ICELANDIC-TYPE BERM BREAKWATER: COASTAL STRUCTURE WITH A LOW-CONSTRUCTION CARBON FOOTPRINT

Majid Eskafi[1] and Sigurdur Sigurdarson[2]

Various types of rubble mound structures are used to protect ports and coasts. The construction of these structures has a significant carbon footprint. With an urgency to address climate change, there is growing interest in exploring and using more environmentally friendly coastal structures. In addition to engineering and cost factors, the construction Global Warming Potential (GWP) is an important factor in the selection and design of the structures. Indeed, knowledge of construction GWP supports decision-making in coastal projects to achieve climate goals. Considering the widespread construction of Icelandic-type berm breakwaters (IceBB) worldwide, this structure's design method is commonly accepted in coastal projects. The design method is aimed at maximizing the quarry's utilization and matching the structure's rock gradings with the predicted quarry yield. This eliminates the need for reinforcement of the structure by concrete armor units and thus reduces the GWP associated with breakwater construction. In this study, the construction process GWP of IceBB is assessed and compared with a conventional rubble mound breakwater with Cubipod concrete armor units (ConRMB). The Life Cycle Assessment (LCA) method is applied to calculate the construction carbon footprint of the structures. The GaBi software is used for the LCA in this study. The assessments and comparisons are made for different scenarios in two Icelandic port projects, namely, the port of Thorlakshofn project and the port of Straumsvik project. The results indicate that IceBB has a significantly lower GWP compared to ConRMB with Cubipod concrete armor units. The findings support decision-making in coastal protection projects for adopting the IceBB design method aimed at meeting climate change mitigating policies.

Keywords: Icelandic-type berm breakwater; carbon footprint, climate change, sustainability

INTRODUCTION

Coastal communities benefit from proximity to coastal and marine resources as well as the economic advantages of ports (Eskafi 2021). However, ports and coasts have been increasingly experiencing natural hazards and extreme events from the sea due to climate change (Eskafi et al. 2021). Hard structures such as breakwaters are commonly used to protect ports and coasts. The construction of these structures itself has a significant carbon footprint (CF).

Carbon accounting has become a requirement for engineering option appraisal in coastal projects (Gunnarsdottir et al. 2024). Decision-making for the construction of coastal structures accounts for national and international climate change mitigating goals (Eskafi et al. 2020). Control and quantification of emissions in projects are based on global-scale agreements such as the 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 nearly 40 years. The design of IceBB is based on utilizing available rock sizes from an armorstone quarry and consists of several relatively narrow-graded stone 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).

The 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.

The stability of the rubble mound breakwater can be investigated by physical modeling. Using physical modeling tests the design of IceBB has been optimized to increase its structural stability (van der Meer and Sigurdarson 2016). Using the stability number, van der Meer and Sigurdarson (2016) classified berm breakwater as given in Table 1.

Although Berm Breakwaters can be strengthened by concrete units, Sigurdarson et al. (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. Therefore, in this study, a Life Cycle Assessment (LCA) methodology is applied to assess the construction CF of IceBB and its potential contribution to climate change policies.

---

[1] EFLA Consulting Engineers, Reykjavik, Iceland, majid.eskafi@efla.is.

[2] IceBreak Consulting Engineers; The Icelandic Road and Coastal Administration, Gardabaer, Iceland, sigurdur.sigurdarson@vegagerdin.is.

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

Type of breakwater	Stability number $\frac{H_s}{\Delta D_{n50}}$	Damage S_d	Recession/Rock's nominal diameter $\frac{Rec}{D_{n50}}$
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

where H_s is the significant wave height and Δ is the relative buoyant density of the stone.

METHODS

Life Cycle Assessment and System Boundaries

The carbon footprint calculations in this study 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.

This study 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) 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.

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

Procurement/Production of Materials

Carbon emissions for rock production are based on the type of quarrying, in this case, dedicated armor stone quarrying (CIRIA, CUR, CETMEF 2007). The armor stone should meet the quality requirements, for instance, durability, specific gravity, and water absorption (Sigurdarson et al. 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 study, armor units are not reinforced and thus no additional EC component for steel reinforcement is added. The concrete armor type chosen for this study is called Cubipod which is a cube that features protrusions on each face (Medina and Gómez-Martín 2012). Excavators were used to load the rocks and concrete armor onto trucks for transport to the construction site. In this study, the machinery was fueled by fossil fuels.

