Climate change impact and cost assessment of Compressed Earth Blocks

Evaluation of affordable housing solutions in Kenya

TNO Public ⟩ TNO 2025 R10710
27 March 2025

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TNO 2025 R10710 – 27 March 2025

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Classification report	TNO Public
Title	TNO Public
Report text	TNO Public
Number of pages	20 (excl. front and back cover)
Number of appendices	0
Project number	060.52315

Contents

1 Introduction

In 2050, half of the population of Kenya is estimated to live in urban areas. Additionally, an estimated urban population growth of 4% per year is projected [1]. This growth imposes challenges for urban areas in Kenya, such as providing sustainable and affordable housing solutions. It requires an increase in construction activities in urban and rural areas, which will increase the carbon emissions for Kenya dramatically [2]. As part of multiple other solutions, compressed earth blocks (CEBs) have emerged as a viable alternative to conventional walling materials, offering a potential solution for the economic and environmental challenges the Kenyan construction sector faces. CEBs can be manufactured locally using available soil and a stabilizer, which are compressed under high pressure to form durable blocks. CEBs have been around since the 1950s, and the first manual press has been produced for a social housing program in Colombia [3]. It made its way to Africa, and despite the potential benefits, the application in Kenya has been limited. This seems to come from a combination of misconceptions about their durability and performance, and insufficient evidence of their cost and environmental benefits. This knowledge gap seems to be a barrier for the technology to really take off.

Here, we evaluated the climate change impact through Life Cycle Assessment (LCA) and costs using Life Cycle Costing (LCC) of CEBs. We compared our results to those of conventional construction material used in Kenya, machine cut stones (MCS). MCS are a widely used building material in Kenya, particularly in Nairobi. The popularity of MCS in Nairobi is partly due to the nearby quarry in the Thika region. K'Akumu found that 41,1% of households in Nairobi are built using stone [4], underscoring the importance of stone use in the construction sector. In addition, Dormohamadi, et al. [5] demonstrated that transportation distances greatly influence the total climate change impact and costs, particularly when comparing locally produced walling materials with quarry-dependent options. Based on these insights, we identified break-even points for climate change impact and costs relative to transport distances from MCS quarries to determine the most efficient material choice for specific locations.

The results of the LCA provide insights into the environmental hotspots throughout the life cycle, highlighting areas with potential for optimization and improved efficiency. Similarly, the LCC provides the total costs over the product life cycle, showing more than just its market value or initial costs. These findings can potentially be used to optimize production processes, inform policymakers, and raise community awareness about the technologies.

2 Goal & scope

2.1 Goal

The goal of this study is to overcome the knowledge gap by providing insights in the climate change impact and costs associated with CEBs. The research was conducted as part of a housing project in the Mukima community, located near Nanyuki in Laikipia County. For this project, six houses are constructed using CEBs.

2.2 Scope

The technology was evaluated based on the impact category of climate change. The climate change impact was quantified following the IPCC 2021 method for Global Warming Potential over a 100-year time horizon (GWP100). Additionally, the costs are expressed in Kenyan Shilling (KES). Costs often vary and this volatility is not considered in this analysis. The costs are based on the prices at the time of data collection, which is November 2024. The foreground data was collected in Kenya, with background processes such as electricity mix, transportation modes, and land-use changes adjusted to the Kenyan context. The background processes are represented using datasets from ecoinvent [6]. The wall is designed to have a load-bearing capacity suitable for a single-story house, lasting 75 years.

Figure 2.1 depicts the system boundaries of our product system, covering the full lifecycle, including production, construction, use, deconstruction, waste processing and end of life (EoL) phase. The functional unit (FU) for this research is defined as *1 m² load-bearing wall for a single story-house in Mukima, lasting 75 years*.

