BUILDING COMPONENTS AND BUILDINGS

Life cycle assessment and life cycle cost analysis of different walling materials with an environmental approach (comparison between earth-based vs. conventional construction techniques in Iran)

Mansoure Dormohamadi[1] · **Reza Rahimnia[2]** · **Victor Bunster[3]**

Abstract

Purpose Climate change, environmental concerns, and economic problems pose challenges to the construction sector in Iran, which must provide affordable solutions while addressing environmental issues. Hence, natural earthen building materials are critically needed to reduce energy-intensive and costly construction practices dramatically. The purpose of this paper is to provide a framework for comparing life cycle assessments (LCA) and life cycle costs (LCC), for load-bearing walls of an single-family affordable housing unit in a desert part of Iran, Ardakan City.

Methods To do so, both LCA and LCC for the unit were performed, considering a cradle-to-site perspective. For this purpose, 22 load bearing wall systems are assessed, including 18 stabilized and unstabilized earthen construction techniques, such as adobe, rammed earth (RE), and compressed earth block (CEB), in addition to four conventional wall assemblies of fired brick (FB), autoclaved aerated concrete block (AAC), ceramic block (CB), and concrete masonry unit (CMU). As well as assessing the environmental impact and life cycle costs associated with the life cycle of each wall, the optimal assembly of the wall is also examined.

Results Results show that unstabilized earthen walling alternatives have significantly lower environmental impacts than conventional materials.

Conclusions Sensitivity analysis indicates that by utilizing local materials to the maximum extent possible, impacts can be further minimized. Considering the results, transportation may even account for a greater proportion of EI than wall components.

Keywords LCA · LCC · Cradle-to-site · Wall · Earth-based construction · Conventional construction thechniques

Abbreviations

A-A	Alkali-activated
AAC	Autoclaved aerated concrete block

✉ Mansoure Dormohamadi
  mdo@build.aau.dk

  Reza Rahimnia
  rahimnia@arc.ikiu.ac.ir

  Victor Bunster
  Victor.Bunster@monash.edu

[1] Department of the Built Environment, Aalborg University, Copenhagen, Denmark

[2] Faculty of Architecture and Urbanism, Imam Khomeini International University (IKIU), Qazvin, Iran

[3] Department of Architecture, Monash University, Melbourne, Australia

CB	Ceramic block (hollow clay tile)
CEB	Compressed earth block
CH	Calcium hydroxide
CL.F	Clay finishing plaster
CL.P	Clay plaster
CM	Cement mortar
CMU	Concrete masonry unit
CO_2eq	Carbon dioxide equivalent
CP	Cement plaster
CP. F	Cement plaster-finishing
EC	Embodied carbon
EI	Environmental impact
FA	Fly ash
FB	Fired brick
GGBS	Ground granulated blast slag
GHG	Greenhouse gas
GP	Gypsum plaster
GP. F	Gypsum plaster-finishing

GP. S	Gypsum plaster + sand aggregate
GWP	Global warming potential
LB	Load bearing
LCA	Life cycle assessment
LCC	Life cycle cost
LCIA	Life cycle impact assessment
LCI	Life cycle inventory
NaOH	Sodium hydroxide
NBRI	National buildings regulations of Iran
RE	Rammed earth
SA	Stabilized adobe
SB	Soil block
SCEB	Stabilized compressed earth block
SRE	Stabilized rammed earth
SS	Sodium silicate
UA	Unstabilized adobe
USCEB	Unstabilized compressed earth block
URE	Unstabilized rammed earth
ICE	Inventory of carbon and energy

1 Introduction

Housing, as one of the basic needs of everyone, presents a particularly challenging situation in emerging economies. The UN reports that worldwide, the population may reach 9.6 billion by 2050, which will naturally increase housing demand. In this context, the building sector contributes 39% of CO_2 emissions related to energy, leading to global warming (Nejat et al. 2015). Therefore, urbanization and construction exacerbate the pressure on the environment, by consuming finite resources, releasing greenhouse gases (GHG), generating energy, and generating waste (Pomponi et al. 2017). In recent years, Iran's population has grown rapidly, particularly in urban areas. In light of this, Iran's government faces a considerable challenge in providing low-cost housing units for a large population. Observing the massive growth of new constructions in economies in transition, some researchers have shown that if nothing is done, greenhouse gas emissions from buildings will be more than double over the next few decades (Nematchoua et al. 2020), and on the other hand, Iran ranks first in the Middle East among the seven most carbon-emitting countries in the world (GCP 2021). Due to the fact that Iran is following the global trend of increasing residential demand, there is an urgent need for affordable and low-carbon strategies to be integrated into new housing construction (MOE 2022; MRUD 2022).

Meanwhile, Iran regulations have been developed focusing on operational energy reduction while ignoring the embodied carbon emission, which means due to increased energy efficiency policies, buildings are expected to become more efficient during their operation stage, thereby

increasing embodied carbon (Pomponi et al. 2017). In order to address this issue of carbon intensity in the embodied stage, it is important to select materials and construction systems that have the least impact on the environment. (Cabeza et al. 2014). Generally, Iran's residential built environment exhibits two main types of construction: contemporary and traditional. In the former, construction and building technologies follow conventional construction trends; which uses highly processed, industrially produced materials (e.g., concrete, aluminum, steel, glass), resulting in natural resource depletion (Bribián et al. 2011; Fernandes et al. 2014). However, in the latter, earthen building techniques and earth-based materials are used, as Iran has a rich history in earthen architecture. Earthen materials have been shown to have significant environmental benefits, although few studies have examined the impacts of earthen construction techniques on the environment within the country.

Recently, interest has increased in using natural building materials, especially earthen building materials, which are minimally processed and naturally low carbon (Morel et al. 2001). Compared to other building materials, bio-based and earthen materials exhibit (a) thermal inertia and compression strength; (b) greater resistance to insects, fungus, and rodents than cellulose materials; (c) potential abundance at and near the construction site; (d) diverse building forms and construction techniques, including sculptural monolithic assemblies and modular components (Racusin and McArleton 2012). There is substantial evidence that earthen materials can significantly reduce the impact of buildings on the environment (Arrigoni et al. 2017; Christoforou et al. 2016; Fernandes et al. 2014; Melià et al. 2014; Reddy 2009; Reddy et al. 2010; Reddy and Jagadish 2003; Sanz-Calcedo et al. 2012; Serrano et al. 2013; Shukla et al. 2009).

A quantitative comparison of several materials by Fernandes et al. (2014), Bribian et al. (2011), and Melia et al. (2014) indicated that vernacular and natural materials have lower carbon dioxide emissions and embodied energy than conventional materials. In addition, these studies emphasized the importance of using locally sourced and low-processed materials to reduce environmental impacts. Existing earthen construction LCA studies now include environmental impact assessments of construction techniques such as rammed earth (Fernandes et al. 2019; Morel et al. 2001; Serrano et al. 2013), cob (Estrada 2014; Kutarna et al. 2013), adobe bricks (Binici et al. 2005; Christoforou et al. 2016; Shukla et al. 2009), earth plasters (Melià et al. 2014; Morel et al. 2001), compressed earth blocks (Fernandes et al. 2019), and earthbags (Cataldo-Born et al. 2016). As well as environmental advantages, Morel et al. (2001) and Ramesh (2012) concluded that socioeconomic benefits can be derived from local materials, including a reduction in construction costs and the building of local economies by paying local costs for materials and labor. Typically, stakeholders and developers justify their decisions

based on the cost of a project. In the case of sustainability, costs have always been seen as a significant barrier, since environmentally friendly materials are believed to increase costs by 30% (Ross et al. 2007). Therefore, cost–benefit analyses are helpful for demonstrating the environmental advantages of different environmentally friendly wall configurations, thus encouraging more people to use them. The literature reviewed generally compares alternative EWs based on their EI (Ioannidou et al. 2014; Monteiro and Freire 2012). This paper aims to fill the gap in the scientific literature regarding the environmental impact of earth-based construction methods compared to conventional wall configurations in Iran. It focuses on a fundamental component of the structure: the load bearing (LB) walls.

Thus, this paper presents a simplified LCA and LCC for an single-family low-cost house comparing four conventional and 18 earth-based LB wall solutions aimed at identifying environmentally preferable solutions. Based on this, the life cycle analysis of a single building was examined from a construction-focused viewpoint, encompassing stages A1–A4. Cradle-to-site analysis is applied to several walling methods, considering all processes, from the raw material extraction through the production phase and the transportation of the end product to the site. With a functional unit of 1 m^2 of a wall assembly, this study can be used to compare and analyze the system in the future while accounting for operational considerations. In addition, ranking of comparing solutions and presenting acceptable alternatives will be presented. Using the results, this study will facilitate the future promulgation of regulations allowing architects and engineers to select adequate and sustainable wall systems.

2 Materials and methods

This research methodology is composed of three main sections; the first is the description of an affordable housing unit as a case study. The structure of the case building is supported by load-bearing walls, which are analyzed in this paper, as presented in Table 1. Then, data collection and life cycle inventory for alternative walling methods are considered, where a selection criteria (will be described in Sect. 2.2) is used to identify all wall configurations. Thirdly, a simplified LCA and a life cycle cost analysis (LCC) are being investigated. Using equal weights for each of the two categories, a scoring system is developed, and LB walls are ranked based on their final score.

2.1 Description of the case study

The geographical area of the present study is Ardakan County (32°18′36″ N, 54°01′03″ E), one of the largest

counties in Yazd Province, located in the middle of the central desert of Iran. A case study is derived from thesis research done by the first author, which was undertaken to propose a model of an affordable housing for Afghan refugees in Yazd, Ardakan as one of the most significant transitional settlements in Iran.[1] The main objective of the thesis was to investigate a passively and affordably designed housing unit (ground floor area of 96.75 m^2 and wall height of 3 m), with an earthen structure (adobe). This research suggested a common housing type for refugee families, as the extended family type is still going on among them and proposed a solution to help the Iranian government put the displaced community on the road to permanent housing.

2.2 Data collection for wall alternatives

Economic feasibility and environmental impacts are the primary criteria and alternative construction methods. Thus, it is essential to use and develop low-cost and low-carbon solutions to address these challenges. In order to carry out a comparative assessment, the calculations were performed for conventional and earth-based walling systems, so 22 LB wall systems were selected; four of them are conventionally used in Iranian low-cost housing, while the other 18 walls are classified into prevalent earthen construction systems: adobe, rammed earth, and compressed earth block. Each of the LB wall systems included in this LCA and LCC was analyzed according to the constituent materials, as detailed in the following subsections.

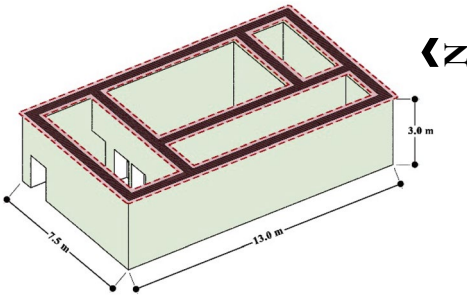#### 2.2.1 Conventional construction techniques

As a primary concern with affordable housing, costs must be kept to a minimum. Over the last decades, the government of Iran has tried to deal with low-cost housing by implementing some housing development patterns such as "supportive" housing, "rental" housing, "social" housing, and "Mehr" housing (Sobhiyah and Radaiee 2015). These examples of low-cost housing in Iran are mainly constructed with fired brick (FB, $10 \times 20 \times 5$ cm^3), ceramic hollow block (CB, $20 \times 20 \times 10$ cm^3), autoclaved aerated concrete (AAC, $20 \times 60 \times 20$ cm^3) block, and concrete masonry block (CMU, hollow-celled, $20 \times 20 \times 10$ cm^3), which are considered in the present research as conventional construction techniques. The wall configurations used for this method were developed based on the NBRI,[2] where construction operations

---

[1] It is important to highlight that only the schematic design of the case study has been derived from the first author's thesis, not the detailed designed prototypes.

[2] NBRI consists of 22 issues covering all the legal, technical, and executive regulations from design to construction. All new buildings in Iran must be aligned with NBRI issues.

Table 1 Based case affordable housing unit description

Description
Load Bearing walls (External & Internal)

should be designed, implemented, and supervised in accordance with this technical, executive, and legal guideline (NBRI 1390). The 9th issue[3] of NBRI has established the minimum thickness for of the load-bearing (LB) walls of buildings as 0.2 m (NBRI 1392).

A building wall is not only a single-component load-bearing wall, but it also commonly consists of many layers in order to meet comfort standards. Thus, a wall configuration, regardless of its primary structure, has exterior and interior plaster layers depending on whether it is internal or external. For the interior face of conventional walls, interior plaster is gypsum plaster (GP) of 1 cm thickness and a 0.2-cm final finishing layer (GP. F), which is in direct contact with the habitable space. The indoor substrate is 2 cm of a combination of gypsum and sand (GP. S), plastered before the finishing layer. This mortar is cheaper, because of the lower price of sand. FB, AAC, CB, and CMU as the structure are covered with three cement-based layers in the outdoor surface. The external walls are composed of cement mortar (CM) as the outdoor substrate with a general ratio of 1:3 (cement:sand mix) and a thickness of 1.5 cm followed by a 1-cm cement plaster (CP) (1:1:6 cement:lime:sand mix), which helps provide a smooth surface for the finishing layer. Outdoor finishing is 0.3 cm of cement plaster (CP. F) with a ratio of 1:1/2:4 1/2 (cement:lime:sand mix). The configuration of the conventional walls is shown in Table 2.