Transport to Site

In this study, machinery equipment is classified into two groups of transport machinery for transporting the material to the site, and construction machinery for constructing the structure on site (van der Meer and Sigurdarson 2016).

Construction on site

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

PORT PROJECTS

In this study, the assessments and comparisons are made for different scenarios in two Icelandic port projects in southwest Iceland. Figure 1 shows the location of the two projects, the port of Straumsvik and the port of Thorlakshofn.

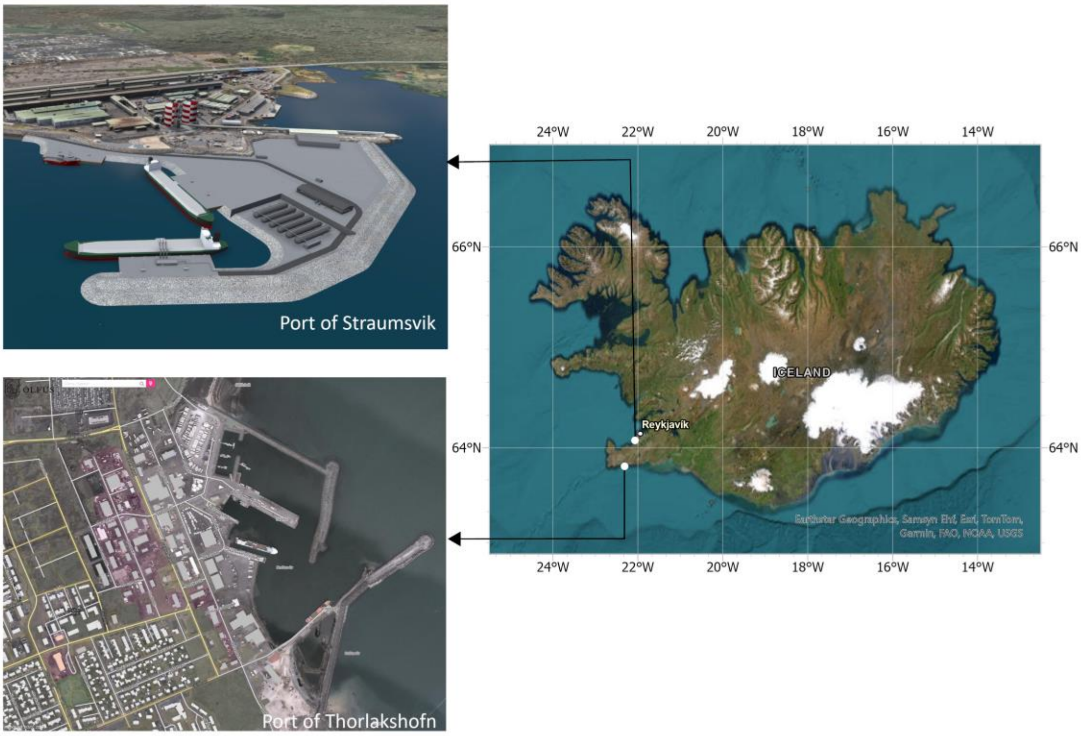

Figure 1. The location of the two port projects, the port of Straumsvik and the port of Thorlakshofn in Iceland.

The port of Straumsvik is located in Faxafloi Bay. An 800 m long breakwater is planned to protect a new landfill and a new port basin. The breakwater could be designed as an IceBB or ConRMB. The main function of the port will be to receive ships to unload CO2 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 where the CO2 will be transformed permanently into solid minerals.

The port of Thorlakshofn on the south coast has a competitive advantage, due to its geographical location, infrastructure, and services among the other ports in the south of the country. The port provides services to container and RoRo vessels as well as bulk carriers. Furthermore, there are industrial value-added activities including fisheries and aquaculture around the port area. The expansion of the port requires a 250 m long extension of an existing main breakwater in the port which can be designed as an IceBB or ConRMB. The extension of the breakwater in the port of Thorlakshofn has already been constructed as an IceBB structure, see Figure 2.