2.3 System definition

The soil layer suitable for construction lies beneath the organic topsoil [7], which is typically extracted locally by hand during the excavation of foundations and pit latrines. This soil is then pulverized and dry mixed with cement before water is added. The resulting mixture is placed into the manual CEB press, where the block is compressed, after which the block is cured for 3-4 weeks under a tarpaulin. There are also hydraulic presses available, however, this study focuses only on manually pressed CEBs. When cured, the CEB is ready for use. Since the production of CEBs is carried out manually on a local scale, the quality of the block depends on the individuals involved in the process and the local soil type. Proper mixing and sufficient curing time are crucial to ensure high-quality blocks. Any shortcuts during the production process can compromise the quality of the final product.

The following processes were excluded from the scope and cut off from the product system:

- Production and initial cost investment of CEB press, the pulverizer and the mixer were not included.
- Use of oils or tarpaulin during the production process of CEBs.
- Plastering during construction phase.

- Varnish during construction phase.
- Maintenance during use phase.
- Quality variety of manually produced walling materials

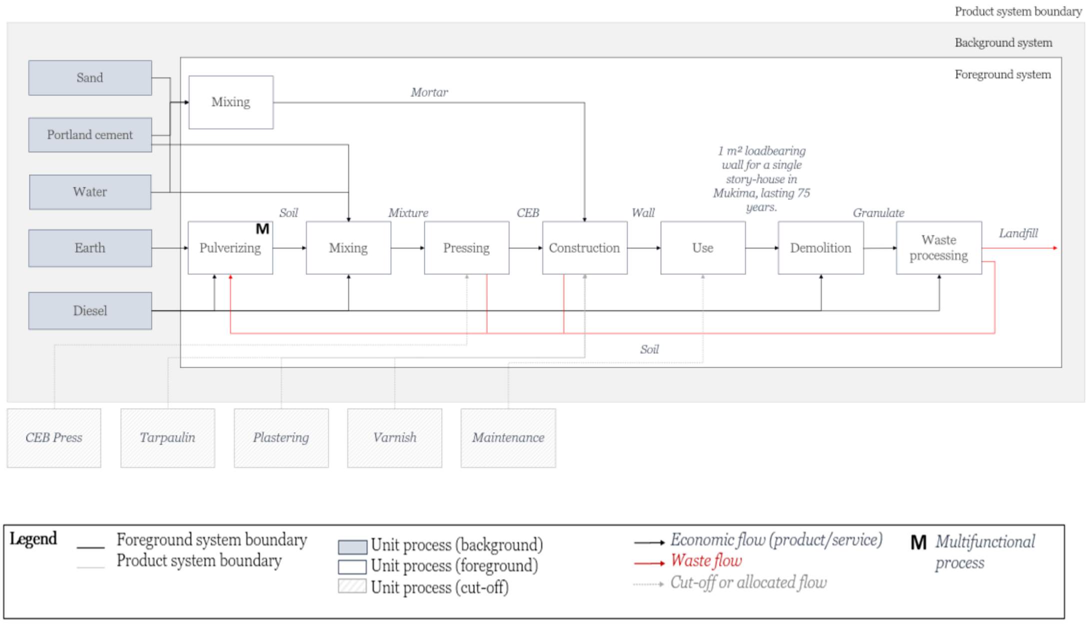

Figure 2.1: System description CEB wall

A variation of the CEB is an interlocking variant. Their production process is the same as the non-interlocking CEBs, however they require a different mold. Additionally, during construction there is no mortar requirement. Mortar, particularly cement, is a major contributor to climate change [8]. Reducing cement use is therefore a priority in product optimization, which is why interlocking CEBs were included in this study.

The study compared CEBs and interlocking CEBs to MCS, with the specifications of the building blocks detailed in Table 2.1.

Table 2.1: Dimensions and specifics of building blocks

Specifications	Unit	Non-interlocking CEB	Interlocking CEB	MCS
Appearance		 [1]	 [2]	 [3]
Length	cm	29.5	29.5	20
Width	cm	14	14	40
Height	cm	9	9	20
Mass per piece	kg	7.8	7.8	20

[1] Example of non-interlocking CEB [20]
[2] Example of interlocking CEB [20]
[3] Example of Machine-cut stone

Density	kg/m^3	2098	2098	1250
Blocks per m2	piece	32	38	9.5
Mortar per m2	kg	50	0	60

The transport variable is highly project-specific and varies for each product. To address this variability, and to broaden the relevance of the findings beyond the Mukima community, the study assessed variations in the transport distances from the MCS quarry to construction sites. We considered the transport distances to the manufacturing site of CEBs to be fixed.