2.2.2 Earth-based construction techniques

In Ardakan, with desert climate — cold winters and hot-dry summers — selecting walling construction techniques require not only consideration of the cost to meet the low-cost criterion, but also common local construction methods that are environmentally efficient. Backing on the historical

architecture of the desert part of Iran, Ardakan highlights the potential of earthen architecture to be used for constructing affordable residential buildings (Dormohamadi and Farahza 2013). Earthen materials are abundant and locally available materials that are used without requiring extensive skills or tools and are primarily associated with low cost, rapid pace, and low environmental impacts (Racusin and McArleton 2012).

The present study investigates the most common earthen construction techniques, namely adobe, rammed earth, and compressed earth block, which are divided usually into two types: stabilized and unstabilized materials. Due to the lack of a local database in Iran, data on embodied carbon coefficients (EC) were obtained from the inventory of carbon and energy (ICE). However, there is limited data for earthen materials, and in the absence of required data, information is derived from the literature review. Table 3 shows eight papers selected among the literature reviewed — including references mentioned in Table 3 and Ben-Alon et al. (2021); Narayanaswamy et al. (2020); Mateus et al. (2020); Oti and Kinuthia (2012); Dabaieh et al. (2020) — based on the goal and scope of the paper in assessing embodied carbon and system boundary; thus, all selected papers have studied carbon dioxide equivalent (CO_2eq) emissions during the embodied stage with a system boundary from cradle to site (A1–A4), which is the same as this study. The functional unit was converted to that of the present paper if needed.

Earth construction techniques have two main limitations: If the earth used to manufacture them is not suitable, their compressive strength will not be sufficient to meet structural requirements (Ouedraogo et al. 2020), and regardless of the type of earth used in their manufacture, these materials have some durability issues: They degrade under certain atmospheric conditions, particularly when they come into contact with water (Laborel-Préneron et al. 2017).

Both limitations can be minimized by using stabilizing methods that enhance their strength and durability by improving their physical–mechanical properties

---

[3] Design and construction of buildings with reinforced concrete.

Table 2 Configuration of the conventional wall alternatives. There is an acronym list on the left side of the table

Wall type / Thickness / cm			Fired Brick 1	AAC 2	CB 3	CMU 4
Indoor finishing	CL.F	0.3				
	GP.F	0.2				
Indoor substrate	GP.S	3				
	GP	1				
	CL.P	1.5				
Structure	AAC	20				
	FB	20				
	CMU	20				
	CB	20				
	RE	60				
	SA	40				
	CEB	30				
Outdoor substrate	CM	1.5				
	CP	1				
	CL.P	1.5				
Outdoor finishing	CP.F	0.3				

Internal wall — Fired Brick: 26 cm; AAC: 27 cm; CB: 26 cm; CMU: 27 cm.
External wall — Fired Brick: 26 cm; AAC: 26 cm; CB: 26 cm; CMU: 26 cm.

(Dormohamadi and Rahimnia 2020). Many studies have been conducted regarding earthen materials focusing on both chemical and physical stabilizations (Guillaud et al. 1995; Rigassi 1985; Toure et al. 2017), and different additives have been used in the stabilization of earthen materials: from natural substances like straw (Aranda-Jiménez and Suárez-Domínguez 2014) to industrial byproducts and geopolymers (Narayanaswamy et al. 2020). Despite this, Portland cement has always been the most widely used stabilizer (Elahi et al. 2020; Houben and Guillaud 2008). Lime (both aerial and hydraulic) is also commonly used in stabilizing earthen materials (Malkanthi et al. 2020), which has a much lower environmental impact than Portland cement (Cabrera et al. 2020).

The environmental impacts of cement manufacture, particularly carbon dioxide emissions, have led researchers to explore alternative binders for concrete and stabilized earth materials in recent years. One alternative approach is alkali-activated (A-A) binders, also known as geopolymers[4] (Narayanaswamy et al. 2020). Alkali-activated materials offer the opportunity to reduce carbon dioxide emissions during manufacture, in comparison to cement and lime (Narayanaswamy et al. 2020).

Stabilized earth construction, including compressed earth masonry units and rammed earth walls, has become well-established as a contemporary building material in many countries (Narayanaswamy et al. 2020). Thus, to present a comprehensive life cycle assessment, this study will consider both unstabilized and stabilized earthen materials. In this paper, a variety of stabilizers are considered, including straw, cement, and lime, as well as alkali-activators, such as fly ash[5] (FA), ground granulated blast slag[6] (GGBS), sodium silicate (SS), sodium hydroxide (NaOH), and calcium hydroxide (CH). The following subsections include an overview of the earth-based walling methods considered in this work: adobe, rammed earth, and compressed earth block. Table 4 illustrates the physical characteristics of the walls.

Adobe wall Unfired clay bricks or adobes were typically used as load-bearing materials in masonry structures. They are usually produced by mixing clay/silt-rich soil, stabilizers like organic fibers (e.g., straw or animal hair) to primarily improve the mechanical properties, and water to a plastic consistency. This study applies the figure of CO_2eq for stabilized adobe brick (SA) using wheat straw as fiber additive taken from Christoforou et al. (2016). The soil to straw volumetric reference composition of adobe bricks investigated in this study comprises 70% clay rich soil and 30% straw (Christoforou et al. 2016). The scenario of this study considered the on-site production of adobe bricks using locally available soil and transported straw (Christoforou et al. 2016).

[4] Alkali-activated materials are produced by a reaction of aluminosilicates under alkaline conditions (Provis 2018).

[5] A by-product of coal combustion.

[6] A slightly treated by-product of iron and steel production commonly used as a supplementary cementitious material in concrete.

Table 3 Sources of selected earthen materials

Name			Functional unit	System boundary	Database	Analyzing software	Context	Additive	Embodied carbon	Ref
Clay plaster	Unstabilized	CL.F	$1 \, m^2$ of wall (0.3 cm)	Cradle-to-gate	Local data and Ecoinvent[a]	SimaPro	Italy	Vegetable origin	0.34 kg CO_2eq	Meliá et al. (2014)
		CL.P	$1 \, m^2$ of wall (1.5 cm)	Cradle-to-gate	Local data and Ecoinvent	SimaPro	Italy	Straw	0.88 kg CO_2eq	Meliá et al. (2014)
Rammed earth	Unstabilized	USRE	-	Cradle-to-gate	ICE[b]	-	UK	-	0.024 kg CO_2eq	G. P. Hammond et al. (2011a, b)
	Stabilized	SRE	-	Cradle-to-gate	ICE	-	UK	5% cement	0.061 kg CO_2eq	G. P. Hammond et al. (2011a, b)
		SRE	-	Cradle-to-gate	ICE	-	UK	6% cement + 2% lime	0.083 kg CO_2eq	G. P. Hammond et al. (2011a, b)
		SRE	-	Cradle-to-gate	ICE	-	UK	8% GGBS + 2% lime	0.047 kg CO_2eq	G. P. Hammond et al. (2011a, b)
		SRE	-	Cradle-to-gate	ICE	-	UK	8% fly ash + 2% lime	0.041 kg CO_2eq	G. P. Hammond et al. (2011a, b)
		SRE	$1 \, m^2$ of wall (60 cm)	Cradle-to-gate	Local data and Ecoinvent	SimaPro	Portugal	3% hydraulic lime	28.5 kg CO_2eq	Fernandes et al. (2019)
Compressed earth block	Uncompressed	SA	1 kg of adobe (9 bricks: $30 \times 45 \times 5 \, cm^3$)	Cradle-to-site	Local data and Gabi	Gabi	Cyprus	70% clay rich soil + 30% wheat straw	0.00176 kg CO_2eq	Christoforou et al. (2016)
	Compressed/ stabilized	A-A CEB	1 hollow-block: $39 \times 19 \times 19 \, cm^3$	Cradle-to-gate	Ecoinvent and US-LCI	Quantis Suite[c]	United States	1% sodium silicate + 2.5% sodium hydroxide	1.03 kg CO_2eq	Dahmen et al. (2018)
		Cement SCEB	1 hollow-block measuring $39 \times 19 \times 19 \, cm^3$	Cradle-to-gate	Ecoinvent and US-LCI	Quantis Suite	USA	4% cement	0.95 kg CO_2eq	Dahmen et al. (2018)
		A-A CEB	$1 \, m^2$ of wall, CEB measuring $10 \times 14 \times 29 \, cm^3$ (30 cm)	Cradle-to-gate	US-LCI and Ecoinvent	SimaPro	United States	7% calcium Hydroxide	35.74 kg CO_2eq	Roux Gutiérrez et al. (2015)
		Lime SCEB	$1 \, m^2$ of CEB wall (30 cm)	Cradle-to-gate	Local data and Ecoinvent	SimaPro	Portugal	6.5% lime	33.2 kg CO_2eq	Fernandes et al. (2019)
		SCEB	1 CEB measuring $15 \times 30 \times 7 \, cm^3$ with two 6 cm diameter holes	Cradle-to-gate	Ecoinvent	SimaPro	Santa Fe, Argentina	Cement 5% / Cement 10% / Cement 20% / Lime 5% / Lime 10% / Lime 20%	0.231 kg CO_2eq / 0.416 kg CO_2eq / 0.787 kg CO_2eq / 0.228 kg CO_2eq / 0.415 kg CO_2eq / 0.787 kg CO_2eq	Cabrera et al. (2020)
	Compressed/ unstabilized	USCEB	1 CEB measuring $15 \times 30 \times 7 \, cm^3$ with two 6 cm diameter holes	Cradle-to-gate	Ecoinvent	SimaPro	Santa Fe, Argentina	-	0.0453 kg CO_2eq	Cabrera et al. (2020)

[a] A comprehensive global database developed by a not-for-profit association

[b] Inventory of carbon and energy

[c] An LCA software developed in Switzerland

Table 4 Configuration of the earth-based wall alternatives. There is an acronym list on the left side of the table.

Acronym list (left side):

Category	Acronym	Thickness (cm)
Indoor finishing	CL.F	0.3
Indoor finishing	GP.F	0.2
Indoor substrate	GP.S	3
Indoor substrate	GP	1
Indoor substrate	CL.P	1.5
Structure	AAC	20
Structure	FB	20
Structure	CMU	20
Structure	CB	20
Structure	RE	60
Structure	UA	40
Structure	CEB	30
Outdoor substrate	CM	1.5
Outdoor substrate	CP	1
Outdoor substrate	CL.P	1.5
Outdoor finishing	CP.F	0.3

Wall alternatives (right side):

Wall type	Sub-type	No.	Thickness	Stabilizer
Adobe	SA	5	Internal: 43cm / External: 44	30% Straw
Rammed Earth	URE	6	60 cm	-
Rammed Earth	SRE	7 (SRE1)	60 cm	5% Cement
Rammed Earth	SRE	8 (SRE2)	60 cm	3% Lime
Rammed Earth	SRE	9 (SRE3)	60 cm	6% Cement / 2% Lime
Rammed Earth	SRE	10 (SRE4)	60 cm	8% GGBS / 2% Lime / 8% Fly Ash
Rammed Earth	SRE	11 (SRE5)	60 cm	2% Lime
Compressed Earth Block	UCEB	12	30 cm	-
Compressed Earth Block	SCEB	13 (SCEB1)	60 cm	4% cement
Compressed Earth Block	SCEB	14 (SCEB2)	60 cm	7% CH
Compressed Earth Block	SCEB	15 (SCEB3)	60 cm	6.5% lime
Compressed Earth Block	SCEB	16 (SCEB4)	60 cm	5% cement
Compressed Earth Block	SCEB	17 (SCEB5)	60 cm	10% cement
Compressed Earth Block	SCEB	18 (SCEB6)	60 cm	20% cement
Compressed Earth Block	SCEB	19 (SCEB7)	60 cm	5% lime
Compressed Earth Block	SCEB	20 (SCEB8)	60 cm	10% lime
Compressed Earth Block	SCEB	21 (SCEB9)	60 cm	20% lime
Compressed Earth Block	SCEB	22 (SCEB10)	60 cm	1% SS 2.5% NaOH

The adobe wall configuration in this study uses two different plaster layers: a base (leveling) plaster and a finishing plaster. This data are derived from a comparative study of the environmental performances of conventional (hydraulic lime and cement) and earth plasters done by Melià et al. in 2014. The earthen base plaster mixes Italian natural materials: clay, sand, and vegetal fibers (rice straw). Finishing plaster is an indoor product used to coat vertical and horizontal surfaces. It is a mix of clay, sand, and a vegetal additive — a food-grade, semi-synthetic compound used as a rheology modifier and water retention agent (Melià et al. 2014). The stabilized adobe wall, as illustrated in Table 4, includes the following layers, listed from interior to exterior: 0.3 cm clay finishing plaster (CL.F), 1.5 cm clay plaster (CL.P), 40 cm adobe structure consisting of 2 bricks, each measuring $20 \times 20 \times 5$ cm, and finally 1.5 cm clay plaster.