Figure 2. The port of Thorlakshofn after the 250 m elongation of the breakwater in August 2024 (photo Pall Marvin Jonsson).

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 study had been derived from similar projects undertaken in Iceland. The designed cross-sections of IceBB and ConRMB can be seen in Figure 3 and Figure 4.

Table 2 and Table 3 provide the weight range of rock size classes used in the IceBB and concrete armor units used in the ConRMB, as well as the total volume of rocks and quarry run sorted and loaded onto trucks by each excavator.

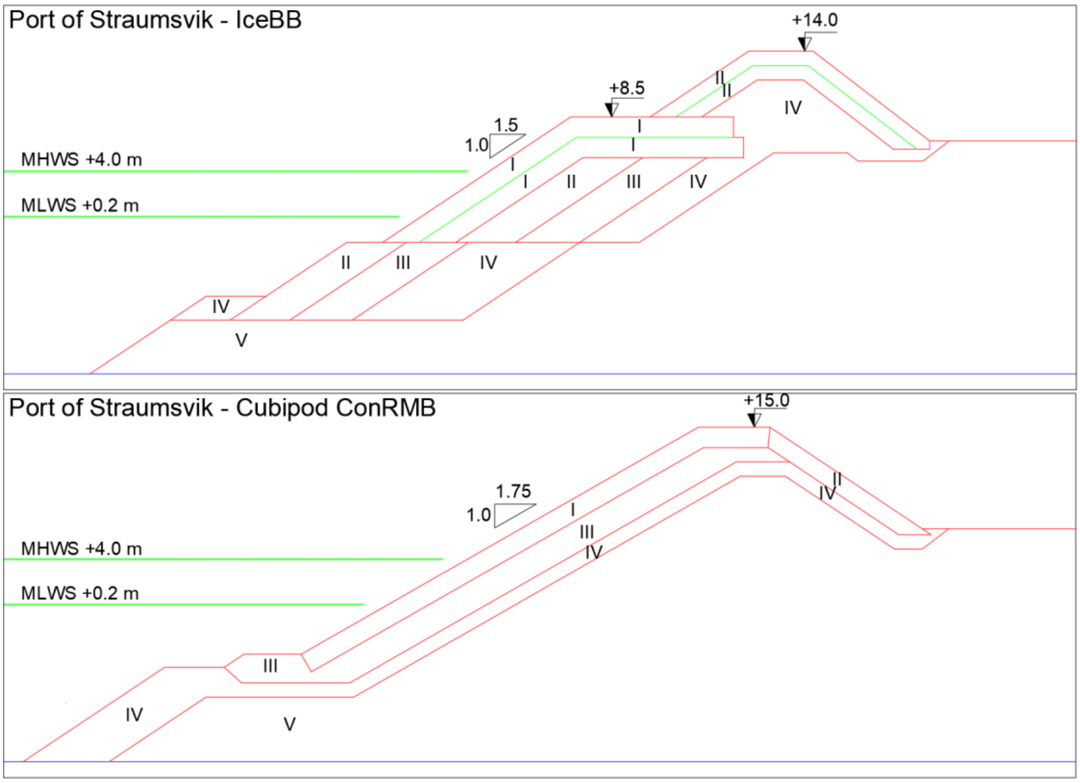

Figure 3. The cross-section of IceBB and ConRMB for the port of Straumsvik.

Table 2. Port of Straumsvik, volume in different rock and armor classes for IceBB and ConRMB design. All data is per linear meter of the breakwater.