Finally, variations in cement content were included, as soil types can vary in quality and thus may require a higher cement content. Studies suggest that the cement dosage used for CEB should be between 4% and 10% of the dry mass of soil [9]. Therefore, two scenarios were analyzed: one with 5% cement and another with 10% cement.

3 Life Cycle Inventory

The primary foreground data was collected by means of interviews with experts from NGOs, construction companies, and manufacturers leading to quantitative estimates and indications. Additional data was derived from literature. Uncertainties were addressed by including several scenarios.

3.1 LCA

In Table 3.1, all the processes for the cradle to construction phase are depicted. These quantities include losses that occur during the production phase, which is 10% for soil and 75% for water evaporation [10], and for the construction phase, which is 3% for any prefabricated products, and 5% for in-situ products [11]. These waste streams are reused as input for producing new blocks, and stay within the system boundaries.

Table 3.1: Text Flows for cradle to construction phase of the evaluated building blocks

				Non-interlocking		Interlocking		
Object	**Process**	**Unit**	**MCS**	**CEB 5% cement**	**CEB 10% cement**	**CEB 5% cement**	**CEB 10% cement**	**Database process**
CEB	Portland cement	kg		15	24	18	29	Cement, Portland (adjusted to Kenya)
CEB	Earth	kg		270	264	317	310	Manually excavated soil
CEB	Water	kg		15	15	18	18	Tap water (Locally sourced)
MCS	Natural stone production adjusted [12]	kg	209					Natural stone plate, cut (adjusted to Kenya)
Mortar	Portland cement	kg	15	13	13			Cement, Portland (adjusted to Kenya)
Mortar	Sand	kg	45	38	38			Sand quarry operation, extraction from river bed (adjusted to Kenya)
Cement transport to production	EURO 3 unspecified	kgkm	3375	6183	8204	3966	6346	Transport, lorry, unspecified, EURO 3
Sand transport to production	EURO 3 unspecified	kgkm	2475	2063	2063			Transport, lorry, unspecified, EURO 3
CEB	Pulverizing	MJ		8.35	8.35	9.83	9.83	Diesel, burned in building machine
CEB	Mixing	MJ		11.14	11.14	13.11	13.11	Diesel, burned in building machine

Mortar	Mortar mixing	kg	60	50	50			Cement, Portland (adjusted to Kenya) & Sand quarry operation, extraction from river bed (adjusted to Kenya)
Transport to site	EURO 3 unspecified	kgkm	33250					Transport, lorry, unspecified, EURO 3

Table 3.2 shows the inventory for all processes in the demolition and EoL phase. Defining general assumptions regarding recycling or reusing materials during EoL phase was challenging. Private homeowners are the largest client group, and particularly difficult to reach and influence. There are no standardized regulations or approaches to guide this group, leaving individuals to decide on their own. Leading to varied outcomes, blocks may be directly reused, recycled for foundation and as input for new CEBs, or sent to landfills. To address this uncertainty, we included a scenario in which we included a scenario for 99 percent recycling rate and 1 percent landfill. All the materials are recycled on location either as foundation, or for the CEBs as new input material for the presses, leading to no additional transport. Additionally, we included a scenario in which nothing was recycled, and all materials are landfilled.

