm breakwater (IceBB) has been constructed worldwide in diverse conditions of wave climates, water depth, and tide. The planning and design of IceBB are generally determined by the availability of armor stones and utilizing the whole quarry run. The quarry run is sorted into narrow-graded rock classes which provide higher porosity compared to wide-graded rock classes. This results in a structure with more stability, higher permeability, as well as higher wave energy absorption and thus low wave penetration and less overtopping. Furthermore, it lowers the wave reflection from the trunk and head of the breakwater (van der Meer & Sigurdarson, 2016).

IceBB is completely made from natural rock which reduces the IceBB's Global Warming Potential (GWP) compared to conventional rubble mound berm breakwater (ConRMB) made with concrete armor unit. A wide range of precast concrete armor units have been developed to be used in coastal projects. These units come in various shapes and designs, ranging from simple cubes to more complex forms (Smith, 2016). The concrete armor type used in this study 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. The design of Cubipod armor units is based on international design guidelines, as well as safety factors of concrete armor units (Medina and Gómez-Martín, 2012).

Currently, there is limited knowledge regarding the GWP of coastal structures such as IceBB. Hence, this study aims to assess the Carbon Footprint (CF) from IceBB and ConRMB constructions using the LCA method. This is in line with the goal of the Housing and Construction Agency to provide information about infrastructure for future assessments of the construction sector (Housing and Construction Agency, 2022). The results facilitate informed decision making for using more environmentally friendly structures in coastal projects.

This paper begins with Section 2 reviewing the characteristics of IceBB, followed by a comparison with other berm breakwaters. Section 3 states the LCA method, Section 4 presents the numerical data and assumptions, and Section 5 describes the study area. Section 6 discusses the findings of the study and finally, Section 7 concludes the findings concerning the construction GWP of breakwaters.

2. Berm Breakwater

The origin of berm breakwaters dates to the nineteenth century when they were primitive and unstable. These coastal structures featured a horizontal berm with a steep seaward profile that allowed movement of rocks under wave force and thus resulted in reshaping of the berm. This could cause cavities to fill up with smaller rocks, which decreased the permeability of the structure and reduced the dissipation of wave energy. Through experiences and studies, the importance of porosity and permeability was discovered, and hence, the design of the berm breakwaters evolved into a more stable structure.

In the early eighties, the Icelandic Harbour Authority (Hafnamálastofnun ríkisins) recognized the suitability of the breakwater design for Icelandic conditions. The design of the breakwater was eventually developed into what is now known as IceBB, a higher-engineered berm breakwater with only minor reshaping. IceBB has been constructed worldwide for 40 years and has proven to maintain its stability and overtopping performance throughout its design lifetime. Table 1 gives a list of IceBB structures in Icelandic ports.

The preliminary design of IceBB is based on the estimated rock size 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 rock classes of narrow-size gradation and utilizes the whole quarry run. Due to the thicker armor layer of IceBB, its armor stone size can be smaller compared to conventional rubble mound structures. This helps to use available local heavy construction equipment (van der Meer & Sigurdarson, 2016).

Table 1: *List of ports that are protected by IceBB in Iceland.*

No.	Port	Year of construction		Design wave on trunk		Class I on top of berm on trunk	
			Volume	H_s	T_p	M_{50}	$H_s/\Delta Dn_{50}$
			(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

Continued

Table 1: *(Continued) List of ports that are protected by IceBB in Iceland.*

No.	Port	Year of construction		Design wave on trunk		Class I on top of berm on trunk	
			Volume	H_s	T_p	M_{50}	$H_s/\Delta D_{n50}$
			(Km^3)	(m)	(s)	(t)	(-)
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
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

Continued

Table 1: *(Continued) List of ports that are protected by IceBB in Iceland.*

No.	Port	Year of construction		Design wave on trunk		Class I on top of berm on trunk	
			Volume	H_s	T_p	M_{50}	$H_s/\Delta Dn_{50}$
			(Km^3)	(m)	(s)	(t)	(-)
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

The 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 (van der Meer and Sigurdarson 2016). Both parameters are a measure of the degree of reshaping. The Rec is the recession or retreat of the intersection of the horizontal berm and the front slope, measured on top of the berm, while the S_D is a nondimensional damage parameter measured on the front slope as the erosional area divided by the nominal diameter or the stones squared. The stability number of a berm breakwater can be expressed as (van der Meer and Sigurdarson 2016):

$$H_o = \frac{H_s}{\Delta D_{n50}}$$

where H_s is the significant wave height, Δ is the relative mass density, and D_{n50} is the nominal diameter of the rocks. Berm breakwaters can be split into two types, mass-armored berm breakwaters with a homogeneous berm which are allowed to reshape, and the more stable IceBB which is built up of more rock classes. Furthermore, they can be classified based on their structural behavior. Using the stability number, Van der Meer and Sigurdarson (2016) classified berm breakwater as given in Table 2.