Rock / Armor Class			IceBB	ConRMB
IceBB	ConRMB		(m^3/m)	(m^3/m)
I		8.0 t $< M \leq$ 20.0 t, $M_{50} \geq$ 12.0 t	100	
	I	12,0 t Cubipod, 2400 kg/m^3		75
	II	8,0 t Cubipod, 2400 kg/m^3		22
II	III	3.0 t $< M \leq$ 8.0 t, $M_{50} \geq$ 4.7 t	125	113
III	IV	1.0 t $< M \leq$ 3.0 t, $M_{50} \geq$ 1.7 t	72	137
IV		0.3 t $< M \leq$ 1.0 t, $M_{50} \geq$ 0.5 t	181	
V	V	Quarry run	690	927
Total			1,168	1,274

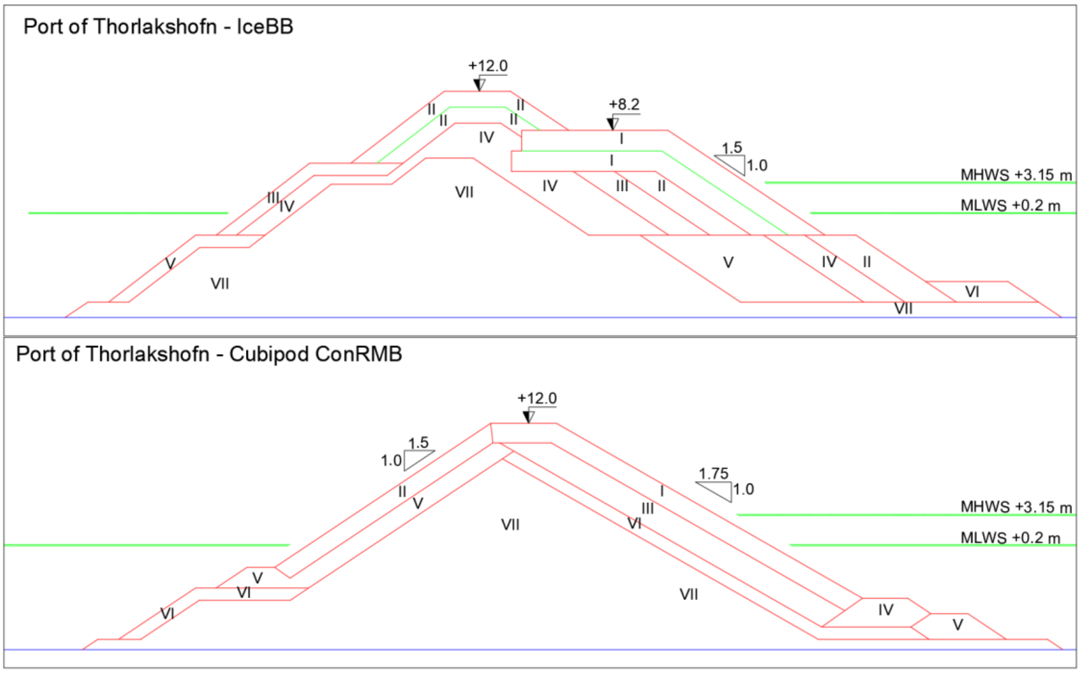

Figure 4. The cross-section of IceBB and ConRMB for the port of Thorlakshofn.

Table 3. Port of Thorlakshofn, volume in different rock and armor classes for IceBB and ConRMB design. All data is per linear meter of the breakwater.

Rock / Armor Class			IceBB	ConRMB
IceBB	ConRMB		(m^3/m)	(m^3/m)
I		$15.0 \text{ t} < M \leq 30.0 \text{ t}, M_{50} \geq 20.0 \text{ t}$	116	
	I	16,0 t Cubipod, 2400 kg/m^3		75
	II	11,0 t Cubipod, 2400 kg/m^3		42
II		$8.0 \text{ t} < M \leq 15.0 \text{ t}, M_{50} \geq 10.3 \text{ t}$	115	
	III	$3.5 \text{ t} < M \leq 10.0 \text{ t}, M_{50} \geq 5.7 \text{ t}$		86
III		$3.0 \text{ t} < M \leq 8.0 \text{ t}, M_{50} \geq 4.7 \text{ t}$	47	
	IV	$2.0 \text{ t} < M \leq 7.0 \text{ t}, M_{50} \geq 3.7 \text{ t}$		21
	V	$1.0 \text{ t} < M \leq 3.5 \text{ t}, M_{50} \geq 1.8 \text{ t}$		71
IV		$1.0 \text{ t} < M \leq 3.0 \text{ t}, M_{50} \geq 1.7 \text{ t}$	129	
V	VI	$0.3 \text{ t} < M \leq 1.0 \text{ t}, M_{50} \geq 0.5 \text{ t}$	97	75
VI		$0.1 \text{ t} < M \leq 0.3 \text{ t}, M_{50} \geq 0.17 \text{ t}$	16	
VII	VII	Quarry run	606	628
Total			1,126	998