Rammed earth wall Rammed earth (RE) requires mainly clay-rich soil, sand, and gravel, without fiber, and a small amount of water for optimal compaction (Ben-Alon et al. 2021). This study compares the environmental performance of six rammed earth solutions, one of which is unstabilized (URE), while the others are stabilized (SRE) with cement, lime, and two alkali-activators, namely fly ash and GGBS. RE materials using alkali-activators as alternatives to cement stabilization possess adequate structural and durability characteristics for low-rise construction (Meek 2020; Meek et al. 2021).

The data to analyze the CO_2eq of target LB walls are obtained from ICE and a study by Fernandes et al. (2019). The rammed earth wall section, illustrated in Table 4, was designed according to common practice and code requirements (NMAC 2015). Rammed earth walls are mostly 60 cm thick and assumed to have no plaster (Table 4), which is the common practice to achieve the desired aesthetic effect of rammed earth components (Ben-Alon et al. 2021).

Compressed earth block Compressed earth block or CEB is masonry manufactured with a mixture of raw earth and a stabilizer, like lime, cement, asphalt, or gypsum, using the compression or pressing of the combination inside a mechanical or hydraulic press (Roux Gutiérrez et al. 2015). CEB masonry provides better durability and strength than adobe structures, and the units of CEB masonry can be industrialized (Villa 2018). This research conducts a comparative study in evaluating the environmental properties of an unstabilized CEB wall (USCEB) (Cabrera et al. 2020), eight CEB walls (SCEB) stabilized with different percentages of lime and cement (Cabrera et al. 2020; Dahmen et al. 2018; Fernandes et al. 2019), as well as two alkali-activated walls with industrial precursors namely sodium silicate (SS), sodium hydroxide (SH), and calcium hydroxide (CH) (Dahmen et al. 2018; Roux Gutiérrez et al. 2015). As shown in Table 4, CEB walls with bricks measuring $15 \times 30 \times 9$ cm are 30 cm thick and the same as RE walls, have no plaster.

2.3 LCA methodology

To determine the environmental impact (EI) of alternative walls, a process-based life cycle assessment (LCA) based on the LCA framework stated in the ISO 14040 series is conducted (IOFS 2006a). The following subsections will include four steps: (1) goal and scope, (2) life cycle inventory (LCI), (3) life cycle impact assessment (LCIA), and (4) interpretation of results (IOFS 2006b). To achieve the study's purpose, the goal and scope were identified in the first step. Some elements of the study were included, such as the system boundary and functional units. In the second step, the LCI was set up, where the data were generated. Afterward, the LCIA was performed, in which the impact category was selected. Finally, the interpretation of the results was undertaken to establish a comparative study between carbon dioxide equivalent (CO_2eq) emissions for the two investigated walling categories, conventional and earthen construction methods.

2.3.1 Goal and scope definition

The aim of this study is to quantitatively assess the environmental impacts and cost efficiency of 22 alternative load-bearing walling systems for the given low-cost housing model and to determine whether and to what extent earth construction techniques can assist in saving money and reducing greenhouse gas emissions in the context of Iran. Four conventional (industrial) wall assemblies are compared with 18 earthen walling methods in the study. Conventional construction techniques have been adopted as the base cases, because they are solutions widely used in Iranian low-cost building practices.

This study was motivated by the lack of literature on the environmental and cost benefits of earthen materials in Iran. The application of this study is to achieve low-carbon, sustainable built environments by mitigating the environmental impacts and clarifying the hotspots of the studied wall configurations (Pakdel 2022). A further objective of this study is to investigate sensitivity analysis and how transportation (A4) affects the environmental impact and cost–benefit of the different walling systems.

Due to the lack of a database to conduct whole-life carbon assessments in Iran, results might vary widely depending on the different datasets used. Therefore, for developing the LCI, this study uses the published LCA studies, and ICE developed by Bath University. There have been studies in Middle East countries and Iran that demonstrate the usefulness and reliability of this database (Hammond et al. 2011a, b; Pakdel et al. 2021).

Some simplifications have been employed in the LCA model. Based on the approach used in other LC studies of similar scope (Galán-Marín et al. 2015; Nemry et al. 2010), the embodied energy as well as the operational stage have not been included.

Functional unit (FU) This functional unit is a physical element; it is easy to conduct, understand, and compare. According to previous studies (Chau et al. 2015; Valencia-Barba et al. 2021), this criterion has assured reliable results from functional units. The functional unit used for this work is 1 m^2 of load-bearing wall for the low-cost housing unit.

System boundary (SB) The study covers the life cycle from cradle to construction site, including raw materials supply (A1), transport (A2), manufacturing (A3), and transport to the construction site (A4) (Lutzkendorf and Balouktsi 2016). The system boundary is defined following the environmental product declaration for construction products. Nevertheless, the LCI considers material production and transportation, rather than operation (B1–B7) or end-of-life (C1–C4). During post-construction life cycle stages in Iran, there is a great deal of variability and uncertainty, which, in turn, led to the establishment of the boundary between systems A1 and A4 (i.e., cradle to the site). This system boundary provides tools for researchers to contribute to a better understanding of the construction stages (Gámez-García et al. 2018). Figure 1 illustrates the system boundary of this research.

Fig. 1 System boundaries for the proposed study, which encompasses A1-A4
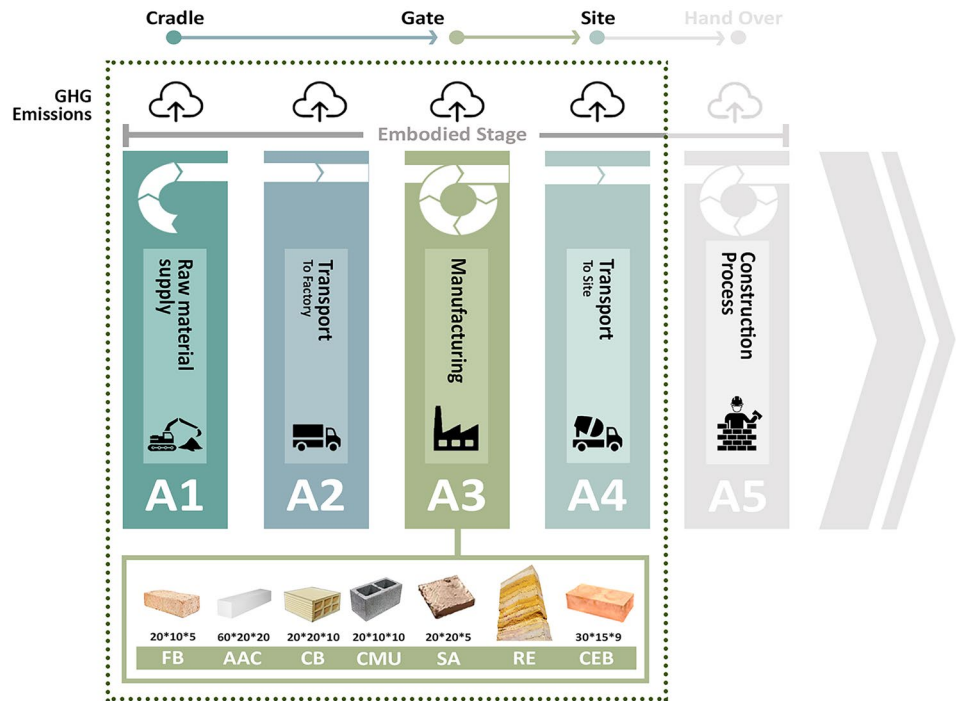
2.3.2 Life cycle inventory analysis

The life cycle inventory (LCI) of the study was carried out after the samples and their physical characteristics had been defined. Then, all the components required to build each type of wall were quantified independently. Tables 2 and 5 detail the inventory analysis for each constituent material in each of the wall assemblies for stages A1–A3 and A4. The material volumes calculated for each wall include the whole required for the walling of the prototype.

Material production (A1–A3) In order to assess the product stages (A1–A3), Revit Architecture software was used to prepare a BIM model and a bill of quantity was extracted. Accordingly, material quantities (by weight) required to construct each element of the LB wall were determined and multiplied by embodied carbon coefficients (ECCs) to obtain the total carbon of the structure. The ECCs of material production have been calculated using the following equation by taking into account the density of materials and carbon emission coefficients:

$$EI_{A1-A3} = \sum_{i=0}^{n}(EC_i \times V_i) \times 10^{-3} \qquad (1)$$

where EI is an environmental impact for material production i in kilograms of carbon dioxide equivalent per kilogram material, EC_i is carbon emission coefficients in carbon dioxide equivalent, V_i is the quantity of material in kilograms, and n is the number of materials.

The calculation results were expressed in metric tons of carbon dioxide equivalent, which represents the main unit of the potential impact of the global warming category. Table 5 shows the numbers and the quantities of materials for each alternative wall proposed for the studied case within the boundaries established (A1–A3, and A4).

Transportation (A4) A4 is evaluated based on the weight of the materials (in 1000 kg/1 tonnes) and distance from the supplier to the site (in kilometers/km); thus, the number of travels and fuel consumption were accounted. According to the information from consulting with different providers based in Ardakan, materials are mainly provided from different suppliers inside of the Yazd Province; however, in some cases, including straw or alkali-activators, they are obtained from outside the province. Distances were calculated by starting with the location of each material's supplier, moving to Ardakan's headquarters, and finishing on the construction site. Using geo-referenced maps and Google Maps' route optimizer, distances were calculated. Even though the vehicle was empty, the return distance was included in the calculation. Following this procedure, ten supplier companies (in or out of Ardakan City) and three distributors (in the city) were selected, and their two-part distance was estimated, as presented in Fig. 2.

Details from Table 6 and Eq. (2) are used for the evaluation of transportation EC in liter-kilometer for each wall:

Table 5 Life cycle inventory for each load-bearing wall

Wall element	Material/process	Unit	FB	AAC	CB	CMU	UA	URE	SRE1	SRE2	SRE3	SRE4	SRE5
			1	2	3	4	5	6	7	8	9	10	11
A1–A3	IF[a] CL.F	kg	–	–	–	–	686.2	–	–	–	–	–	–
	GP.F	kg	1568	1556.8	1556.8	1568	–	–	–	–	–	–	–
	IS[b] GP.S	kg	3494.4	7005.6	7005.6	3494.4	–	–	–	–	–	–	–
	GP	kg	313.6	302.4	302.4	313.6	–	–	–	–	–	–	–
	CL.P	kg	–	–	–	–	8891.4	–	–	–	–	–	–
	S[c] AAC	m³	–	29962.5	–	–	–	–	–	–	–	–	–
	FB	kg	62865	–	–	–	–	–	–	–	–	–	–
	CMU	kg	–	–	–	46939.2	–	–	–	–	–	–	–
	CB	kg	–	–	21746.4	–	–	–	–	–	–	–	–
	RE	kg	–	–	–	–	–	174893.4	174893.4	174893.4	174893.4	174893.4	174893.4
	SA	kg	–	–	–	–	118566.6	–	–	–	–	–	–
	CEB	kg	–	–	–	–	–	–	–	–	–	–	–
	Ad[d] Cement	kg	–	–	–	–	–	–	8744.67	–	10493.6	–	–
	Lime	kg	–	–	–	–	–	–	–	5246.802	3497.868	3497.868	3497.868
	GGBS	kg	–	–	–	–	–	–	–	–	–	13991.47	–
	FA	kg	–	–	–	–	–	–	–	–	–	–	13991.47
	Straw	kg	–	–	–	–	35569.98	–	–	–	–	–	–
	SS	kg	–	–	–	–	–	–	–	–	–	–	–
	NaOH	kg	–	–	–	–	–	–	–	–	–	–	–
	CH	kg	–	–	–	–	–	–	–	–	–	–	–
	OS[e] CM	kg	7961	7923	7923	7961	–	–	–	–	–	–	–
	CP	kg	4480	4464	4464	4480	–	–	–	–	–	–	–
	OF[f] CP.F	kg	1344	1344	1344	1344	–	–	–	–	–	–	–
A4	EW Transportation	t km	1342	1152.8	1853.6	1281.6	3338.4	525.6	1048.8	636.8	1421.6	2093.6	888.8

Wall element	Material/process	Unit	UCEB	SCEB1	SCEB2	SCEB3	SCEB4	SCEB5	SCEB6	SCEB7	SCEB8	SCEB9	SCEB10
			12	13	14	15	16	17	18	19	20	21	22
A1–A3	IF[g] CL.F	kg	–	–	–	–	–	–	–	–	–	–	–
	GP.F	kg	–	–	–	–	–	–	–	–	–	–	–
	IS[h] GP.S	kg	–	–	–	–	–	–	–	–	–	–	–
	GP	kg	–	–	–	–	–	–	–	–	–	–	–
	CL.P	kg	–	–	–	–	–	–	–	–	–	–	–
	S[i] AAC	m³	–	–	–	–	–	–	–	–	–	–	–
	FB	kg	–	–	–	–	–	–	–	–	–	–	–
	CMU	kg	–	–	–	–	–	–	–	–	–	–	–
	CB	kg	–	–	–	–	–	–	–	–	–	–	–

Table 5 (continued)