Table 3.2: Flows for Demolition and EoL phase of the evaluated building blocks

				Non-interlocking		Interlocking	
Object	**Process**	**Unit**	**MCS**	**CEB 5% cement**	**CEB 10% cement**	**CEB 5% cement**	**CEB 10% cement**
Demolition	Diesel	MJ	96	115	115	132	132
Waste processing	Diesel	MJ		8,35	8,35	9,83	9,83
Recycling	Raw material equivalent: Gravel [13]	%	99%				
Recycling	Raw material equivalent: Soil [13]	%		99%	99%	99%	99%
Landfill	Landfill	%	1%	1%	1%	1%	1%

3.2 LCC

Table 3.3 shows the inventory for the LCC. The same scope and system boundaries were considered for the LCC. However, there are some differences on aggregation level for some elements. For instance, prices of transport are included in the total price of the product. Prices of manual labour of soil extraction, mixing, pulverizing and pressing is included in the production of the brick. Table 4 shows the inventory for the LCC, for both the CEB variants and the MCS variants.

Table 3.3: Inventory for the LCC

Material / process	Amount	Unit	Justification
Cement Portland (including transport)	16	KES/kg	Data inventory done by Habitat for Humanity
Water	1	KES/kg	Data inventory done by Habitat for Humanity
MCS production	285	KES/m^2	Prices from quarry [14]
Cement Portland for Mortar (including transport)	16	KES/kg	Data inventory done by Habitat for Humanity
Sand for Mortar (including transport)	2.20	KES/kg	Data inventory done by Habitat for Humanity
Producing CEB (including excavating soil, pulverizing, mixing and pressing)	215.33	KES/ m^2	Data inventory done by Habitat for Humanity
Mortar Production	22.32	KES/ m^2	Data inventory done by Habitat for Humanity
Transport MCS to site (175 km)	323	KES/ m^2	Prices from quarry [14]
Construction labour	200	KES/ m^2	Data inventory done by Habitat for Humanity
Demolition	22.32	KES/ m^2	Data inventory done by Habitat for Humanity
Raw material equivalent: Gravel	1.81	KES/kg	Data inventory done by Habitat for Humanity

4 Results and interpretation

4.1 Climate change impact

Figure 4.1 shows the climate change impact for each considered building block and scenario per FU in Nanyuki. Cement is found to be the most significant contributor to the climate change impact of CEBs, during the production phase. For the variant with 5% cement, the carbon contribution of cement is 83%, increasing to 91% for the 10% cement scenarios. Mortar contributes 25% to MCSs, 26% to the CEB 5% cement scenarios, and 20% for the CEB 10% scenarios. The contribution of MCS production to its total climate change impact is 40% in both MCS scenarios.

For the CEBs, the production phase contributes 30% for the non-interlocking 5% cement scenarios and 44% for the interlocking variant to the climate change impact. In the 10% cement scenarios, the production phase accounts for 46% of the footprint for the non-interlocking variant and 60% for the interlocking variant. Notably, the interlocking variant has the lowest climate change impact among all scenarios, mainly due to dry-stacking, for which no mortar is assumed. As expected, the 5% cement variants show a lower climate change impact than the 10% variants due to reduced cement usage.

The production phase of MCS has a higher climate change impact compared to the 5% cement CEB scenarios, but is lower than the 10% cement CEB scenarios. These findings underscore the importance of CEB composition, particularly the cement content, in selecting construction materials based on climate change impact.

Transportation to the construction site is another key contributor for the MCS, where it accounts for 11% of the total climate change impact. This factor is less significant for CEBs, as they are produced locally, avoiding the need for bulk material transportation to the construction site. Cement transport is assumed to be fixed.

Recycling has a minimal effect on the total climate change impact. For CEBs, recycling avoids soil extraction, which has no direct climate change impact in our product system. There is, however, a land use change effect here, which is overseen when only considering climate change impact. Since we are reporting on climate change impact, the CEB variants with recycling are excluded from the graph. In the case of MCS, recycling eliminates the need for gravel, this has a relatively minor effect on the overall climate change impact, but is included in the graphs.