Procurement/Production of Materials

In this comparative LCA study, 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 tonnes for the port of Straumsvik, and 90 and 45 tonnes 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 project, the 70-ton excavator handled rocks weighing over 1.0 tonnes, while the 50-ton excavator dealt with rocks lighter than 3.0 tonnes. For the port of Thorlakshofn project the 90-ton excavator is used to sort and load rocks that are heavier than 3 tonnes onto trucks, and the 45-tonnes excavator is used to sort and load rocks lighter than 8 tonnes. It was assumed that the two excavators evenly sort rocks based on the total volume of rocks.

The density of rock was considered approximately 40% porosity of the breakwater (van der Meer and Sigurdarson 2016). The same porosity assumption was made for the ConRMB. Gunnarsdottir et al. (2024) and Eskafi et al. (2024) 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 et al. 2016). Therefore, fuel use of 0.235 kg/(kW·h) diesel fuel (0.85 kg/L), and a load factor of 0.56 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 et al. 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.

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 including 12.0 t and 8.0 t for the port of Straumsvik project, and 16.0 t and 11.0 t 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 project and the port of Thorlakshofn project, respectively. Gunnarsdottir et al. (2024) and Eskafi et al. (2024) have provided 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 for the port of Thorlakshofn and port of Straumsvik.

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 empty trucks, 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 in both port projects.

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 concerning 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. Gunnarsdottir et al. (2024) and Eskafi et al. (2024) have provided 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.

RESULTS AND DISCUSSION

The calculated results of the construction CF for the port of Thorlakshofn and the port of Straumsvik projects reveal that the total GWP for the construction of IceBB is 3.68 t CO2-eq/m and 4.44 t CO2-eq/m, while for ConRMB, is 24.0 t CO2-eq/m and 22.1 t CO2-eq/m, respectively. The significant difference in GWP between IceBB and ConRMB is a direct consequence of the production of concrete used for the Cubipod armor units.

Figure 5 provides an overview of the carbon emissions associated with each breakwater construction at the ports.

In 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.