Wall element		Material/process	Unit	UCEB 12	SCEB1 13	SCEB2 14	SCEB3 15	SCEB4 16	SCEB5 17	SCEB6 18	SCEB7 19	SCEB8 20	SCEB9 21	SCEB10 22
		RE	kg	-	-	-	-	-	-	-	-	-	-	-
		SA	kg	-	-	-	-	-	-	-	-	-	-	-
		CEB	kg	91060.2	91060.2	91060.2	91060.2	91060.2	91060.2	91060.2	91060.2	91060.2	91060.2	91060.2
	Ad[j]	Cement	kg	-	3642.408	-	-	4553.01	9106.02	18,212.04	-	-	-	-
		Lime	kg	-	-	-	5918.913	-	-	-	4553.01	9106.02	18212.04	-
		GGBS	kg	-	-	-	-	-	-	-	-	-	-	-
		FA	kg	-	-	-	-	-	-	-	-	-	-	-
		Straw	kg	-	-	-	-	-	-	-	-	-	-	-
		SS	kg	-	-	-	-	-	-	-	-	-	-	910.602
		NaOH	kg	-	-	-	-	-	-	-	-	-	-	2276.505
		CH	kg	-	-	6374.214	-	-	-	-	-	-	-	-
	OS[k]	CM	kg	-	-	-	-	-	-	-	-	-	-	-
		CP	kg	-	-	-	-	-	-	-	-	-	-	-
	OF[l]	CP.F	kg	-	-	-	-	-	-	-	-	-	-	-
A4	EW	Transportation	t km	292	815.2	2664	403.2	1076.8	815.2	815.2	458.8	403.2	403.2	3850

[a]Indoor finishing
[b]Indoor substrate
[c]Structure
[d]Additives
[e]Outdoor substrate
[f]Outdoor finishing
[g]Indoor finishing
[h]Indoor substrate
[i]Structure
[j]Additives
[k]Outdoor substrate
[l]Outdoor finishing
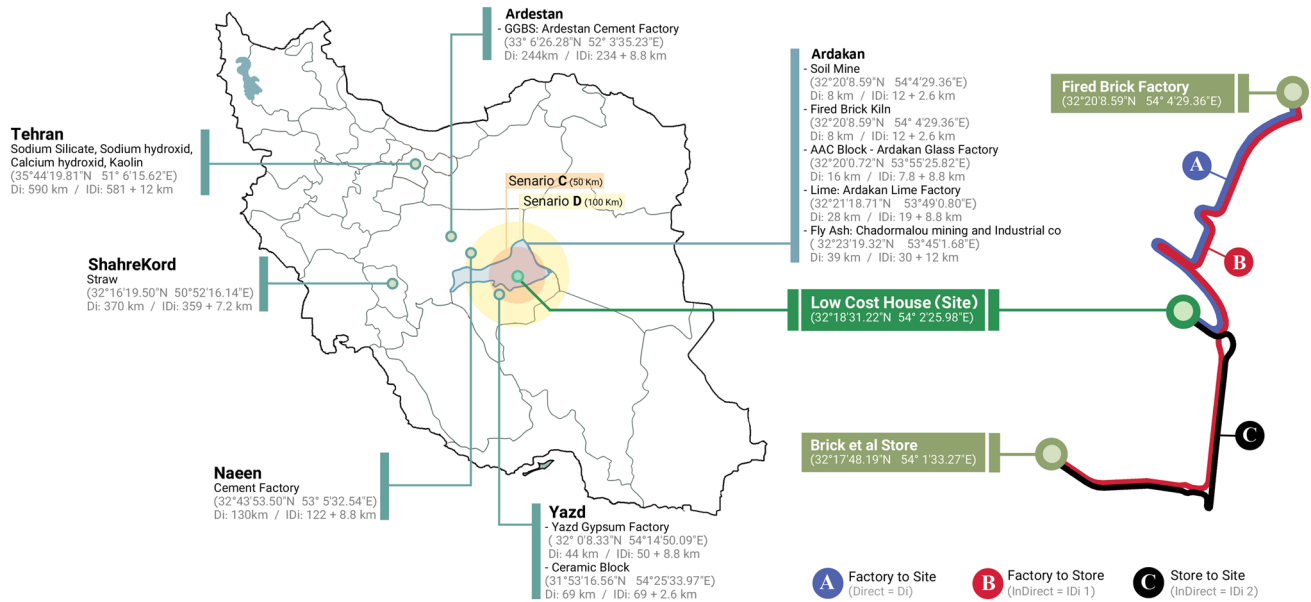
Fig. 2 The location of the construction site and suppliers, a schematic estimated distance from supplier to headquarters and then to the site

$$TF_{A4} = \sum_{i=1}^{n}(int(1 + \frac{W_{Mi}}{LVehicle_{Mi}}) \times D_{Mi} \times FV_{Mi} \times 2) \quad (2)$$

where TF_{A4} is total fuel consumption in the A4 stage, W_{Mi} is the quantity (weight) of the materials, $L\,Vehicle_{Mi}$ is the load capacity of the vehicle that carries material i, D_{Mi} is the distance traveled for each material in kilometers, and FV_{Mi} is the consumed fuel in the vehicle for transporting the material i in liter. For the transport of the components of the LB wall, the following lorries were considered: A diesel-powered 10-tonne truck is used for the transportation of high-quantity materials like those of structures; The use of a Euro 3 mini-truck with 5-tonne capacity was considered for the transportation of stabilizers, while a 2-tonne diesel-powered pickup is used to transport the other ancillary materials, namely alkali-activators. Each of the three vehicles consumes 69, 35, and 15-L diesel every 100 km, respectively. There is a Euro 4 standard for diesel in Iran (NIOPDC 2022). The final CO_2eq emission for the A4 stage will be calculated using Eq. (3). For final carbon emission calculations, Eq. (4) was used to calculate the A1–A4 stages.

$$EI_{A4} = TF_{A4} \times \text{ fuel conversion factor} \quad (3)$$

where EI_{A4} is the environmental impact for transportation of material in kilograms of carbon dioxide equivalent per kilometer distance, the fuel consumption is in liter-kilometer, and the fuel conversion factor is in kilograms of carbon dioxide equivalent. In the absence of local information, this study utilizes the average CO_2eq factor per liter-km recommended

by the UK government for company reporting, which is 2.7 kg CO_2/t km (Environment and Affairs 2021).

$$EI_{Final} = EI_{A1-A3} + EI_{A4} \quad (4)$$

EI_{A1-A3} is the carbon emissions at the A1–A3 stages, and EI_{A4} is the carbon emissions at the A4 stage.

2.4 Life cycle impact assessment (LCIA)

The LCIA compares the environmental impacts and risks associated with inventory results (IOFS 2006a). This impact assessment was conducted based on selected environmental impact factors that are relevant to the study's objectives and scope (IOFS 2006b). Environment impacts can be divided into three categories: ecosystem impacts, human impacts, resource depletion, and other subcategories. For the purpose of assigning LCI results to impact categories and calculating potential impact indicators, it is necessary to select an impact category for analysis. The following is a simplified comparison of carbon emissions based on Iran's international commitments to reduce GHG emissions.

A discussion of the highest and lowest EI in LB walls will be presented in this section. In addition, EI per each of the target life cycle stages (A1–A3, A4) and per each conventional wall's component is investigated. The final contribution of 22 wall configurations to GHG emissions can provide insight into EI mitigation opportunities. According to the results, USCEB has the highest environmental performance with 270.3 kg CO_2eq per functional

Table 6 Transportation data and fuel consumption for each wall alternative

	Wall type	Types of raw materials used	Total weight of each category	Distance	Vehicle type	Number of travels	Total fuel
			Tonne	km			Lit
1	FB	FB	62.97656	14.6	Truck	7	14,103.6
		Cement (CM, CP)	13.785	130.8	M.truck[a]	3	27,468
		Gypsum (GP.S, GP, GP.F)	5.376	58.8	Pick up	3	5292
2	AAC	Cement (CM, CP)	13.747	130.8	M.truck	3	27,468
		AAC	31.365	16.6	Truck	4	9163.2
		Gypsum (GP.S, GP, GP.F)	8.8648	58.8	M.truck	2	8232
3	CB	Cement (CM, CP)	13.785	130.8	M.truck	3	27,468
		CB	47.05076	71.6	Truck	5	49,404
		Gypsum (GP.S, GP, GP.F)	5.376	58.8	Pick up	3	5292
4	CMU	CMU	35.4934	130.8	Truck	4	72,201.6
		Cement (CM, CP)					
		Gypsum (GP.S, GP, GP.F)	8.8648	58.8	M.truck	2	8232
5	SA	Adobe	118.5666	14.6	Truck	12	24,177.6
		Straw	35.56998	366.2	Truck	4	202,142.4
		Earth (CL.P, CL.F)	9.5776	14.6	M.truck	2	2044
6	URE	RE	174.89	14.6	Truck	18	36,266.4
7	SRE1	Cement 5%	8.74467	130.8	M.truck	2	18,312
		RE	174.8934	14.6	Truck	18	36,266.4
8	SRE2	Lime 3%	5.246802	27.8	M.truck	2	3892
		RE	174.8934	14.6	Truck	18	36,266.4
9	SRE3	Cement 6%	10.493604	130.8	M.truck	3	27,468
		Lime 2%	3.497868	27.8	Pick up	2	1668
		RE	174.8934	14.6	Truck	18	36,266.4
10	SRE4	GGBS 8%	13.991472	242.8	M.truck	3	50,988
		Lime 2%	3.497868	27.8	Pick up	2	1668
		RE	174.8934	14.6	Truck	18	36,266.4
11	SRE5	Fly ash 8%	13.991472	42	M.truck	3	8820
		Lime 2%	3.497868	27.8	Pick up	2	1668
		RE	174.8934	14.6	Truck	18	36,266.4
12	UCEB	CEB	91.0602	14.6	Truck	10	20,148
13	SCEB1	Cement 4%	3.642408	130.8	Pick up	2	18,312
		CEB	91.0602	14.6	Truck	10	20,148
14	SCEB2	7% calcium hydroxide	6.374214	593	M.truck	2	83,020
		CEB	91.0602	14.6	Truck	10	20,148
15	SCEB3	6.5% lime	5.918913	27.8	M.truck	2	3892
		CEB	91.0602	14.6	Truck	10	20,148
16	SCEB4	Cmt. 5%	4.55301	130.8	Pick up	3	11,772
		CEB	91.0602	14.6	Truck	10	20,148
17	SCEB5	Cmt. 10%	9.10602	130.8	M.truck	2	18,312
		CEB	91.0602	14.6	Truck	10	20,148
18	SCEB6	Cmt. 20%	18.21204	130.8	Truck	2	36,100.8
		CEB	91.0602	14.6	Truck	10	20,148
19	SCEB7	Lime. 5%	4.55301	27.8	Pick up	3	2502
		CEB	91.0602	14.6	Truck	10	20,148
20	SCEB8	Lime. 10%	9.10602	27.8	M.truck	2	3892
		CEB	91.0602	14.6	Truck	10	20,148
21	SCEB9	Lime. 20%	18.21204	27.8	Truck	2	7672.8
		CEB	91.0602	14.6	Truck	10	20,148

Table 6 (continued)

Wall type		Types of raw materials used	Total weight of each category	Distance	Vehicle type	Number of travels	Total fuel
			Tonne	km			Lit
22	SCEB10	1% sodium silicate	0.910602	593	Pick up	1	41,510
		2.5% sodium hydroxide	2.276505	593	Pick up	2	83,020
		CEB	91.0602	14.6	Truck	10	20,148

[a]Mini truck

unit, followed by SCEB7 with 335.5, and SCEB3 with 346 kg CO_2eq, respectively, while the least favorable construction method is SA with 3043.6 kgCO_2eq due to geographical limitations.

2.5 Life cycle cost (LCC)

It is essential to consider the cost of construction materials when selecting materials for affordable housing. Economic comparison of earth-based construction methods with conventional systems is thus highly relevant when assessing whether sustainable alternatives are likely to be adopted in the construction marketplace.

Based on the study's system boundary, it is beyond the scope of this study to examine the costs of heating and cooling throughout the life cycle, and the cost assessment only covers manufacturing and transportation. According to previous studies, a building's total Life Cycle Cost (LCC) is calculated as the sum of all costs associated with each phase of the building's life cycle (Atmaca 2016; Ioannidou et al. 2014). A cost estimate for each type of wall can be obtained using Eq. (5). According to this equation, in September 2022, 1 US dollar ($) equaled 316,200 Iranian rials.

$$\text{Cost}_{LB.W}(\$) = \frac{\text{Production cost} + \text{Transportation cost}}{\text{Currency}} \quad (5)$$

Materials costs were estimated based on official government price lists (1401 versions) published by Plan and Budget Organization (PBO 2022), as well as price estimates from different material stores in Ardakan City. Costs associated with transporting materials from the distributor to the construction site are calculated on the basis of tonne-kilometer. Figure 3 illustrates an additional charge for distances greater than 100 km and 300 km.