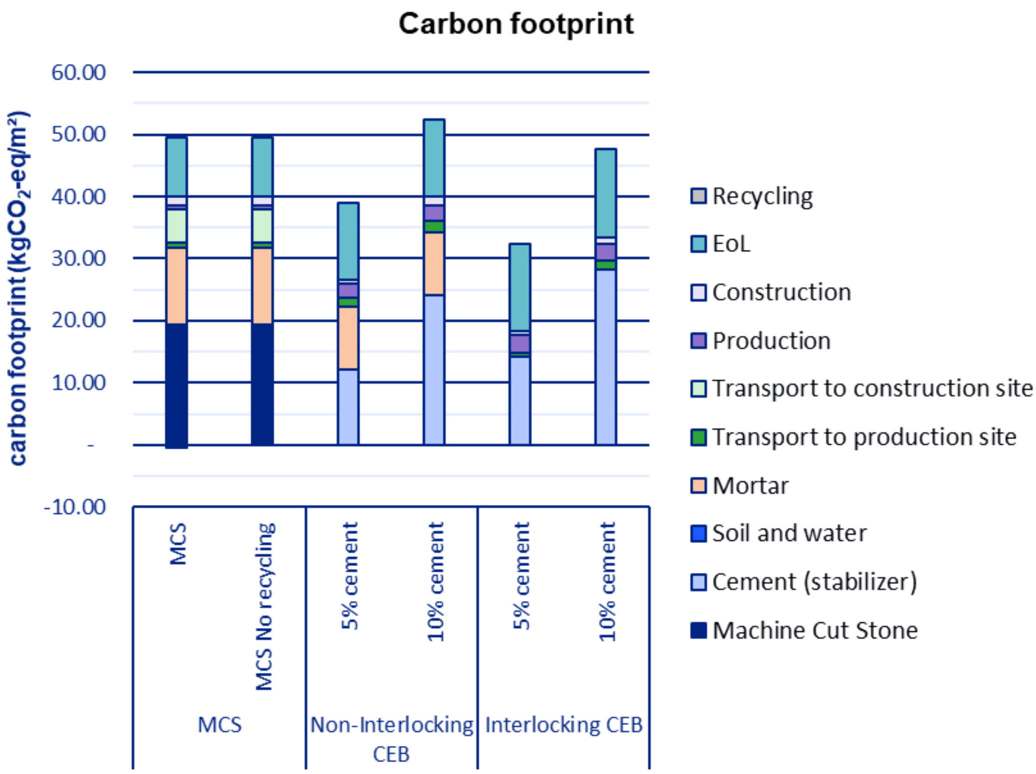

Figure 4.1: Climate change impact per FU

4.1.1 Comparison with literature

Table 4.1 presents the cradle-to-gate, cradle-to-construction, and cradle-to-grave climate change impacts of the various scenarios per FU. Previous studies provide useful comparisons. Dormohamadi, et al. [5] studied various walling materials in Iran, considering a cradle-to-gate scope for one square meter of wall. Their results showed a climate change impact of 4.23 kgCO_2-eq for CEBs with 4% cement and 15.44 kgCO_2-eq for those with 10% cement. This highlights a strong dependence on cement content, consistent with the results of this study. The study does, however, indicate a lower climate change impact for the production phase, than our findings. This can be attributed to geographical variables or to the impact assessment method, however, we were not able to find the impact assessment method used in the study. This study also reported a cradle-to-gate climate change impact of 18.56 kgCO_2-eq for fired brick, a widely used building material in Kenya, which lands right in the middle of our CEBs results, and is slightly lower than the MCS results.

Gutiérrez, et al. [15] investigated compressed stabilized blocks in the United States and found a cradle-to-gate climate change impact of 35.74 kgCO_2-eq per square meter of wall. Similarly, Fernandes, et al. [7] reported 33.2 kgCO_2-eq for one square meter of wall in Portugal. These values are notably higher than the cradle-to-gate footprints found in this study. However, Fernandes also documented a cradle-to-gate climate change impact of 28.5 kgCO_2-eq per square meter for stabilized rammed earth blocks in Portugal, which aligns closely with our results for the interlocking 10% cement variant but is less comparable to other scenarios.

Carbrera, et al. [16] evaluated the climate change impact of CEBs with varying cement content in Argentina, finding 0.23 kg CO_2-eq per piece for the 5% cement variant and 0.42

$kgCO_2$-eq for the 10% variant. These values are lower than our findings of 0.38 $kgCO_2$-eq and 0.75 $kgCO_2$-eq for the 5% and 10% cement variants, respectively.