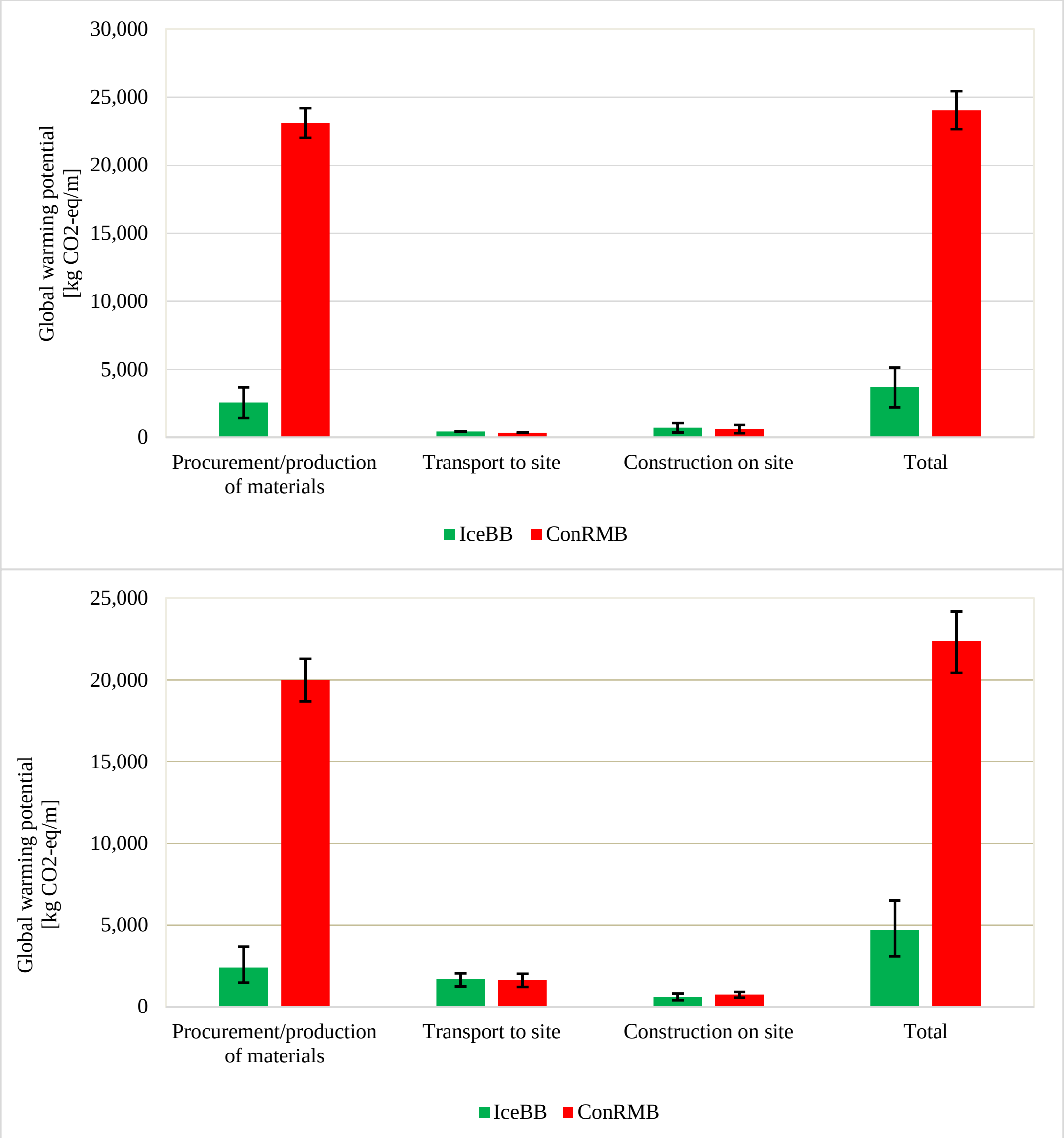

Figure 5. Comparative results of the calculation of the CF of IceBB and ConRMB for the port of Thorlakshofn (top row) and the port of Straumsvik (bottom row), the Global Warming Potential per meter breakwater.

This finding shows that coastal protection solutions utilizing natural rocks can 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 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 and Jones 2008). To reach near-zero-carbon cement production CO2 emissions need to be captured and stored permanently. The emission factor used in this study for ready-mix concrete production is 296 kg CO2-eq/m^3 concrete. Even with the assumption of using low-carbon concrete with an emission factor of, for instance, 150 kg CO2-eq/m^3, the climate benefit of IceBB construction is still evident.

It is important to note that the present study 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, see Figure 6.