2.6 Scoring system

To understand the overall comparison between performances of different wall configurations for an affordable housing unit in Iran, a scoring section is developed. Few studies have established scoring tools to assess the final performance of their studied materials or construction methods (Dickson and Pavía 2021; Pakdel 2022). All walling systems are ranked based on their values for EC carbon and cost efficiency using RANK.EQ function syntax in Excel spreadsheets. The ranks in each category are assigned considering the best case as the reference and

Fig. 3 Cost of travel based on vehicle type and distance
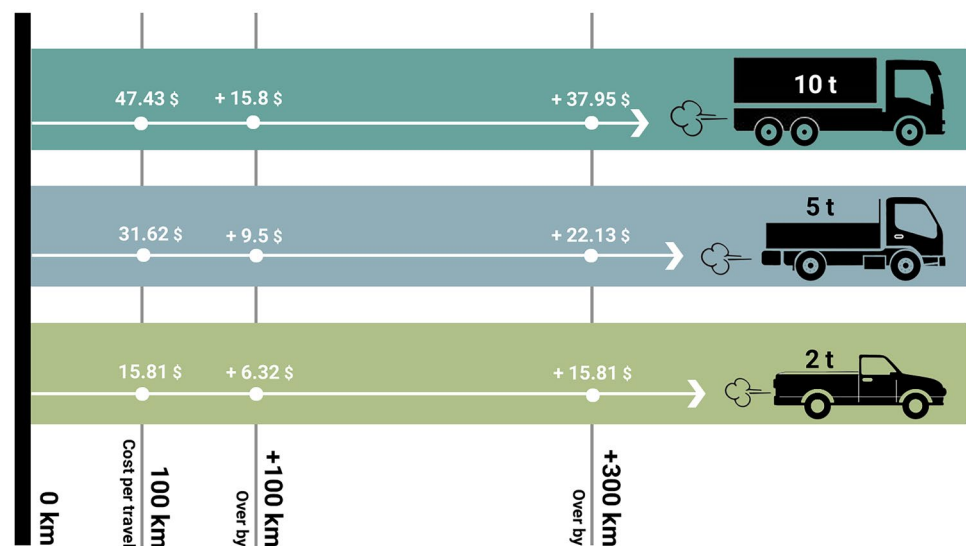
ordered from starting the lowest to the highest. Thus, the lowest embedded carbon walling material is the best case, and the rest were ordered simultaneously. It is important to note that the lower the EC and cost for each wall, the better its performance. Since the study aimed to evaluate affordable housing, the priority of ranking walls is life cycle cost and then EC. Walls with lower costs perform better. As such, walling systems are ranked in order of highest cost to lowest cost.

3 Results and discussion

In this part, the preliminary results and the analysis are presented in four main sub-sections.

3.1 Comparative assessment of environmental impacts

Life cycle impact assessments establish a connection between the primary inputs into a system and the potential environmental impacts of products and processes analyzed. To highlight the potential environmental advantages of using local earthen materials, a comparative LCA between unstabilized and stabilized earthen walling systems and conventional wall assemblies is carried out based on the functional unit of 1 m² of a wall. It should be noted that wall 8 (SRE2) stabilized with 3% lime is removed from the analysis as the EC output does not conform to other studied cases. It can be related to different reasons like the context, so wall eight is not considered in the subsequent analyses too. Figure 4 shows the results of CO_2eq emissions per A1–A3 stages for the 22 LB wall systems.

The best-performing wall was selected as a reference wall, wall 5 (SA). Based on the assumption that these walls are equivalent to the reference wall, the following four walling systems have been selected. Thus, the LB walls with the most favorable values were earth-based systems, including walls 5 (SA), 12 (UCEB), 6 (URE), 13 (SCEB1), and 22 (SCEB10), contributing to 0.62, 1.68, 4.2, 4.23, and 4.59 kg CO_2eq emissions, respectively. Two of these walls (6 and 12) are not stabilized made of pour soil, wall 5 is stabilized with straw as a low-carbon bio-based material, wall 13 is stabilized with the lowest amount of cement among studied cases, and wall 22 eliminates conventional cement using alkali-activators of sodium hydroxide and sodium silicate as stabilizers. The embodied carbon of the cement is significantly higher than that of NaOH and SS, due to the carbon released during the calcination phase of producing cement (Worrell et al. 2001).

As mentioned in Sect. 2.2.2., walls 10 (SRE4), 11 (SRE5), 14 (SCEB2), and 22 (SCEB10) use alkali-activated binders of GGBS, FA, CH, and NaOH plus SS, respectively, to eliminate cement. Due to the weight of rammed earth walls, which is substantially higher than adobe, CEB, and conventional building systems, ECs are not too low in walls 10 and 11. With a much lower weight of CEB, wall 14 shows almost the same EC as the latter; this can be explained by studying the chemical properties of the precursors.

In search of the most negative value for environmental performance, Fig. 4 illustrates the minimum value in walls 18 (SCEB6) and 21 (SCEB9), constituting 20% cement and 20% lime, respectively, and both emitting 29.22 kg CO_2eq. This is followed by 15.44 in wall 17 (SCEB5) and 15.41 in wall 20 (SCEB8); these walls are stabilized with 10% cement and 10% lime, respectively. According to Cabrera et al. (2020), the stabilization of CEB with lime or cement,

Fig. 4 CO_2eq emissions emitted per A1–A3 stages for each wall assembly
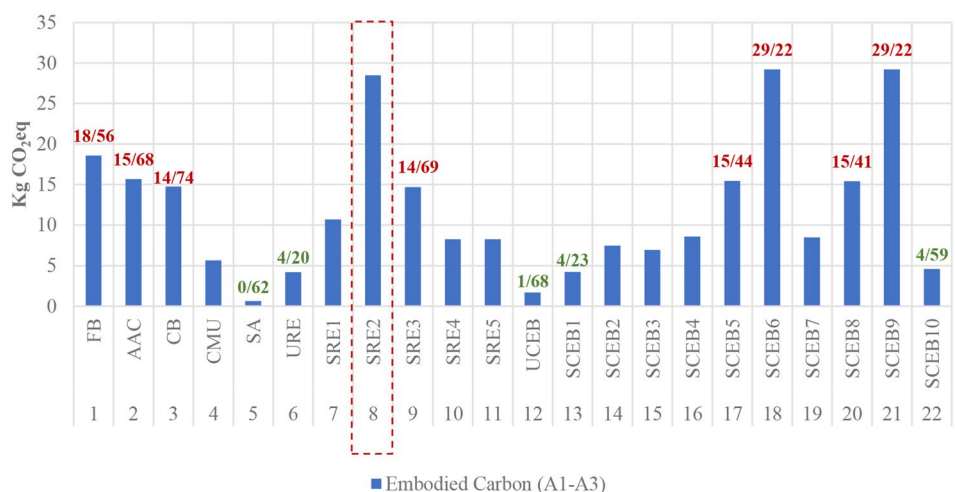
even in small amounts, has a great responsibility for adverse environmental impacts. Interestingly, Lime replacement with cement was not found to significantly reduce the environmental impact of CEB stabilization (Cabrera et al. 2020).

Three conventional walls, FB, AAC, and CB, are the next significant contributors to the EI with 18.56, 15.68, and 14.74 kg CO_2eq. The calcination process is responsible for most of the greenhouse gas emissions from the materials. In the case of FB, it is the energy required to heat the kiln causing CO_2 emissions, while in the case of AAC, CO_2 is emitted during the heating of the kiln, as well as during clinker production, an intermediate step in cement manufacture (Gibbs et al. 2001). Prior studies indicate that cement contributes 90.7% of the total embodied carbon of concrete blocks (Nisbet et al. 1997; NREL 2021). CO_2 emissions result from CB firing temperatures of over 1300 °C and the high carbonate content of their raw materials (limestone and clay) (Damtoft et al. 2008).

3.1.1 The EI per each life cycle stage and each component

The contribution of each module to the EC is illustrated in Fig. 5 to help us understand how each module impacts the environment. There is a significant difference in EC between the product stage (A1–A3) and the transportation stage (A4). According to previous research, most significant environmental impact occurs in the product stage (A1–A3), followed by the subsequent stage (A4) (Escamilla et al. 2018; Gámez-García et al. 2018; Valencia-Barba et al. 2021). Nevertheless, the results of this study indicate that module A4 is the largest contributor to the embodied carbon of each wall assembly. It is due to the lack of agricultural and industrial facilities in the studied area. Thus, most stabilizers for earth-based walling systems are not locally available and must be transported; so, material transportation to the site results in fuel consumption and environmental impacts in this module.

Consequently, the transport values stand out by contributing most to all systems. Figure 5 shows that A4 is the significant impact source, accounting for 98–99% of the carbon emissions of studied wall assemblies.

The contribution of A4 to EC of wall 5 is the most significant share among all cases with 617.58 kg CO_2eq, which is due to the long-distance traveled and the number of travels. The straw represents 30% of the total SA weight. Module impact is significantly impacted by the addition of this stabilizer. To reduce this, other local fibers could be used, or the fibers could only be used in critical situations to improve the consistency of the soil. The value of transportation EC for walls 22, 14, and 10, referred to as alkali-activated blocks, are following substantial proportions with 391.43, 279.12, and 240.58 kg CO_2eq. As shown in Fig. 2, obtaining alkali-activated stabilizers from outside the province requires long distances to be traveled. Both walls 18 and 21 have the same amount of stabilizers; however, the EC for wall 18 is significantly higher due to the cement factory's distance compared to the lime plant. On the other hand, the best values among all LB walls are shown by unstabilized wall systems, with wall 12 presenting the least figure for A4. Wall 6 influences environmental performance more through material quantity than type; considering the thickness of the wall and the weight of the earth, transportation takes up a greater proportion of the budget.

3.1.2 Comparison of the total EI of different wall configurations

The comparison of total carbon dioxide equivalent per functional unit among all 22 wall systems is shown in Fig. 6. Overall, the difference in environmental performances of unstabilized earth-based materials on the one hand, and conventional and stabilized earthen wall assemblies on the other, stems mainly from direct CO_2 emissions during the

Fig. 5 CO_2eq emissions emitted per each life cycle stage for each wall assembly (A1–A3 and A4)
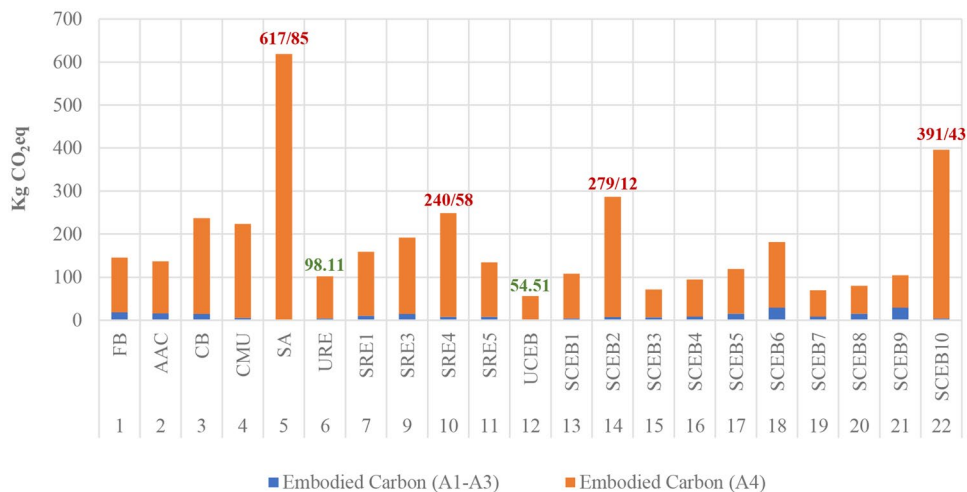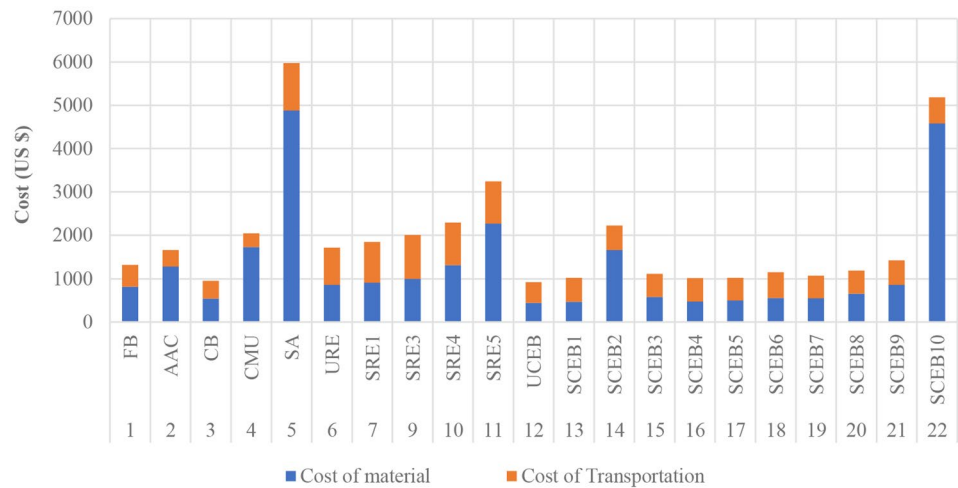
Fig. 6 Cost assessment at each stage of the life cycle

calcination process in cement manufacturing, heating the kiln, or burning of primary structural materials.