Table 2: *Classification of berm breakwaters based on the stability parameters.*

Type of breakwater	$\frac{H_s}{\Delta D_{n50}}$	S_D	$\frac{Rec}{D_{n50}}$
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

As the stability number is the wave height divided by stone diameter and relative mass density, a more stable structure has a lower stability number. The threshold for stability numbers, recession, and damage are based on the results of a series of experimental modeling (van der Meer and Sigurdarson 2016).

From the introduction of the berm breakwaters in the early 1980s where considerable reshaping was allowed the design criteria of IceBB have been developed over the past 30 years towards more stable structures (Sigurdarson et al., 2001).

3. Life cycle assessment and system boundaries

In this study, an LCA method was applied to assess the construction CF, which is a measure of greenhouse gas emissions, specifically focusing on CO_2 emissions, of two types of breakwaters: IceBB and concrete armor unit ConRMB.

LCA was conducted according to ISO standard 14044:2006 titled Environmental Management, Life Cycle Assessment, Requirements, and Guidelines. The impact assessment method was CML 2001 - January 2016. LCA is a systematic approach that outlines a comprehensive evaluation of environmental impacts associated with all stages of the infrastructure’s life cycle (International Organization for Standardization, 2006). In this study, the focus of LCA is to evaluate CF associated with the different life stages of two types of breakwaters, namely IceBB and ConRMB, see Table 3.

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 rock 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, quarry operation of armor stone including drilling, blasting, sorting, internal transport on site, and production of rock 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 materials until the end of the product's lifetime.

[2] carbon is released until the product has reached the point of use.

[3] carbon release until the product leaves the factory.

[4] sources not used in this study

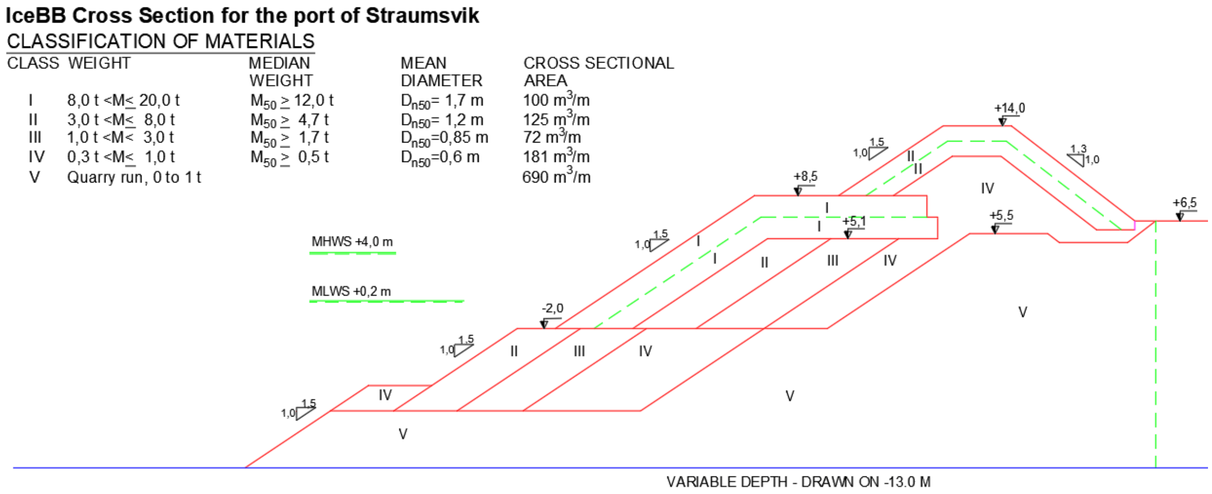
The CF analyses encompassed the procurement/production of materials, transport to site, and construction on site. It is important to note that the CF of the operation and maintenance of the breakwaters is relatively small compared to the construction phase. In this study, the primary focus lies on the construction phase, as it generally accounts for a vast majority of the total emissions (Broekens et al., 2011).