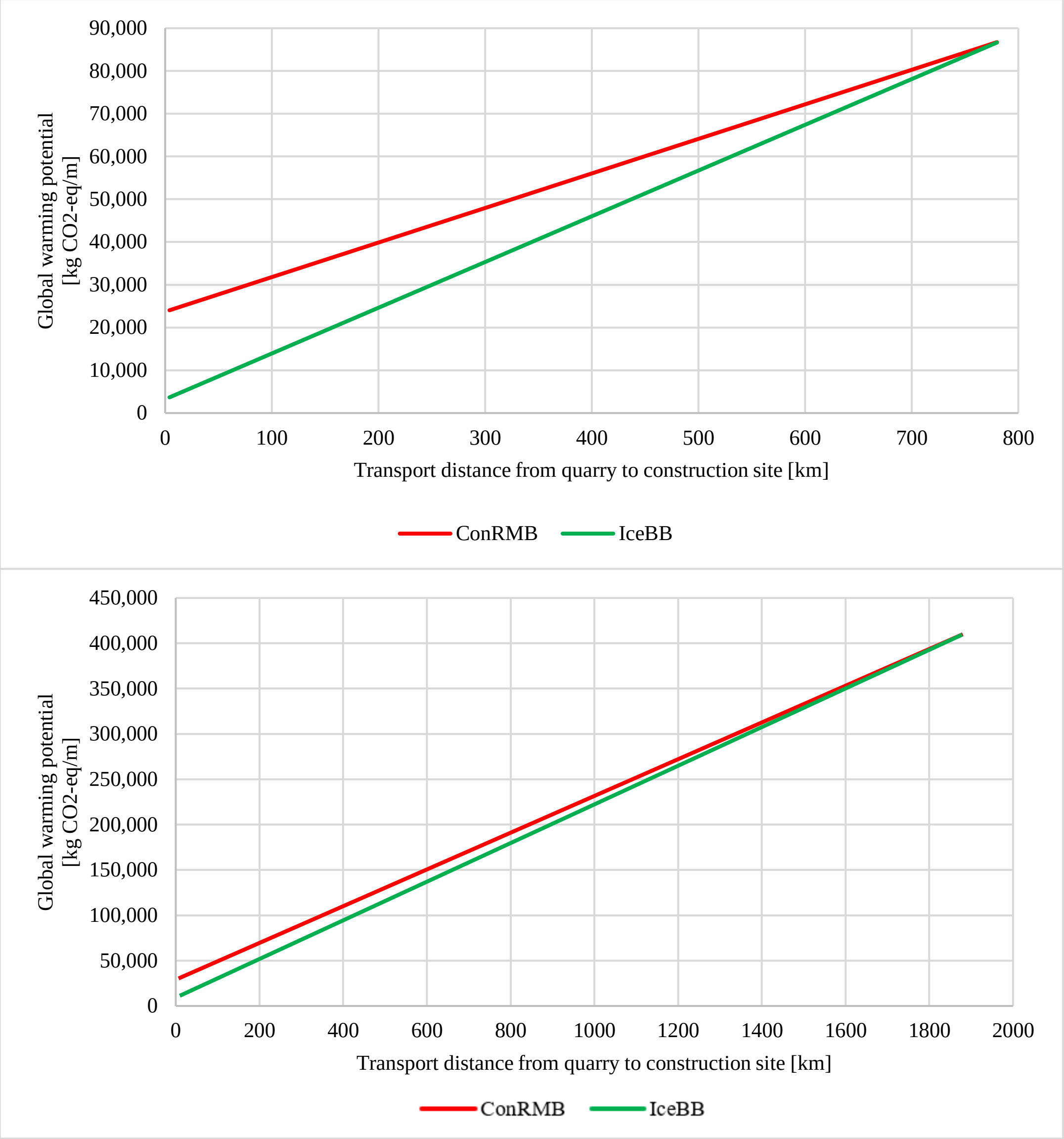

Figure 6 Comparison of the CF, the Global Warming Potential per meter breakwater, of the construction of IceBB and ConRMB, for the port of Thorlakshofn (top row) and the port of Straumsvik (bottom row) for different transport distances from the quarry to the construction site.

As depicted in Figure 6, 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 800 km in the port of Thorlakshofn project and 2000 km in the port of Straumsvik project, the climate benefit of using natural stone instead of concrete armor units is negligible.

CONCLUSION

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.

In this study, using GaBi software the 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 focus was to evaluate the CO2-eq emissions from these structures. The results provided insights into the CF associated with the construction phase of IceBB and ConRMB. The system boundaries of the study 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. The results indicated that the IceBB has significantly lower GWP associated with the construction. IceBB is made entirely from natural rock and thus is a structure with a lower CF compared to ConRMB.

ACKNOWLEDGMENT

The authors would like to thank the Icelandic Road and Coastal Administration for providing data and the Port of Hafnarfjordur for agreeing to publish the results of this study. This study was supported in part by the Icelandic Road and Coastal Administration research fund and the Icelandic Student Innovation Fund of the Icelandic Centre for Research.

REFERENCES

Bruce, T., and J. Chick. 2010. “Energy and carbon costing of breakwaters.” *Coasts Mar. Struct. Break. Adapt. Change*, 582–590. Thomas Telford Ltd.