As shown, the unstabilized earth has a minimum contribution to the overall EI of the wall. This is also confirmed by Arrigoni et al. (2017) and Cabeza et al. (2013). In earth-based wall assemblies stabilized with less prevalent additives and hardly available materials in desert parts such as industrial and herbaceous additives, transportation EC is intriguingly higher than other walling systems. Therefore, wall configurations stabilized with even low amounts of alkali activators or straw are several times more carbon intensive than unstabilized ones. Greenhouse gas emissions for producing 1 FU of SA (3043.63 kg CO_2eq) are about 11 times more than UCEB (270.31 kg CO_2eq). According to Reddy and Jagadish (2003), in the case of earthen construction, transportation EC could be higher than that of product stage.

Excluding A4 module, herbaceous and alkali-activated stabilizers showed low impacts compared with cement and lime. This indicates that reducing and replacing cement and lime content are effective ways to reduce the embodied carbon, even where embodied energy of the alkali activators is similar (Dahmen et al. 2018).

3.2 Cost–benefit assessment

Life cycle cost is investigated in two subsections, including cost assessment per each life cycle stage and each component and total cost of different wall assemblies.

3.2.1 Cost assessment per each life cycle stage and each component

Figure 7 illustrates the detailed costs per life cycle stage for each LB wall sample. Materials are the most cost-demanding factor in every wall type, with SA and SCEB10 being the

most expensive types. The high figure for SA originates from the high cost of both straw and adobe, as straw is preferred to be used for animal feed in Iran, while producing adobe samples is labor-intensive. As shown in Fig 7, alkali activators used as stabilizers are another leading cost driver for stabilized earth blocks. Alkali-activated walls, namely walls 22, 11, 14, and 10, respectively, have the most significant figures for material cost among earth-based walls because geopolymers are expensive in Iran. Walls 16, 17, and 18, with 5%, 10%, and 20% cement, have a gradual price increase. A similar trend can be demonstrated for walls 19, 20, and 21 with 5%, 10%, and 20% lime. Although walls stabilized with cement and lime have lower figures compared to alkali-activated walls, the results show that replacing lime and cement with geopolymer alternatives has high-cost implications.

Overall, regarding earth-based walls, RE walls are much more cost-intensive than CEB configurations, as RE walls weigh more. In comparison to other LB walls, the UCEB wall has the lowest material cost. Conventional walling systems do not differ significantly in cost, while CMU and AAC, as cement-based types, are more expensive than FB and CB, which are burnt earth-based materials. It is important to note that transportation costs vary depending on each wall's weight. According to the results, CMU has the lowest transportation cost with $316.25, while RE walls and SA have the highest.

Figure 7 shows the initial cost of different walling materials. Again, it is evident that alkali-activated walls plus SA are more expensive alternatives than other stabilized earth-based walls. Alkali-activated stabilizers' availability and distribution should therefore be considered when assessing what benefits they represent in terms of reducing greenhouse gas emissions (Meek et al. 2021). Additionally, the main structures account for a significant portion of the overall costs of the prototype house walls.

Fig. 7 Construction cost for each constituent of walling assembles
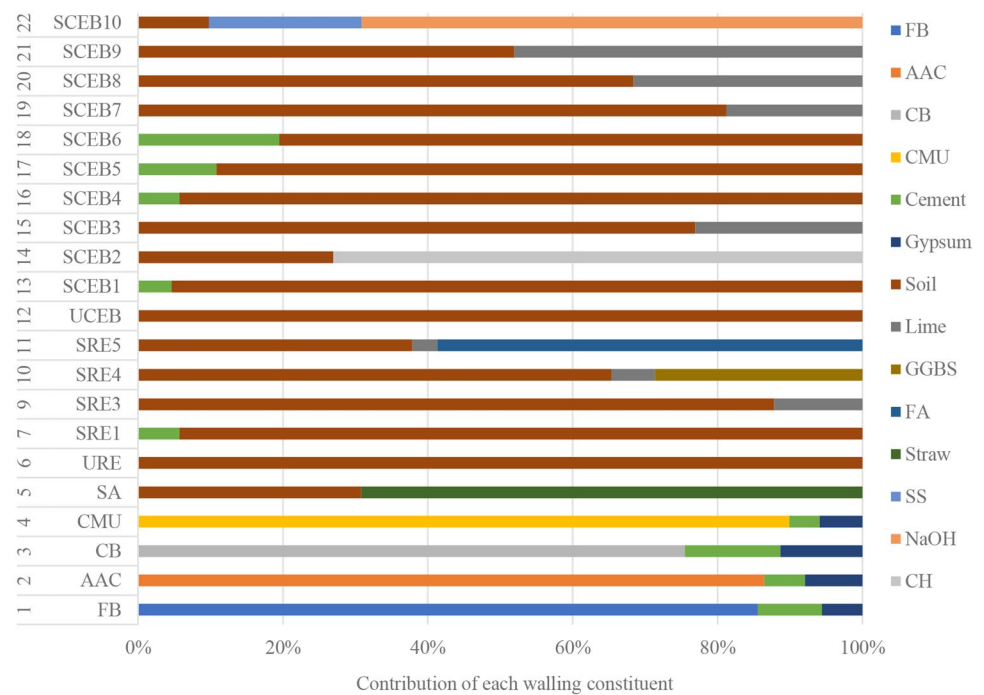
3.2.2 Total cost of different wall configurations

Figure 8 illustrates LB wall costs. UCEB is the lowest-cost beneficiary with $4.43, followed by SCEB4 (4.88), and SCEB1 (4.93). The most expensive wall is SA, with an average price of $29.41, followed by alkali-activated walls, SCEB10, SRE5, SRE4, and SCEB2.

3.3 Sensitivity analyses

An LCA model is subject to sensitivity analysis at the LCIA stage in order to assess the uncertainty of the model by creating hypothetical scenarios and examining their impacts. This analysis increases the reliability and robustness of the final result (IOFS 2006a; Pakdel 2022).

Many factors affect the uncertainty of an LCA (Pomponi et al. 2017). However, in the case of this research, the main limitation is the lack of local data and using different existing sources of data for earth-based materials. The results of those studies cannot be applied directly to other buildings outside the scope of their studies because the results are highly dependent on the geographical regions, different sources of data, the system boundaries, assessment methods, and building material types (Almeida et al. 2015), especially for non-conventional materials like earthen ones. The fact that the present study does not use actual data in a specific regional context may lead to a wide range of variability. Hence, the reduced accuracy of the results does not allow a transparent comparison between materials within the Yazd

context. The same type of issue was also addressed by Arrigoni et al. (2017).

As depicted in Fig. 5, the inputs with the greatest influence on the LCIA are the transportation distances of constituent materials, the average wall thickness, and the number of acquired stabilizers. Furthermore, various factors affect the transportation distance of construction materials in each project, such as geographical limitations, material distributors, and price. This sensitivity analysis assesses direct and indirect transportation, and the impact of site location on carbon dioxide emissions, and cost benefits of different walling systems.

Hence, the sensitivity analysis is illustrated through four scenarios based on different travel distances. The base route model (in the "Rammed earth wall" section) follows indirect (IDi) transportation — scenario A — considering two-part distances. New alternative scenarios are established and compared with the original model: (B) direct (Di) transportation eliminating distributor and calculating the one-part distance from supplier to the construction site, (C) direct transportation considering an average distance of 100 km for those transported beyond this diameter, and (D) direct transportation calculating an average distance of 50 km for those transported beyond 50 km diameter. In the second and third scenarios, only distances beyond the intended diameter have changed to 50 and 100 km, respectively, and other distances have remained unchanged. Altered figures in scenarios C and D are highlighted in Table 7. Similar approaches have been used in previous research (Gámez-García et al. 2018;

Fig. 8 Final CO_2eq and cost per functional unit for each wall configuration
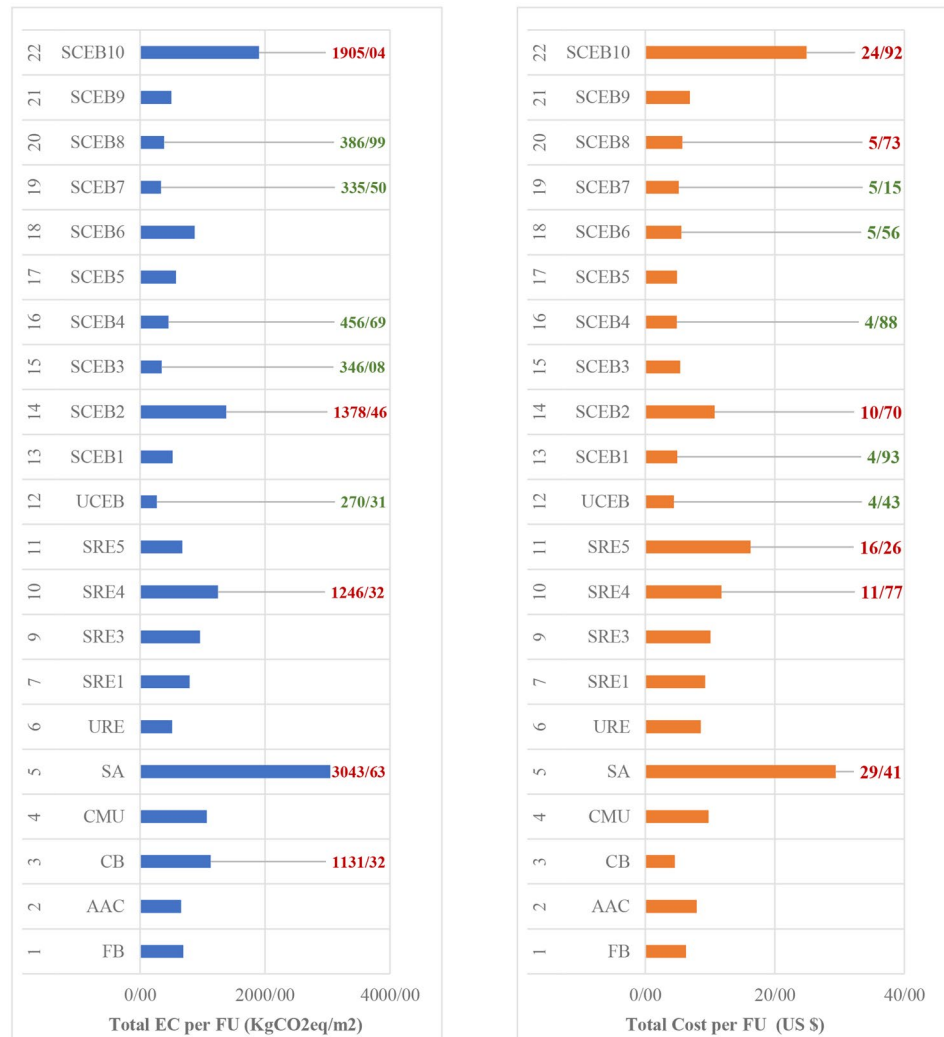
Valencia-Barba et al. 2021). The distance for each group of materials in different scenarios is as presented in Table 7 and Fig. 2.

Based on the results in Fig. 9, a significant CO_2eq variation exists between different scenarios, highlighting the importance of the transportation stage (A4). The EI is influenced by transportation protocols, supplier choices, respective distances, and fuel consumption. Due to the reduced travel distances, EI decreases continuously from scenario (A) to scenario (D). This pattern is sharper for materials provided from far distances outside the province, notably SA and SCEB10.

The high dependence of the environmental impacts of earth-based construction techniques on the amount of acquired soil demonstrates the benefits of using on-site subsoil. The soils available from foundation excavation or nearby excavation projects can be used for this purpose. This scenario provides the added benefit of avoiding transportation impacts. Finally, the results show that the environmental benefits of materials are strongly linked to the

local availability of their constituent materials, especially those that are heavier.

According to Fig. 10, the cost of walls exhibits a similar trend, despite the lower slope. A decrease in the distance also results in a decrease in costs. If the component is a local material and the stabilizer materials make up a relatively small component of the total mass, the transportation contribution is not extreme compared to the total cost. The potential to use local materials for the bulk of plain wall components significantly increases the relative benefit of earth-based mixes over business-as-usual building materials (Meek et al. 2021).