What we take from this, is that the climate change impacts of walling material are dependent on location, but cement is always a critical factor. Notably, no studies were found that analyzed the cradle-to-grave climate change impact for the considered walling materials.

Table 4.1: Climate change impact per FU of cradle to gate, construction and grave

	MCS		Non-Interlocking CEB		Interlocking CEB	
Phase	**MCS**	**MCS No recycling**	**5% cement**	**10% cement**	**5% cement**	**10% cement**
Cradle-to-gate ($kgCO^2$-eq per FU)	19.40	19.40	12.04	24.06	14.17	28.32
Cradle-to-construction ($kgCO^2$-eq per FU)	39.97	39.97	26.57	40	18.23	33.39
Cradle-to-grave ($kgCO^2$-eq per FU)	49.02	49.58	38.93	52.36	32.43	47.59

4.1.2 Breakeven analysis

In Table 4.2 the transportation distances to the construction site for the CEBs to breakeven with the MCSs are depicted. The CEBs scenarios with 5% cement have a lower climate change impact than MCSs over any transportation distance. Highlighting the importance of cement quantities used, and the local soil quality, as this influences the needed cement content. When the construction site is located 250 km away or more from a stone quarry, our results show that non-interlocking CEB is the best option from an climate change impact perspective, for interlocking CEB this is the case for 125 km.

Table 4.2: Transportation distances in km to the construction site for the CEBs to breakeven with the MCS from climate change impact perspective

Type	Scenario	Unit	MCS	MCS No recycling
non-Interlocking CEB	5% cement	km	0	0
	10% cement	km	250	225
Interlocking CEB	5% cement	km	0	0
	10% cement	km	125	100

4.2 Costs

Figure 4.2 presents the cost assessment over the life cycle per functional unit (FU) for the evaluated building materials. When looking at the summation of all costs, the six variants have similar proportionality to each other as in the climate change impact assessment, although the contributors are slightly different. Similar to the climate change impact, the attribution of cement, mortar, and MCS production significantly impacts costs. However, the EoL stage is considerably less influential, whereas the production and construction phases are more significant.

The construction phase contributes 21% and 17% of the costs for MCS with and without recycling, respectively. For non-interlocking blocks, this phase accounts for 20% and 16% under the 5% and 10% cement scenarios, respectively, and for interlocking blocks, 24% and 18% under the same scenarios. Particularly, the production phase has relatively high costs for the CEBs, contributing 23% and 19% for the 5% and 10% cement scenarios in non-interlocking blocks, and 34% and 25% for the interlocking blocks under the same scenarios.

In regard to costs, the transport to the construction site is a key contributor for MCSs in contrast for the CEBs, as these are produced locally. Recycling has minimal influence on the costs for CEBs, consistent with its impact on climate change impact. In CEB production, soil is sourced from excavations for foundations and latrine pits. For MCS, however, the cost of gravel is a significant factor, making recycling more relevant from a cost perspective. MCS with 99% recycling is more beneficial over the whole lifecycle, than non-interlocking CEBs for this case study. Interlocking CEB with 5% cement has the lowest overall costs over the whole life cycle.