CIRIA, CUR, CETMEF. 2007*, CUR, CETMEF (2007). The Rock Manual. The use of rock in hydraulic engineering (2nd edition). C683, CIRIA, London*.

Eskafi, M. 2021. *Framework for Dealing with Uncertainty in the Port Planning Process: An Icelandic Case of the Ports of Isafjordur Network*. University of Iceland.

Eskafi, M., A. Dastgheib, P. Taneja, G. F. Ulfarsson, G. Stefansson, and R. I. Thorarinsdottir. 2021. “Framework for Dealing with Uncertainty in the Port Planning Process.” *J. Waterw. Port Coast. Ocean Eng.*, 147 (3): 05021003. American Society of Civil Engineers. https://doi.org/10.1061/(ASCE)WW.1943-5460.0000636.

Eskafi, M., R. Fazeli, A. Dastgheib, P. Taneja, G. F. Ulfarsson, R. I. Thorarinsdottir, and G. Stefansson. 2020. “A value-based definition of success in adaptive port planning: a case study of the Port of Isafjordur in Iceland.” *Marit. Econ. Logist.*, 22 (3): 403–431. https://doi.org/10.1057/s41278-019-00134-6.

Eskafi, M., S. Sigurdarson, B. Brynjarsson, and K. Eliasson. 2024. “Icelandic-Type Berm Breakwater: A Nature-Based Structure with a Low Carbon Footprint.” *J. Waterw. Port Coast. Ocean Eng.*, 150 (1): 05023003. American Society of Civil Engineers. https://doi.org/10.1061/JWPED5.WWENG-2010.

European Union. 2003. *Directive 2003/87/EC of the European parliament and of the council of 13 October 2003 establishing a scheme for greenhouse gas emission allowance trading within the community and amending council directive 96/ 61/EC*. 32–46. Official Journal of the European Union L 275. Luxembourg.

Gunnarsdottir, E. S., M. Eskafi, S. Sigurdarson, K. Eliasson, and P. I. Sveinbjornsson. 2024. “Life Cycle Assessment of Icelandic-Type Berm Breakwater.” *Icel. J. Eng.* https://doi.org/10.33112/ije.30.1.

Hammond, G. P., and C. I. Jones. 2008. “Embodied energy and carbon in construction materials.” *Proc. Inst. Civ. Eng. - Energy*, 161 (2): 87–98. ICE Publishing. https://doi.org/10.1680/ener.2008.161.2.87.

International Organization for Standardization. 2006. “Environmental management — Life cycle assessment — Requirements and guidelines. (ISO Standard No. 14044:2006).”

Klanfar, M., T. Korman, and T. Kujundžić. 2016. “Fuel consumption and engine load factors of equipment in quarrying of crushed stone.” *Teh. Vjesn. - Tech. Gaz.*, 23 (1). https://doi.org/10.17559/TV-20141027115647.

Labrujere, A. L., and H. J. Verhagen. 2012. “Analysis of the carbon footprint of coastal protection systems.” *ICCE 2012 Proc. 33rd Int. Conf. Coast. Eng. Santander Spain 1-6 July 2012*. Citeseer.

Medina, J. R., and M. E. Gómez-Martín. 2012. “KD and Safety Factors of Concrete Armor Units.” *Coast. Eng. Proc.*, (33): 29–29. https://doi.org/10.9753/icce.v33.structures.29.

van der Meer, J., and S. Sigurdarson. 2016. *Design and Construction of Berm Breakwaters*. Advanced Series on Ocean Engineering. World Scientific. Advanced Series on Ocean Engineering Vol40 ISBN 978-981-4749- 60-2.

Sigurdarson, S., O. Smarason, and G. Viggosson. 2000. “Design Considerations of Berm Breakwaters.” Sydney, Australia.

Sphera. 2022a. *GaBi Professional database 2022*.

Sphera. 2022b. *GaBi Extension database XIV: Construction materials*.

United Nations. 1998. *Kyoto Protocol to the United Nations Framework Convention on Climate Change*. Kioto, Japan.