The equation used to calculate the total CF in this study is presented in the appendix section. The LCA for Experts software, developed by Sphera, and the Professional Database and Extension Database XIV: Construction Materials were used for the LCA and CF calculations in this study (Sphera, 2023).

4. Numerical data and assumptions

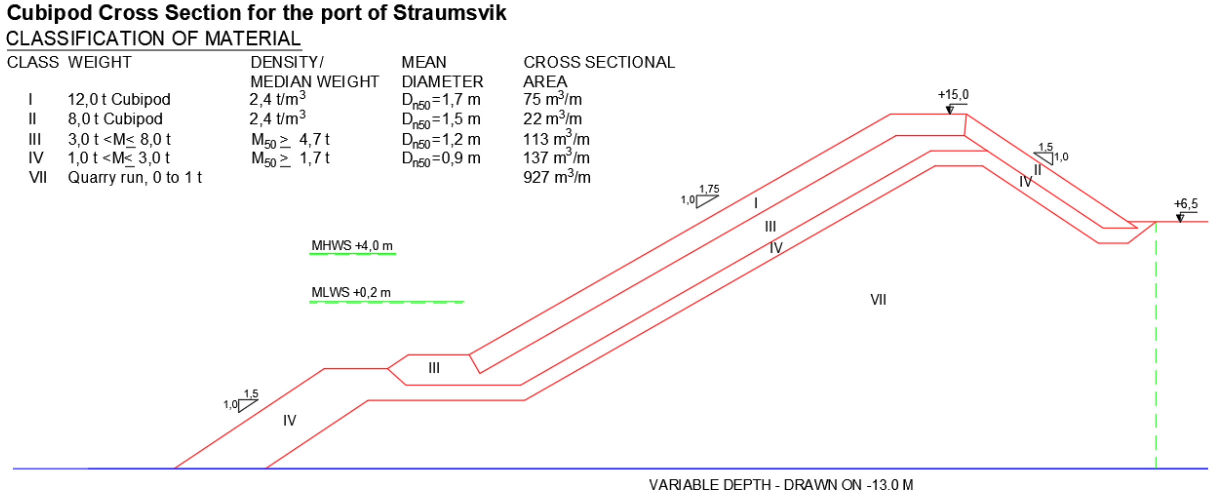
To compare the construction CF of two breakwaters, i.e., IceBB and ConRMB, a full design was carried out. The designed IceBB and ConRMB can be seen in Figure 1, showcasing their respective cross-sections.

The construction assumptions and numerical values used in this study had been derived from similar projects undertaken in Iceland. The design conditions at the Coda Terminal consist of a 100-year return period significant wave height of Hs=5,7 m with a peak period of Tp=16,4 s.


IceBB Cross Section for the port of Straumsvik

CLASSIFICATION OF MATERIALS

CLASS	WEIGHT	MEDIAN WEIGHT	MEAN DIAMETER	CROSS SECTIONAL AREA
I	8,0 t <M≤ 20,0 t	$M_{50} \geq$ 12,0 t	D_{n50}= 1,7 m	100 m^3/m
II	3,0 t <M≤ 8,0 t	$M_{50} \geq$ 4,7 t	D_{n50}= 1,2 m	125 m^3/m
III	1,0 t <M< 3,0 t	$M_{50} \geq$ 1,7 t	D_{n50}=0,85 m	72 m^3/m
IV	0,3 t <M≤ 1,0 t	$M_{50} \geq$ 0,5 t	D_{n50}=0,6 m	181 m^3/m
V	Quarry run, 0 to 1 t			690 m^3/m


Cubipod Cross Section for the port of Straumsvik

CLASSIFICATION OF MATERIAL

CLASS	WEIGHT	DENSITY/ MEDIAN WEIGHT	MEAN DIAMETER	CROSS SECTIONAL AREA
I	12,0 t Cubipod	2,4 t/m^3	D_{n50}=1,7 m	75 m^3/m
II	8,0 t Cubipod	2,4 t/m^3	D_{n50}=1,5 m	22 m^3/m
III	3,0 t <M≤ 8,0 t	$M_{50} \geq$ 4,7 t	D_{n50}=1,2 m	113 m^3/m
IV	1,0 t <M≤ 3,0 t	$M_{50} \geq$ 1,7 t	D_{n50}=0,9 m	137 m^3/m
VII	Quarry run, 0 to 1 t			927 m^3/m