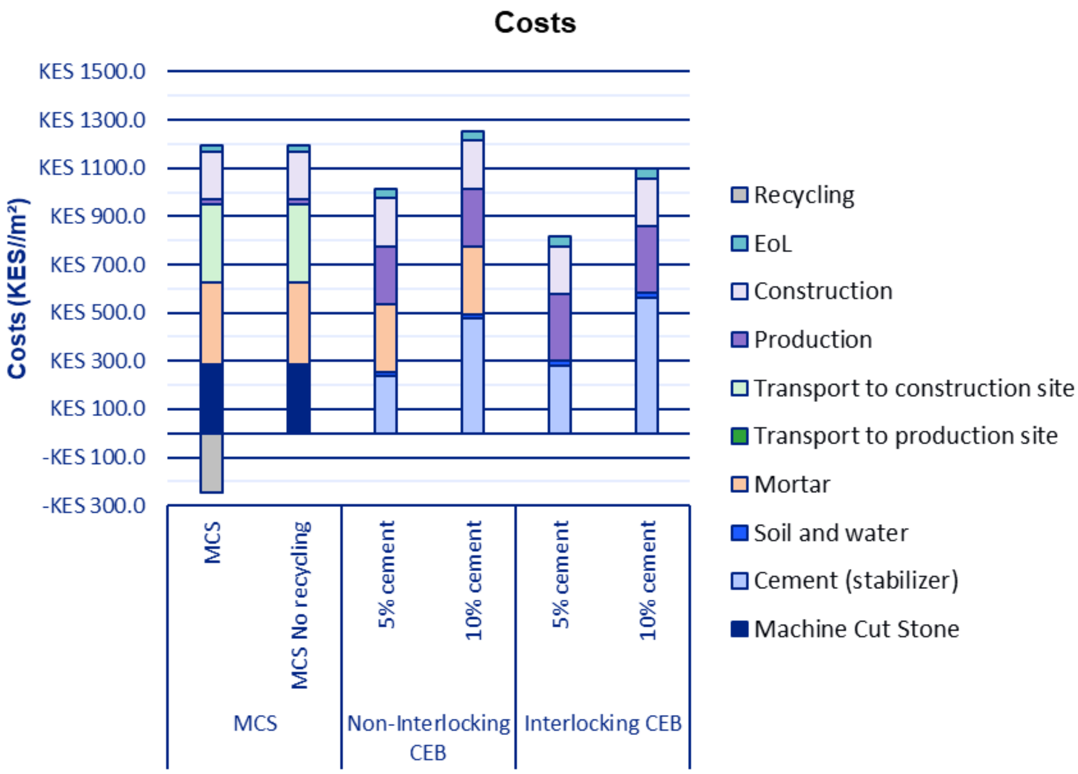

Figure 4.2: Costs per FU

4.2.1 Comparison with literature

Table 4.3 shows the cradle-to-gate, cradle-to-construction, and cradle-to-grave climate change impacts of the various scenarios per FU. Dormohamadi, et al. [5] conducted a cost analysis of several walling materials in Iran, focusing on a cradle-to-gate plus transport to construction site scope for one square meter CEB. Comparing costs cross-country is challenging due to differing local economic conditions, costs vary by region. However, they can provide a rough relative indication between scenarios. For instance, the costs of 588 KES for 4% cement CEB, and 667 KES for 20% show only a 13% difference. This is small compared to our findings, where the 10% cement scenario is 25% higher than the 5% cement scenario for non-interlocking, and 36% higher for interlocking. This suggests a lower cost sensitivity to cement content in Iran. The costs were converted from US dollar to KES using 120 conversion rate [17].

Table 4.3: Costs per FU for cradle to gate, construction and grave

	MCS		Non-Interlocking CEB		Interlocking CEB	
Phase	**MCS**	**MCS No recycling**	**5% cement**	**10% cement**	**5% cement**	**10% cement**
Cradle-to-gate (kgCO^{2}-eq per FU)	KES 285	KES 285	KES 255	KES 494	KES 300	KES 582
Cradle-to-construction (kgCO^{2}-eq per FU)	KES 1.169	KES 1.169	KES 975	KES 1.214	KES 775	KES 1.057
Cradle-to-grave (kgCO^{2}-eq per FU)	KES 948	KES 1.192	KES 1.011	KES 1.251	KES 818	KES 1.100

4.2.2 Breakeven analysis

In Table 4.4 the distances for the CEB to break even with the MCSs for costs are depicted. Similar to the climate change impact, the cement requirement dictates the transportation over which the costs break even. When the construction site is located 200 km away or more from a stone quarry, our results show that non-interlocking CEB is the best option from a cost perspective, for interlocking CEB this is the case for 75 km.