In Iran, adobe is a pertinent bio-based material, and the results of LCIA and LCC show that straw is the only factor leading to high EC and cost. Thus, the sensitivity analysis has also considered unstabilized adobe (UA) without straw, as shown in red in Figs. 9 and 10. Interestingly, it is observed that the range of EI and cost dropped, while the distance traveled for straw was eliminated. Therefore, selecting local

Table 7 Estimation of construction material providers' locations

Wall type	Supplier	Store	A: indirect		B: direct	C: direct (100 km)	D: direct (50 km)
			Producer to store	store to site	Producer to site	Producer to site	Producer to site
Indoor finishing	CL.F	Soil mine. Ardakan	Brick et al. store	12	2.6	8	8	8
	GP.F	Gypsum factory. Yazd	Cement et al. store	50	8.8	44	44	44
Indoor substrate	GP.S	Gypsum factory. Yazd	Cement et al. store	50	8.8	44	44	44
	GP	Gypsum factory. Yazd	Cement et al. store	50	8.8	44	44	44
	CL.P	Soil mine. Ardakan	Brick et al. store	12	2.6	8	8	8
Structure	AAC	Ardakan glass factory	Cement et al. store	7.8	8.8	16	16	16
	FB	Fired brick kiln. Ardakan	Brick et al. store	12	2.6	8	8	8
	CMU	Cement factory. Naeen	Cement et al. store	122	8.8	130	100	50
	CB	Ceramic block. Yazd	Brick et al. store	69	2.6	69	69	50
	RE	Soil mine. Ardakan	Brick et al. store	12	2.6	8	8	8
	SA	Soil mine. Ardakan	Brick et al. store	12	2.6	8	8	8
	CEB	Soil mine. Ardakan	Brick et al. store	12	2.6	8	8	8
Additives	Cement	Cement factory. Naeen	Cement et al. store	122	8.8	130	100	50
	Lime	Lime factory. Ardakan	Cement et al. store	19	8.8	28	28	28
	GGBS	Cement factory. Ardestan	Cement et al. store	234	8.8	220	100	50
	FA	Chadormalu Co. Ardakan	Industrial products store	30	12	39	39	39
	Straw	Shahrekord	Straw Store	359	7.2	370	100	50
	SS	Industrial products Co. Tehran	Industrial products store	581	12	590	100	50
	NaOH	Industrial products Co. Tehran	Industrial products store	581	12	590	100	50
	CH	Industrial products Co. Tehran	Industrial products store	581	12	590	100	50
Outdoor substrate	CM	Cement factory. Naeen	Cement et al. store	122	8.8	130	100	50
	CP	Cement factory. Naeen	Cement et al. store	122	8.8	130	100	50
	CL.P	Soil mine. Ardakan	Brick et al. store	12	2.6	8	8	8
Outdoor finishing	CP.F	Cement factory. Naeen	Cement et al. store	122	8.8	130	100	50

Fig. 9 CO_2eq emissions from the transportation stage sensitivity analysis (A4)
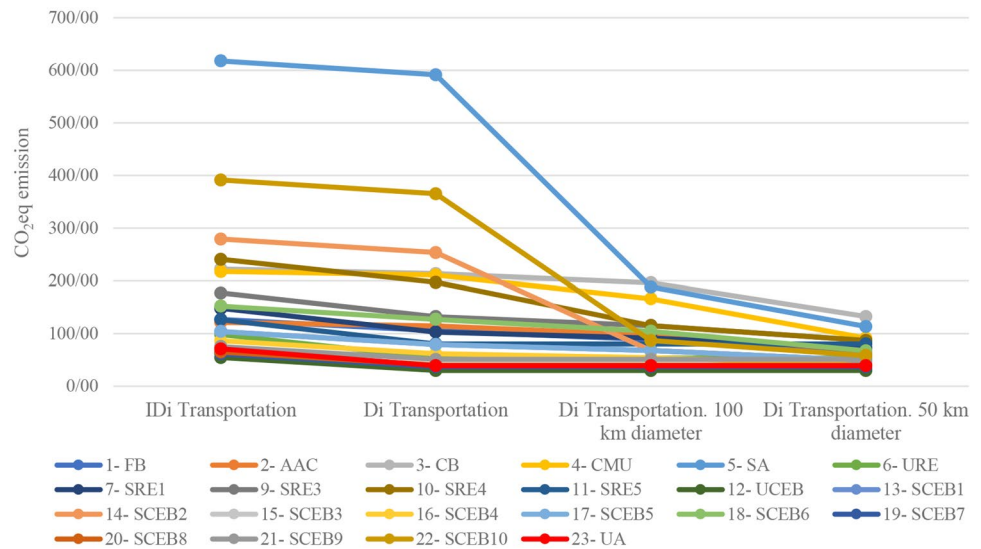
3.4 Scoring and interpretation of life cycle

Final scores revealed the best wall performance; thus, the rank for the cost and EI, as well as the overall rank of all 22 LB walls, are given in Fig. 11, considering the priority of EI and cost indexes. According to the results, the best walling performance to build an affordable house belongs to UCEB with the first rank, followed by SCEB7, and SCEB3, as the next ranks with 5% and 6.5% lime. Intrestingly, SA and SCEB10 are, respectively, the worse building materials.

Our results imply that walling using materials far away from the construction site has the most significant impact on

the environment (attributed to the A4 module). In contrast, locally available materials have a lesser impact on the environment. Architects and engineers can utilize Fig. 11 to select the wall with the highest performance within each category.

Overall, the life cycle impacts of unstabilized earthen materials are substantially better than those of conventional or industrial-based materials. According to previous studies, material choice may affect the embodied energy of building materials and their carbon footprint (Cabeza et al. 2013). Other studies have also shown the benefits of developing unfired clay bricks over traditional fired clay bricks regarding environmental, economic, and energy efficiency effects (Oti and Kinuthia 2012). Despite this, these alternative technologies have been limited because of the incorrect assumption that buildings with high energy efficiency are also more expensive to build and, therefore, less attractive to

Fig. 10 Cost analysis based on the sensitivity analysis of the transportation stage (A4)
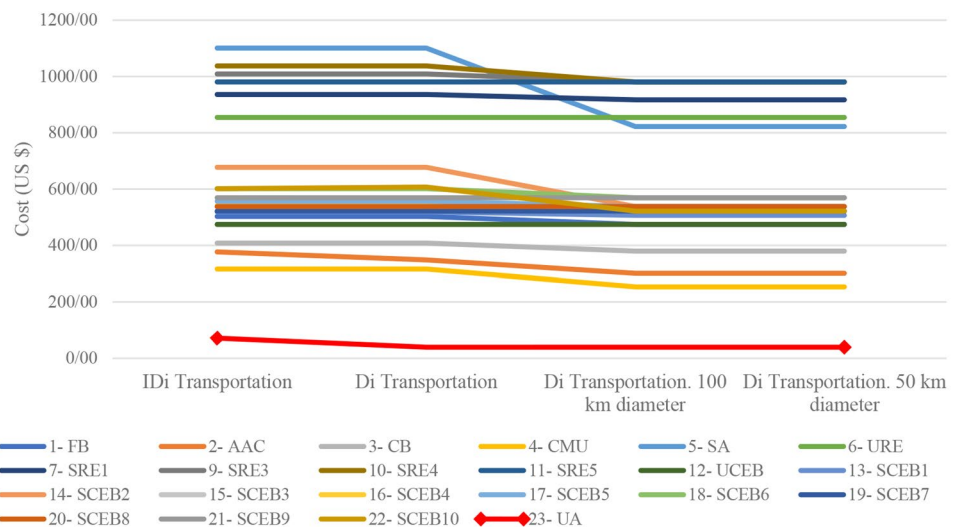
Fig. 11 Scoring of total EC and cost per FU of each wall configuration
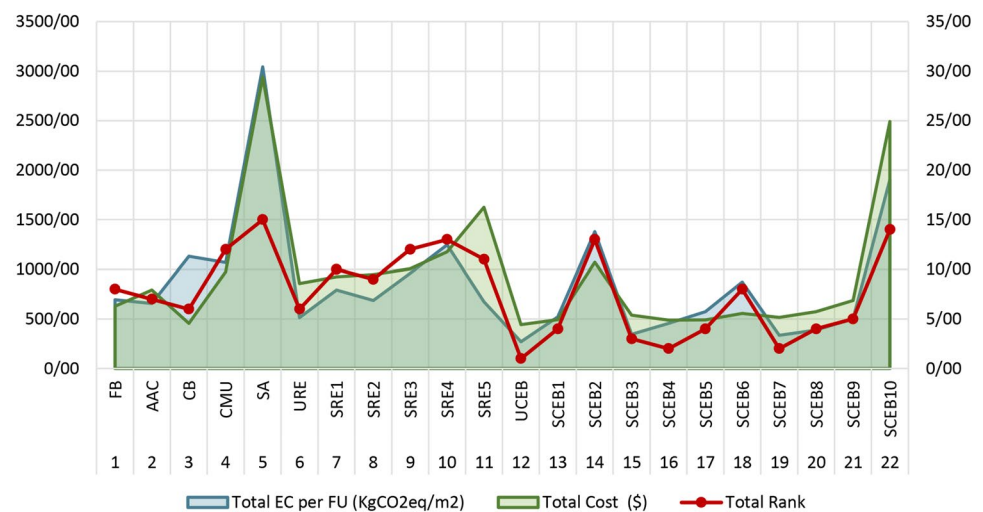
developers from an economic standpoint (Hastak et al. 2003; Hastak and Halpin 2000).

4 Conclusion

An LCA and LCC for a single-family housing unit designed for refugees in Ardakan City, Iran (hot and arid weather), was performed, considering a cradle-to-site perspective. This study compared the embodied carbon emissions and cost benefits of earthen construction LB walling methods (adobe, RE, CEB) with those of conventional construction systems (FB, AAC, CB, CMU). A systematic approach was used from an environmental point of view to identify and rank different earthen and conventional wall configurations for Iranian affordable housing. Twenty-two LB walls were selected based on traditional and contemporary earthen construction methods and Iran's current practice for low-cost housing. With few LCA studies in Iran, this study fills in a scientific gap regarding whether earthen materials are cost-effective and low-emission. Therefore, the study's results reinforce the idea that LCA and LCC are crucial not only to avoid problem shifting but also to identify the most significant lifecycle processes, materials, and hotspots for improvement in new houses. From the results of this study, the following conclusions were drawn:

- Overall, the life cycle impacts of unstabilized earthen walling methods are substantially better than those of stabilized or conventional industrial systems, as the best overall wall performance configuration is UCEB.
- Sensitivity analysis considering different transportation scenarios indicated that stage A4 performs a significant role in reducing emissions within the cradle-to-site life cycle. Considering the results, transportation may

even account for approximately 70 to 95% of EI than wall components: limiting the transportation distance to local resources will significantly affect the environmental footprint of a walling system. Moreover, the impacts of additive materials could be reduced if an alternative material with a less energy-intensive production system could be used.

- For earthen walling techniques, stabilizers, even in small percentages, stood out as having a high contribution to the environmental impacts. Generally, the stabilizers mentioned in this report are produced industrially rather than locally, contain chemicals, require long distances for transportation, and usually do not meet the criteria for regenerative materials.
- Concerning conventional walling alternatives, the high rate of GHG emissions relates mainly to the kiln and calcination. Results indicate that cement and lime materials have a significant environmental impact (attributed to the use of coal for the firing process).
- Unstabilized construction methods can be promoted as environmentally friendly walling systems if decision-makers and local consumers are aware of green issues.

Choosing construction options that have lower embodied impacts is extremely important. In order to reduce the environmental impact of buildings in hot and arid climates, data on the environmental impact embodied in materials should be freely available in the marketplace, for instance, through product environmental footprint (PEF) schemes or widespread environmental product declaration (EPD). A system such as this will be of great benefit to architects, engineers, and households as they consider the environmental impacts of their decisions.

The future research of a complete LCA will demonstrate the various environmental impacts, including embodied

impacts, construction, occupancy, and end-of-life stages. Considering earthen materials' low thermal resistance, they should be not only evaluated as insulation materials, but also as thermal storage materials. Lastly, future research should examine building lifecycle costs at higher resolutions as well as a broader range of social impacts in order to assess the overall sustainability of a variety of building options.

Author contribution Mansoure Dormohamadi: conceptualization; methodology; visualization; validation; formal analysis; investigation; writing — original draft; writing — review and editing; supervision; project administration. Reza Rahimnia: conceptualization; visualization; formal analysis; investigation; writing — original draft; writing — review and editing; project administration. Victor Bunster: investigation; writing — review and editing.

Data availability Data will be made available on request.

Declarations

Competing interest The authors declare no competing interests.

