

Obstacles and motivations for earthbag social housing in Chile: energy, environment, economic and codes implications

Obstáculos y motivaciones para viviendas sociales en base a bolsas de tierra en Chile: implicaciones en energía, ambiente, económicas y normativas

Matías Cataldo-Born (Main author)

Universidad Adolfo Ibáñez. Facultad de Ingeniería y Ciencias.
matias.cataldo2007@alumnos.uai.cl

Gerardo Araya-Letelier (Corresponding author)

Universidad Adolfo Ibáñez. Facultad de Ingeniería y Ciencias.
Diagonal Las Torres 2700, Santiago, Chile.
gerardo.araya@uai.cl

Claudia Pabón

Universidad Adolfo Ibáñez. Facultad de Ingeniería y Ciencias.
claudia.pabon@uai.cl

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Abstract

Chile presents a social housing deficit that needs to be addressed with solutions that increase habitability and environmental benefits. This paper addresses the benefits of implementing earthbag buildings as an option to mitigate the existing social housing deficit in Chile. A literature review presents details on the use of earthbag buildings around the world, and motivations and obstacles for implementing earthbag buildings in Chile. In particular, a case study was simulated to compare an earthbag social house to a reinforced brick masonry social house in terms of environmental and economic performances such as CO₂ emissions, energy and costs. It is concluded that both alternatives generate similar CO₂ emissions, but the earthbag social house can save up to 20% of energy during its life cycle. In economic terms, the earthbag social house generates savings of 50% and 38% for initial investment and life cycle cost, respectively, compared to the reinforced brick masonry social house. The implementation of earthbag social housing projects would be encouraged by the development of a Chilean building code for earthbag design that provides guidance on the safe use of this technique in a seismic country.

Keywords: Earthbag buildings; chilean social housing; environmental performance; economic performance; building code.

Resumen

Chile presenta un déficit habitacional en viviendas sociales que necesita ser abordado con soluciones que incrementen la habitabilidad y beneficios ambientales. Este trabajo aborda los beneficios de implementar viviendas en base a bolsas de tierra como una opción para mitigar el déficit habitacional de viviendas sociales existente en Chile. Una revisión bibliográfica presenta detalles en el uso de viviendas en base a bolsas de tierra alrededor del mundo, y motivaciones y obstáculos para la implementación de viviendas en base a bolsas de tierra en Chile. En particular, un caso de estudio fue simulado para comparar una vivienda social en base a bolsas de tierra a una vivienda social de albañilería reforzada en términos de desempeños ambientales y económicos tales como emisiones de CO₂, energía y costos. Es concluido que ambas alternativas generan emisiones similares de CO₂, pero la vivienda social en base a bolsas de tierra puede ahorrar hasta un 20% de energía durante su ciclo de vida. En términos económicos, la vivienda social en base a bolsas de tierra genera ahorros de 50% y 38% para la inversión inicial y costos en ciclo de vida, respectivamente, comparado a la vivienda social de albañilería reforzada. La implementación de proyectos de vivienda social en base a bolsas de tierra sería incentivada por el desarrollo de una normativa chilena de diseño en base a bolsas de tierra que provea guía en el uso seguro de esta técnica en un país sísmico.

Palabras clave: Viviendas en base a bolsas de tierra; viviendas sociales chilenas; desempeño ambiental; desempeño económico; normativa de edificios.

Introduction

Chile still exhibits several problems associated with social housing such as deficit, poor energy efficiency, and insufficient assessment of the environmental impact during construction, operation and end of life of these facilities (Bustamante, Rozas, Cepeda, Encinas & Martinez, 2009). The Chilean social housing deficit reached 491,000 units in 2011 negatively impacting already existing problems such as poverty, crime and social segregation (MIDEPLAN, 2011). This deficit has

increased as a result of two large earthquakes in northern Chile and a mega fire in Valparaiso during 2014. The two large earthquakes ($M_w=8.2$ and $M_w=6.2$) damaged 9,547 houses only in the region of Tarapaca and 1,800 houses in the region of Arica and Parinacota, where 60% of these were social houses (MINVU, 2014a). The mega fire in the region of Valparaiso damaged 3,230 houses, from which 2,491 units were declared uninhabitable, affecting mainly social houses (MINVU, 2014). Moreover, the residential energy consumption in Chile is significant, accounting for 16% of the country's total energy demand in 2011 (Programa Chile Sustentable, 2013).