Table 4.4: Transportation distances in km to the construction site for the CEBs to breakeven with the MCS from cost perspective

Type	Scenario	Unit	MCS	MCS No recycling
non-Interlocking CEB	5% cement	km	25	0
	10% cement	km	200	25
Interlocking CEB	5% cement	km	0	0
	10% cement	km	75	0

5 Discussion and conclusion

5.1 Discussion

After visiting multiple project sites in Kenya, it became apparent that varnish and plaster is commonly used as a finishing material in CEB construction to mitigate weather effects, such as erosion, and for esthetic purposes. While varnish or plastering can enhance the durability of the walls, this aspect was beyond the scope of our research. Therefore, the environmental impacts and costs associated with it, were not accounted for. We did, however find that for one square meter wall, 1 liter of varnish is typically used. 1 liter of varnish has a climate change impact of 6.34 kgCO2-eq per m^2, derived from ecoinvent [6]. When varnish is applied, it becomes a significant hotspot in the cradle-to-grave climate change impact of the CEB constructions. For non-interlocking 16% for the 5% cement scenario, and 12% for the 10% cement scenario, and for interlocking 20% under 5% cement, and 13% for 10% cement. Changing the proportional differences between CEBs en MCS, in favour of MCS.

Challenges in manufacturing and construction quality control can lead to block imperfections. Typically, these imperfections are corrected using mortar. However, when interlocking blocks are dry-stacked, these imperfections create small gaps between blocks, which can affect the overall compressive strength of the wall [18]. Additionally, shortcuts during manufacturing can influence the quality of both interlocking and non-interlocking CEBs. Since compressive strength was not analyzed in this study, variations in quality were not considered in the assessment. However, when accounting for a 100-year life cycle scope, assuming the MCS wall lasts 100 years and both CEB variants last 75 years to reflect worst-case quality uncertainty, the $kgCO_2$-eq and costs of the CEB increase by 33.33%. Under these conditions, only the interlocking 5% cement variant has a lower $kgCO_2$-eq than the MCS variants for the given transport distances from the MCS quarry. In terms of cost, the MCS with recycling remains the most economical option, followed by the interlocking 5% cement variant. We recommend that future research include more detailed performance indicators of the considered building blocks.

A significant factor in our study was the amount of mortar used, particularly because of its cement content. By reducing mortar usage by 25%, we see an approximate reduction in the cradle-to-grave scope of 3.5 $kgCO_2$-eq per m^2 and around 72 KES per m^2. Additionally, lowering the cement content in the mortar from 25% to 10% results in an estimated reduction of 6.5 $kgCO_2$-eq and a cost saving of 103.5 KES. When combined, changes in mortar use and cement content can potentially lead to a total reduction of 8 $kgCO_2$-eq and a saving of 149 KES per m^2. The impact of this factor varies depending on the manufacturer and the construction phase. For interlocking blocks, our analysis assumed no mortar usage. However, site visits revealed that mortar is used in certain cases. Specifically, for the first layer of masonry stones to give them a fixed connection to the concrete floor and leveling out any inconsistencies. It is also used as a finishing material for the corners.

A limitation of our study regards the use of fired brick, a widely used building material in Kenya due to the abundant availability in many parts of the country [19]. This material is particularly interesting because it is produced both industrially and locally by households.

Despite this it was out of scope for this project, it is however, recommended to include it in further comparable studies regarding affordable housing.

Finally, in our LCA, we only focused on the impact category for climate change (kg CO_2-eq), as it is a key driver of global warming. Given the goal and scope of our study, this focus enables a clear and accessible comparison of different building materials, effectively reaching decision-makers.

5.2 Conclusion

The study concludes that the location of the building site is a critical factor in selecting the optimal building material for affordable housing. The location determines on one hand the soil type and therewith the needed cement content, on the other hand, it determines the transportation distance of MCS from MCS quarries, both effecting the costs and the climate change impact.

Our findings indicate that for projects located over 250 km from a stone quarry, any evaluated CEB solution is the most advantageous option in terms of both climate change impact and cost. Among these, interlocking CEBs have the lowest associated costs and climate change impact, primarily due to the absence of mortar during construction.

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