Figure 1: *The cross section of IceBB (top row) and ConRMB (bottom row) for the protection of the Straumsvik port.*

4.1. Procurement/production of materials

The carbon emissions associated with rock production are determined by the type of quarry, including aggregate, rock dimension, and dedicated armor stone quarries (CIRIA et al., 2007). In this context, Sigurdarson et al. (2000) emphasized the importance of quality requirements for armor stones such as durability, specific gravity, and water absorption. The carbon emissions from concrete production are influenced by various factors, including the compressive strength class of the concrete and the incorporation of cement additives such as fly ash or ground granulated blast furnace slag (Hammond & Jones, 2008).

A standard emission factor for ready-mix concrete production, i.e. 255 kg CO_2-eq/m3 concrete, was used in the impact assessment method in this study. Excavators were used to load the rocks and concrete armor onto trucks for transport to the construction site. The carbon emissions from machinery are directly linked to fuel consumption, which is influenced by various factors, including the distance traveled, type of machinery used, fuel type, and degree of cargo capacity utilization (Aminzadegan et al., 2022). In this study, the machinery was fueled by fossil fuels. Partly or full use of green fuels or electricity would considerably reduce transport emissions and thus the overall construction CF (Lin et al., 2020; Othman et al., 2017).

The construction process involved sourcing rocks of various sizes and quarry run from a quarry. 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, were used to sort and load the rocks and quarry run onto trucks for transport. The 70-ton excavator handled rocks weighing over 1,0 tons, while the 50-ton excavator dealt with rocks lighter than 3,0 tons. 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. 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 provides the weight range of each of the four rock size classes used in the IceBB, as well as the total volume of rocks and quarry run sorted and loaded onto trucks by each excavator.

The fuel consumption of the excavators and drilling rig was estimated based on their power output. According to Klanfar et al. (2016), diesel engines consume fuel within the range of 0,21-0,26 kg/(kW·h) under full-rated power. In this study, a fuel use rate of 0,235 kg/(kW·h) of diesel fuel (0,85 kg/L) was considered for the excavators, with a load factor of 0,56. The drilling rig was assumed to have the same fuel consumption rate as the excavator (0,235 kg/(kW·h)), but with a load factor of 0,61 (Klanfar et al., 2016). To model the excavators and drilling rig, generic background data from the Managed LCA Content databases were utilized. Adjustments were made to the hourly fuel consumption and load factors, while other modeling parameters, such as the number of cycles per minute and bucket volume, were kept at their default values.

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 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: 12,0 tons and 8,0 tons. 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, a 50-ton excavator loaded them onto trucks. Table 4 provides 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 bracket) 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 for concrete unit
I	8,0 t < M < 20,0 t, M50 > 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, M50 > 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, M50 > 1,7 t (3,0 t < M < 8,0 t, M50 > 4,7 t)	72 (113)		14 (113)	58 (0)	(0)
IV	0,3 t < M < 1,0 t, M50 > 0,5 t (1,0 t < M < 3,0 t, M50 > 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)

4.2. Transport to site

Transport of materials included the transport of rocks and quarry run materials from the quarry as well as the transport of Cubipod armor units from an on-site concrete casting plant to the construction site.

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 about 8 km from the quarry to the construction site at the port. The trucks returned empty, resulting in a utilization or load factor of 0,5 per trip. Emissions related to transport were calculated considering trucks weighing more than 32 tons and complying with EU emission standards ranging from Euro I to Euro VI. The same fuel detail was applied for the excavators described in subsection 4.1.

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

4.3. Construction on site

The environmental impact of constructing one linear meter of the breakwater was evaluated.

Machinery equipment was used to construct the breakwater at the construction site based on the design, see Figure 1. An excavator or a bulldozer was used to arrange the materials and the same fuel details were applied as for the other excavators.

At the construction site, the construction of IceBB and ConRMB breakwaters involved the use of a 95-ton excavator or bulldozer to arrange the quarry run and rock materials. The construction machinery's fuel consumption was estimated at 0,235 kg/(kW·h) of diesel fuel (0,85 kg/L), with a load factor of 0,56. The activity of this excavator was modeled similarly to the ones operating at the quarry, utilizing adjusted hourly fuel consumption and load factors. Other modeling parameters, such as the number of cycles per minute and bucket volume, remained at their default values. A comprehensive overview of the inputs and parameters utilized in the modeling of IceBB and ConRMB construction at the Straumsvik port can be found in Table 5.