Given this context, there is a need to implement short-term solutions for the design and construction of social houses that meet minimum standards of habitability in terms of area per inhabitant, aesthetic, thermal, acoustic, fire and seismic performance, just to name a few, balancing these habitability-requirements with budget, time and environmental constraints.

In the last years various players of the construction industry, both public and private, have worked to establish a framework to improve the energy efficiency and thermal behavior of households in Chile. Examples of this are the new system for home energy rating or the updated thermal insulation requirements for housing in the General Ordinance of Urbanism and Construction (OGUC) (MINVU, 2016).

In this scenario, earthbag social housing might be a valid alternative to traditional social houses in Chile, which are mainly reinforced and confined masonry construction (Alvarado, 2010). Earthbag construction might provide enhanced habitability than traditional social houses as well as lower construction cost and time, reduced use of power tools and skilled workers. Additionally earthbag construction also demands less energy consumption during its construction and operation, which reduces the related environmental impacts as compared to traditional construction alternatives.

Earthbag construction

For more than 10,000 years raw earth has been used as a construction material and it is estimated that currently more than a third of the world's population lives in raw earth construction with concentration in developing countries where more than half of the corresponding population lives in this type of construction (Minke, 2006). Raw earth is a low cost and vastly available material, which encourages its use for construction in developing countries. However, its use has increased also in developed countries due to current environmental and energy related problems and the increasing interest for sustainable construction (Gomes, Lopes & De Brito, 2011).

Among raw-earth construction, earthbag construction is a system based on the use of varying-length sandbags of natural or synthetic material filled with compacted earthen material of clay and sand, with straw and water, but almost any earth material can be used. These earthbags are arranged in layers forming walls that provide compression strength with barbed wire placed between them to provide tensile strength to the system. Cement or lime might be added as stabilizers of the structures formed with earthbags (Cal-Earth Institute, 2013).

Global and local use of earthbag construction

Earthbag construction has been successfully implemented mainly in developing countries that lack of building codes normalizing this technique. In developed countries there are also successful examples. The Cal-Earth Foundation obtained in California, USA, the approval of the town of Hesperia to implement earthbag construction. The structures implemented were assessed in accordance with the International Conference of Building Officials, and the building regulations that apply in California, which is a seismically active area. It was determined that these earthbag structures exceeded the requirements demanded by the regulations (Southwest Inspection and Testing, 1995).

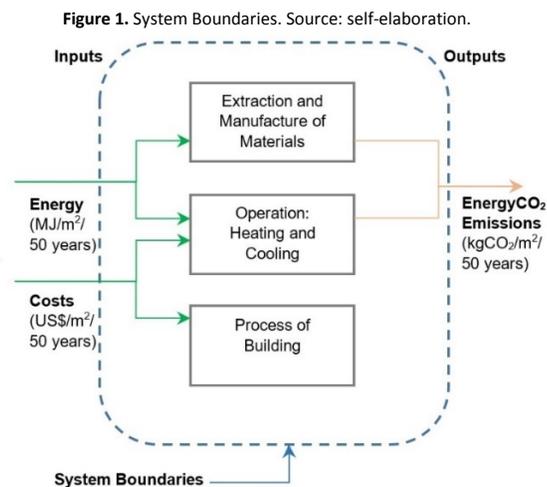
The implementation of earthbag construction in Chile is still reduced, but it has gradually increased mainly as self-developed projects without the formal guidance of building codes. Additionally, some earthbag workshops are being given where guidelines of the building system are taught, resulting in few projects developed and regularized under the corresponding normative in Chile. A good example of this is an earthbag house in Llay-Llay, 5th Region of Chile, that was designed and built in 2009. This house presents an area of 85 m², 3.2 m height walls crowned with two domes, a semi cylindrical room (U-shaped), and a ship with straight walls. The structure was stabilized with lime and underwent the mega earthquake ($M_w=8.8$) of February 27, 2010 damage-free (Meissner, 2013).

Through a literature review, the reasons that have limited the implementation of earthbag construction, and the state of the practice in the development of raw-earth construction building codes in Chile, are presented. Following, qualitative and quantitative reasons supporting the use of earthbag construction in Chile are exposed. In particular, a simulated case study with the results of a simplified Life Cycle Assessment (LCA) comparing the performance of an earthbag social house to a reinforced brick masonry social house in Chile are presented and discussed. The reinforced brick masonry social house corresponds to the average social house in Chile (Alvarado, 2010). Both alternatives satisfy the thermal requirements established by building codes in Chile for Talca, Maule Region, where the units are located.