References

Almeida MI, Dias AC, Demertzi M, Arroja L (2015) Contribution to the development of product category rules for ceramic bricks. J Clean Prod 92:206–215

Aranda-Jiménez YG, Suárez-Domínguez EJ (2014) Efecto de la impermeabilidad del Mucílago de Nopal en bloques de tierra comprimidos. Nova Scientia 6(11):311–323

Arrigoni A, Beckett C, Ciancio D, Dotelli G (2017) Life cycle analysis of environmental impact vs. durability of stabilised rammed earth. Constr Build Mater 142:128–136. https://doi.org/10.1016/j.conbuildmat.2017.03.066

Atmaca A (2016) Life cycle assessment and cost analysis of residential buildings in south east of Turkey: part 1—review and methodology. Int J Life Cycle Assess 21(6):831–846

Ben-Alon L, Loftness V, Harries KA, Cochran Hameen E (2021) Life cycle assessment (LCA) of natural vs conventional building assemblies. Renew Sustain Energy Rev 144:110951. https://doi.org/10.1016/j.rser.2021.110951

Binici H, Aksogan O, Shah T (2005) Investigation of fibre reinforced mud brick as a building material. Constr Build Mater 19(4):313–318

Bribián IZ, Capilla AV, Usón AA (2011) Life cycle assessment of building materials: Comparative analysis of energy and environmental impacts and evaluation of the eco-efficiency improvement potential. Build Environ 46(5):1133–1140

Cabeza LF, Barreneche C, Miró L, Morera JM, Bartolí E, Fernández AI (2013) Low carbon and low embodied energy materials in buildings: a review. Renew Sustain Energy Rev 23:536–542

Cabeza LF, Rincón L, Vilariño V, Pérez G, Castell A (2014) Life cycle assessment (LCA) and life cycle energy analysis (LCEA) of buildings and the building sector: a review. Renew Sustain Energy Rev 29:394–416

Cabrera SP, Jiménez YGA, Domínguez EJS, Rotondaro R (2020) Compressed earth blocks (CEB) stabilized with lime and cement. Evaluation of both their environmental impact and compressive strength. Habitat Sustentable 10(2):70–81. https://doi.org/10.22320/07190700.2020.10.02.05

Cataldo-Born M, Araya-Letelier G, Pabón C (2016) Obstacles and motivations for earthbag social housing in Chile: energy, environment, economic and codes implications. Rev La Construcción J Constr 15(3):17–26

Chau CK, Leung TM, Ng WY (2015) A review on life cycle assessment, life cycle energy assessment and life cycle carbon emissions assessment on buildings. Appl Energy 143:395–413

Christoforou E, Kylili A, Fokaides PA, Ioannou I (2016) Cradle to site life cycle assessment (LCA) of adobe bricks. J Clean Prod 112:443–452. https://doi.org/10.1016/j.jclepro.2015.09.016

Dabaieh M, Heinonen J, El-Mahdy D, Hassan DM (2020) A comparative study of life cycle carbon emissions and embodied energy between sun-dried bricks and fired clay bricks. J Clean Prod 275:122998. https://doi.org/10.1016/j.jclepro.2020.122998

Dahmen J, Kim J, Ouellet-Plamondon CM (2018) Life cycle assessment of emergent masonry blocks. J Clean Prod 171:1622–1637. https://doi.org/10.1016/J.JCLEPRO.2017.10.044

Damtoft JS, Lukasik J, Herfort D, Sorrentino D, Gartner EM (2008) Sustainable development and climate change initiatives. Cem Concr Res 38(2):115–127

Dickson T, Pavía S (2021) Energy performance, environmental impact and cost of a range of insulation materials. Renew Sustain Energy Rev 140:110752

Dormohamadi M, Rahimnia R (2020) Combined effect of compaction and clay content on the mechanical properties of adobe brick. Case Stud Constr Mater 13. https://doi.org/10.1016/j.cscm.2020.e00402

Dormohamadi M, Farahza N (2013) Stabilized Earth Construction : toward a Model of Affordable House for Afghan Refugees in Ardakan Iran 2013(September):11–14

Elahi TE, Shahriar AR, Alam MK, Abedin MZ (2020) Effectiveness of saw dust ash and cement for fabrication of compressed stabilized earth blocks. Constr Build Mater 259:120568

Environment UKD, Affairs FR (2021) Government GHG conversion factors for company reporting: methodology paper for emission factors. Crown London

Escamilla EZ, Habert G, Daza JFC, Archilla HF, Fernández JSE, Trujillo D (2018) Industrial or traditional bamboo construction? Comparative life cycle assessment (LCA) of bamboo-based buildings. Sustain 10(9):3096

Estrada M (2014) A case study of cob earth based building technique in Matagalpa, Nicaragua–LCA perspective and rate of adoption

Fernandes J, Peixoto M, Mateus R, Gervásio H (2019) Life cycle analysis of environmental impacts of earthen materials in the

Portuguese context: rammed earth and compressed earth blocks. J Clean Prod 241:118286. https://doi.org/10.1016/j.jclepro.2019.118286

Fernandes J, Mateus R, Bragança L (2014) The potential of vernacular materials to the sustainable building design

Galán-Marín C, Rivera-Gómez C, García-Martínez A (2015) Embodied energy of conventional load-bearing walls versus natural stabilized earth blocks. Energy Build 97:146–154. https://doi.org/10.1016/j.enbuild.2015.03.054

Gámez-García DC, Gómez-Soberón JM, Corral-Higuera R, Saldaña-Márquez H, Gómez-Soberón MC, Arredondo-Rea SP (2018) A cradle to handover life cycle assessment of external walls: choice of materials and prognosis of elements. Sustain 10(8):1–24. https://doi.org/10.3390/su10082748

GCP TGCP (2021) Global Carbon Atlas. https://www.globalcarbonatlas.org/en/CO2-emissions

Gibbs MJ, Soyka P, Conneely D (2001) CO2 emissions from cement production, good practice guidance and uncertainty management in national greenhouse gas inventories. Intergovernmental Panel on Climate Change (IPCC)

Guillaud H, Joffroy T, Odul P, CRATerre EAG (1995) Compressed earth blocks- manual of design and construction: volume II. GATE & BASSIN

Hammond G, Jones C, Guide AB (2011) Embodied carbon: the Inventory of Carbon and Energy (ICE). BSRIA, Bracknell, England

Hammond GP, Jones CI, Guide AB (2011) Embodied carbon: the inventory of carbon and energy (ICE). BSRIA, Bracknell, England, 136. http://www.ihsti.com/tempimg/57c152b-ENVIRO2042201160372.pdf%0Awww.bath.ac.uk/mech-eng/sert/embodied%0A

Hastak M, Halpin DW (2000) Assessment of life-cycle benefit-cost of composites in construction. J Compos Constr 4(3):103–111

Hastak M, Mirmiran A, Richard D (2003) A framework for life-cycle cost assessment of composites in construction. J Reinf Plast Compos 22(15):1409–1430

Houben H, Guillaud H (2008) Earth construction: a comprehensive guide. Practical Action Publishing

Ioannidou D, Zerbi S, Habert G (2014) When more is better–comparative LCA of wall systems with stone. Build Environ 82:628–639

IOFS ISO (2006a) ISO 14040—environmental management—life cycle assessment—principles and framework. Geneva

IOFS ISO (2006b) ISO 14044: environmental management, life cycle assessment, requirements and guidelines. ISO

Kutarna M, Li K, Radebe N (2013) An investigation into the use of cob and/or straw bale construction in non-residential buildings

Laborel-Préneron A, Aubert J-E, Magniont C, Maillard P, Poirier C (2017) Effect of plant aggregates on mechanical properties of earth bricks. J Mater Civ Eng 29(12):4017244

Lutzkendorf T, Balouktsi M (2016) Guidelines for designers and consultants: part 1; basics for the assessment of embodied energy and embodied GHG emissions. Tokyo: Inst Build Environ Energy Conserv

Malkanthi SN, Balthazaar N, Perera A (2020) Lime stabilization for compressed stabilized earth blocks with reduced clay and silt. Case Stud Constr Mater 12:e00326

Mateus R, Fernandes J, Teixeira ER (2020) Environmental life cycle analysis of earthen building materials. Renew. Sustain. Mater. Elsevier Ltd., In Encycl. https://doi.org/10.1016/b978-0-12-803581-8.11459-6

Meek A, Elchalakani M, Beckett CTS, Dong M (2021) Alternative stabilised rammed earth materials incorporating recycled waste and industrial by-products: a study of mechanical properties, flexure and bond strength. Constr Build Mater 277:122303

Meek A (2020) Sustainable housing in Australia: development of rammed earth materials and quantification of environmental benefits of their wider use. The University of Western Australia

Melià P, Ruggieri G, Sabbadini S, Dotelli G (2014) Environmental impacts of natural and conventional building materials: a case study on earth plasters. J Clean Prod 80:179–186. https://doi.org/10.1016/j.jclepro.2014.05.073

MOE (2022) Ministry of Energy. https://www.moe.gov.ir

Monteiro H, Freire F (2012) Life-cycle assessment of a house with alternative exterior walls: comparison of three impact assessment methods. Energy Build 47:572–583

Morel J-C, Mesbah A, Oggero M, Walker P (2001) Building houses with local materials: means to drastically reduce the environmental impact of construction. Build Environ 36(10):1119–1126

MRUD (2022) Iran ministry of roads & urban development. https://www.mrud.ir/

Narayanaswamy AH, Walker P, Venkatarama Reddy BV, Heath A, Maskell D (2020) Mechanical and thermal properties, and comparative life-cycle impacts, of stabilised earth building products. Constr Build Mater 243:118096. https://doi.org/10.1016/j.conbuildmat.2020.118096

NBRI N building's regulation of I (1390) 19th issue-saving energy consumption . Nashr Tosee

NBRI N building's regulation of I (1392) 9th issue-design and construct of buildings with reinforced. Nashr Tosee Iran

Nejat P, Jomehzadeh F, Taheri MM, Gohari M, Majid MZA (2015) A global review of energy consumption, CO2 emissions and policy in the residential sector (with an overview of the top ten CO2 emitting countries). Renew Sustain Energy Rev 43:843–862

Nematchoua MK, Asadi S, Reiter S (2020) a). Influence of energy mix on the life cycle of an eco-neighborhood, a case study of 150 countries. Renew Energ 162:81–97

Nemry F, Uihlein A, Colodel CM, Wetzel C, Braune A, Wittstock B, Hasan I, Kreißig J, Gallon N, Niemeier S (2010) Options to reduce the environmental impacts of residential buildings in the European Union—potential and costs. Energy Build 42(7):976–984

NIOPDC (2022) National Iranian Oil Products Distribution Company. https://niordc.ir/

Nisbet M, Van Geem MG, Gajda J, Marceau ML (1997) Environmental life cycle inventory of Portland cement and concrete. World Cement 28(4):3

NMAC (2015) New Mexico earthen building materials code. Santa Fe, NM

NREL (2021) Inventory Database, in: National Renewable Energy Laboratory

Oti JE, Kinuthia JM (2012) Stabilised unfired clay bricks for environmental and sustainable use. Appl Clay Sci 58:52–59. https://doi.org/10.1016/j.clay.2012.01.011

Ouedraogo KAJ, Aubert J-E, Tribout C, Escadeillas G (2020) Is stabilization of earth bricks using low cement or lime contents relevant? Constr Build Mater 236:117578

Pakdel A (2022) Towards selecting the optimized external wall solution in Iran: comparison between life cycle assessment (LCA), cost benefits, and thermal performance. Build Environ 223(April):109532. https://doi.org/10.1016/j.buildenv.2022.109532

Pakdel A, Ayatollahi H, Sattary S (2021) Embodied energy and CO2 emissions of life cycle assessment (LCA) in the traditional and contemporary Iranian construction systems. J Build Eng 39(2020). https://doi.org/10.1016/j.jobe.2021.102310

PBO (2022) Planning and budget organization. https://www.mporg.ir/en

Pomponi F, D'Amico B, Moncaster AM (2017) A method to facilitate uncertainty analysis in LCAs of buildings. Energies 10(4):524

Provis JL (2018) Alkali-activated materials. Cem Concr Res 114:40–48

Racusin JD, McArleton A (2012) The natural building companion: a comprehensive guide to integrative design and construction. Chelsea Green Publishing

Ramesh S (2012) Appraisal of vernacular building materials and alternative technoligies for roofing and terracing options of embodied energy in buildings. Energy Procedia 14:1843–1848

Reddy BVV (2009) Sustainable materials for low carbon buildings. Int J Low-Carbon Technol 4(3):175–181

Reddy BVV, Jagadish KS (2003) Embodied energy of common and alternative building materials and technologies. Energy Build 35(2):129–137

Reddy BVV, Kumar PP, Venkatarama Reddy BV, Prasanna Kumar P (2010) Embodied energy in cement stabilised rammed earth walls. Energy Build 42(3):380–385. https://doi.org/10.1016/j.enbuild.2009.10.005

Rigassi V (1985) Compressed earth blocks: manual of production. CRAterre-EAG, GATE, 1

Ross B, López-Alcalá M, Small AA III (2007) Modeling the private financial returns from green building investments. J Green Build 2(1):97–105

Roux Gutiérrez RS, Velazquez Lozano J, Rodríguez Deytz H (2015) Compressed earth blocks, their thermal delay and environmental impact. Congreso Internacional De Costrucción Sostenible y Soluciones Ecoeficientes 2015:871–893

Sanz-Calcedo JG, Luna MF, Soriano RC (2012) Evaluation of the efficiency to use sustainable classical techniques on the modern construction. BSA, 2012, 1st

Serrano S, Barreneche C, Rincón L, Boer D, Cabeza LF (2013) Optimization of three new compositions of stabilized rammed earth incorporating PCM: thermal properties characterization and LCA. Constr Build Mater 47:872–878

Shukla A, Tiwari GN, Sodha MS (2009) Embodied energy analysis of adobe house. Renew Energy 34(3):755–761

Sobhiyah MH, Radaiee A (2015) The realization of objectives and plans of "Maskan-e Mehr" program in Mahdasht Project. Monthly Sci J Bagh-e Nazar 12(33):91–106. http://www.bagh-sj.com/article_9995.html

Toure PM, Sambou V, Faye M, Thiam A (2017) Mechanical and thermal characterization of stabilized earth bricks. Energy Procedia 139:676–681

Valencia-Barba YE, Gómez-Soberón JM, Gómez-Soberón MC, Rojas-Valencia MN (2021) Life cycle assessment of interior partition walls: comparison between functionality requirements and best environmental performance. J Build Eng 44:102978

Villa J de los ÁH (2018) Modelamiento numérico del comportamiento sísmico de viviendas de mampostería con bloques de tierra comprimida. Pontificia Universidad Catolica del Peru-CENTRUM Catolica (Peru)

Worrell E, Price L, Martin N, Hendriks C, Meida LO (2001) Carbon dioxide emissions from the global cement industry. Annu Rev Energy Environ 26(1):303–329