Table 5: *Inputs and parameters used for the modeling of the construction of IceBB and ConRMB in the Straumsvik port. All data is per linear meter of the breakwater.*

Procurement of raw materials				
Explosives	Quantity [g/m^3 excavated material]			
ANFO	250			
Machinery	Assumed power [kW]	Fuel cons. [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 the 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 cons. [L/h]	Load factor	Excavated material [m^3]
95 t excavator/bulldozer	522	144	0,56	1168, 1274*
* For ConRMB				

5. Study area

In this study, LCA was conducted for a breakwater to protect the Coda Terminal in the Straumsvik port in Iceland, Figure 2.

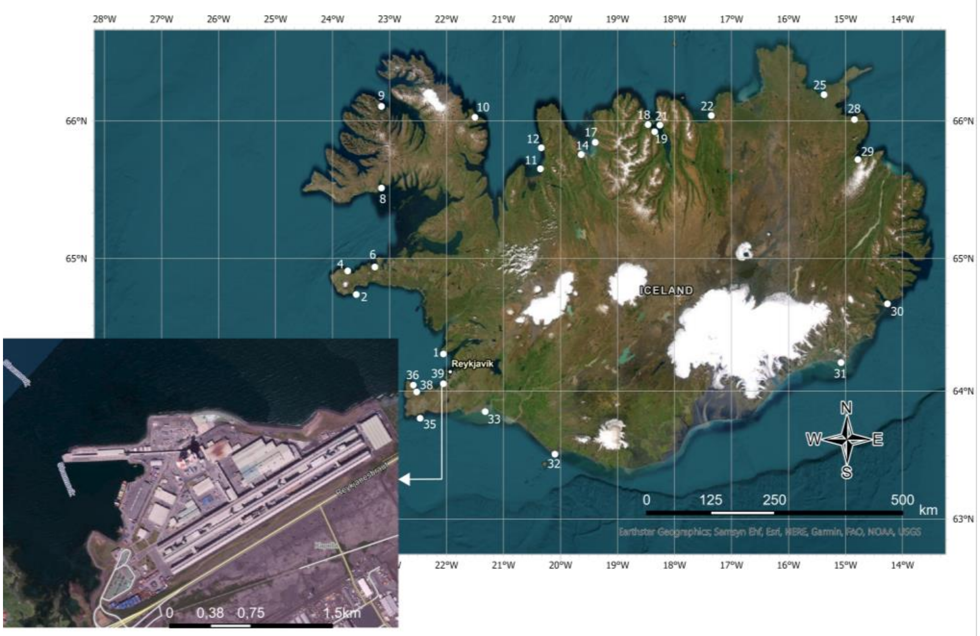


Figure 2: *Locations of IceBB in Iceland; numbers are referred to the ports in Table 1. The Straumsvik port is magnified in the figure.*

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

6. Results and discussion

To protect the new port area in the Straumsvik port in Iceland against waves a breakwater is used. In this study, two different breakwater types were taken into consideration where either is constructed to protect the port. The types are:

1. Protection of the port with an Icelandic-type berm breakwater (IceBB),
2. Protection of the port with a concrete armor unit conventional rubble mound berm breakwater (ConRMB).

These two breakwaters were designed to compare their LCA in terms of CF. The calculated results of the construction CF reveal that the total GWP for the construction of IceBB is 4,96 t CO_2-eq/m, while for ConRMB is 20,1 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 74% of the total emissions, accounting for 14,8 t CO_2-eq/m. This finding shows that coastal protection solutions utilizing natural rocks may have lower CF compared to concrete-based armor units. Figure 3 provides an overview of the carbon emissions associated with each phase of the construction process.

The error bars in Figure 3 account for uncertainties in fuel consumption for excavators and drilling rig. The positive and negative errors represent scenarios where the equipment consumes 50% more or less fuel than estimated, respectively. The results demonstrate that the uncertainties in fuel consumption have a negligible effect on the overall findings.

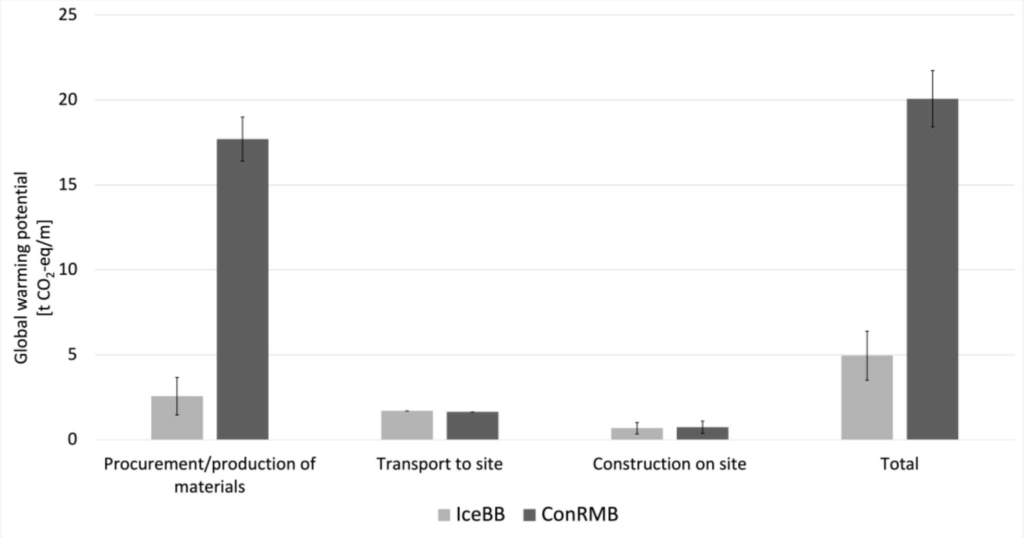


Figure 3: *Comparative results of the construction CF of IceBB and ConRMB.*

Various measures can be implemented to reduce the CF of concrete. Total CF of the concrete can be decreased 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, (Hammond & Jones, 2008). To reach near-zero-carbon cement production CO_2 emissions need to be captured and stored permanently (De Brito & Kurda, 2021).

Even with the assumption of using low-carbon concrete with an emission factor of, for instance, 150 kg CO_2-eq/m^3, instead of the standard 255 kg CO_2-eq/m^3, the climate benefit of IceBB construction is still evident. The emission factor of 150 kg CO_2-eq/m^3 decreases the total ConRMB construction CF to 14,0 t CO_2-eq/m which is still higher than IceBB construction CF.

Effective strategies to reduce construction CF of breakwater include optimizing design and construction processes, maximizing the use of quarry run, and minimizing the utilization of materials and heavy machinery (Broekens et al., 2011), mirroring the approach used in the construction of IceBB. The lower GWP of IceBB offers a substantial potential for climate change mitigation, especially when considering the widespread implementation of IceBB constructions worldwide.

It is important to note that the present study considered a relatively short transport distance of 8 km from the quarry to the construction site at the port. However, in the global context, 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 4 illustrates the sensitivity of the construction CF to varying transport distances from the quarry to the construction site.

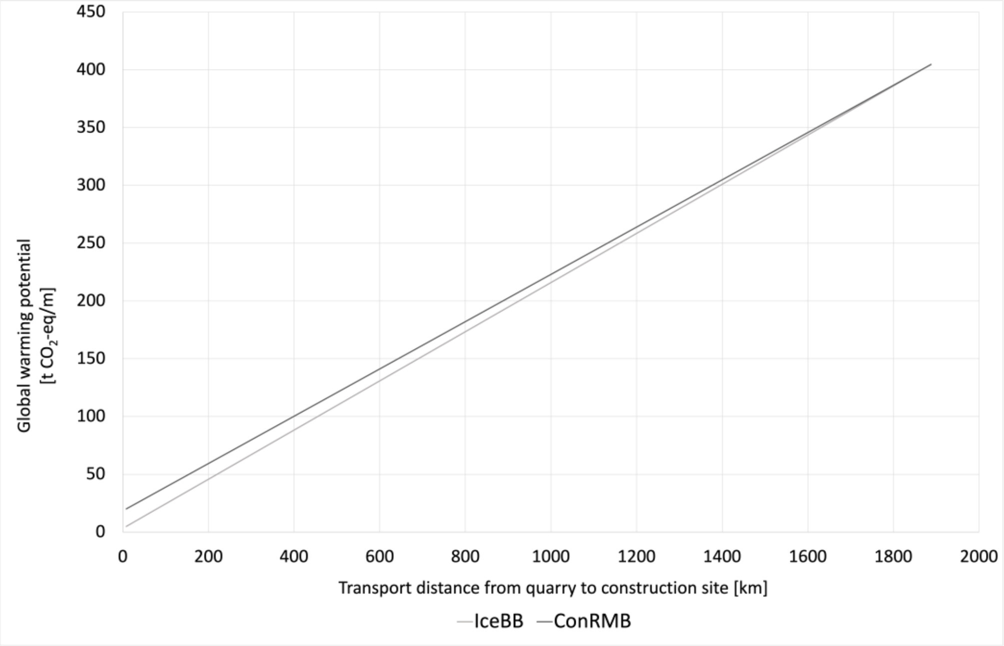


Figure 4: *Comparison of the construction CF of the IceBB and ConRMB, with respect to transport distance from the quarry to the construction site at the port.*

As depicted in Figure 4 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 materials that need to be transported. At a transport distance of approximately 1888 km, the climate benefit of using natural rock instead of concrete armor units is negligible in this study.

7. Conclusion

The assessment of CF in breakwater construction provides valuable information for stakeholders involved in coastal 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.

In this study, an LCA method was applied to assess the construction CF of two types of breakwaters, namely IceBB and concrete armor unit ConRMB. The goal was to evaluate the environmental impact in terms of CO_2-eq emissions from these coastal engineering solutions.

The system boundaries of the study encompassed procurement/production of materials, transport to site, and construction on site. The LCA for Experts software along with its Managed LCA Content databases was used for data assessment and calculation.

The results indicated that the IceBB demonstrates several advantages in terms of CF compared to ConRMB. The LCA of IceBB and ConRMB highlighted the potential of IceBB as a coastal engineering solution with a lower CF compared to ConRMB. The IceBB is made entirely from natural rock which significantly reduces the GWP associated with the construction.

Further research and development in this field would contribute to achieving carbon neutrality goals aiming at the mitigation of climate change and ensuring the long-term sustainability of coastal communities and their associated supply chains.

Future research could focus on the implementation of further carbon footprint reduction measures in breakwater construction. This includes exploring the use of recycled concrete blocks from demolished buildings, utilizing locally available rocks to reduce transport emissions, and transitioning machinery and trucks to greener energy sources. Furthermore, opportunities can be explored 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.

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Appendix

In this study, the following equation was used to calculate the total CF of structures. The first and second line represents the production of the materials, the third line the transport of the materials, and the fourth line the construction of the berm breakwater. The overall CF is expressed in weight.

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

$$+\sum_{i=1}^{n}\left(\left(f_{cs,exc,i} \times e_{f,exc,i}\right) \times V_i\right)$$

$ANFO_i$: 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 $\left[\frac{\mathrm{kg\ CO_2-eq}}{\mathrm{g}}\right]$
$f_{drill,i}$: Fuel consumption of a specific drill needed to extract 1 m^3 of quarry material $\left[\frac{\mathrm{l}}{\mathrm{m^3}}\right]$
$e_{f,drill,i}$: CO_2-eq emissions per liter of the specific fuel for a specific drill $\left[\frac{\mathrm{kg\ CO_2-eq}}{\mathrm{l}}\right]$
$f_{q,exc,i}$: Fuel consumption of a specific excavator needed to excavate 1 m^3 of quarry material $\left[\frac{\mathrm{l}}{\mathrm{m^3}}\right]$
$e_{f,exc,i}$: CO_2-eq emissions per liter of the specific fuel for a specific excavator $\left[\frac{\mathrm{kg\ CO_2-eq}}{\mathrm{l}}\right]$
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 $\left[\frac{\mathrm{l}}{\mathrm{m^3}}\right]$
$e_{concrete,i}$: CO_2-eq emissions per m^3 of ready mix concrete for Cubipod $\left[\frac{\mathrm{kg\ CO_2-eq}}{\mathrm{m^3}}\right]$
$f_{truck,i}$: Fuel consumption of a specific truck needed to transport specific amount of material 1 km $\left[\frac{\mathrm{l}}{\mathrm{km}}\right]$
$e_{f,truck,i}$: CO_2-eq emissions per liter of the specific fuel a specific truck $\left[\frac{\mathrm{kg\ CO_2-eq}}{\mathrm{l}}\right]$
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 $\left[\frac{\mathrm{l}}{\mathrm{m^3}}\right]$
*Only for ConRMB