The LCA is a methodology used to model the complexity of an environmental system with a reduced number of parameters. It is standardized by the ISO 14040 (ISO, 2006) and has been applied in the building sector for 20 years (Fava, 2006). Even though the complexity and uncertainties of LCA results are often seen as the main barriers to more frequent use of LCA, rough estimates of the environmental impacts over the life cycle are still better than ignoring these impacts and LCA is a good tool to compare the environmental impacts of competing alternatives (Adalberth, 1997; Kellenberger & Althaus, 2009). In producing rough estimates, there are a number of possible simplifications that can be made with the aim of promoting LCA to wider group of users (Adalberth, 1997; Bribián, Usón & Scarpellini, 2009; Kellenberger & Althaus, 2009). Therefore, in this study three sustainable performance indicators that best complement with buildings sustainability certification schemes (Bribián et al., 2009) are used:

- Life Cycle Energy: Mega Joule (MJ)/ habitable m^2 /50 years.
- Life Cycle CO₂ emissions: kg CO₂/habitable m^2 /50 years.
- Life Cycle Cost: US\$ Net Present Value (NPV)/habitable m^2 .

This study used a simplified LCA approach covering three stages of the life cycle of a house: (1) Extraction and manufacturing material, quantifying energy and CO₂ emissions embodied in materials. (2) Construction process, where the initial investment costs of materials and labor are quantified. (3) Operation, quantifying energy, CO₂ emissions and costs associated with operation of heating and cooling of the building. As functional unit, 1 m^2 of habitable housing area over 50 years is used. The measured flows within the boundaries of the system are specified in Figure 1.



The life cycle energy is calculated based on the embodied energy of materials, and the energy used for heating and cooling during operation for both social housing alternatives considering Talca region as location and optimal solar orientation. These values are obtained from thermal simulations using the software of the Ministry of Housing and Urban Development, CCTE v2.0 *“Comportamiento Térmico para Edificios en Chile”* (thermal behavior of buildings in Chile). This software allows 3D simulation of the thermal performance of buildings, in terms of building’s energy consumption for heating and cooling during operation, considering the thermal transmittance, thicknesses and surfaces of the building materials, surfaces of roofing, interior and exterior walls, building’s orientation and meteorological conditions of the location of the buildings.

The life cycle CO₂ emissions are calculated based on the embodied CO₂ emissions of materials. For the operational stage the use of certified wood was assumed since this is the most widely used fuel for heating in social housing and the calculation of CO₂ emissions over this stage was simplified because this fuel can be considered neutral in terms of carbon emissions (Velasco, 2013). Due to the lack of databases for embodied energy and CO₂ emissions of building materials in Chile (Letelier, 2011) the embodied energy and CO₂ emissions are obtained using the Inventory of Carbon and Energy 2011 of the University of Bath, UK (Hammond & Jones, 2011).

The life cycle cost considered the initial investment (accounting for materials, overheads and labor) without considering electrical, water and sanitary installations; and operating costs associated solely with heating and cooling. The use of wood stoves of high efficiency (90%) is assumed as well as the purchase of certified wood in a scenario in which the price of firewood increased by 5% per year. An annual real discount rate of 4% is used, with initial investment flows in year 0 and operation flows for 50 years.

Results

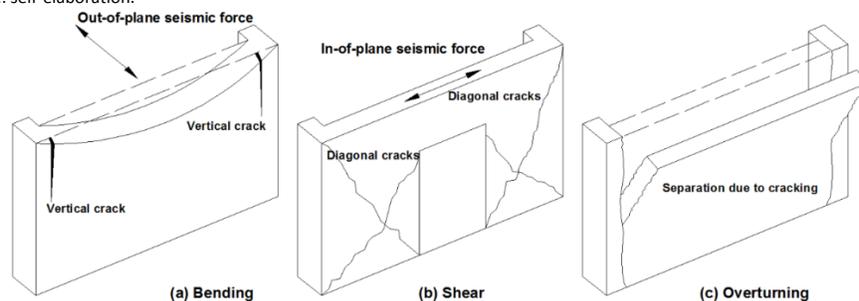
Obstacles for developing earthbag construction in Chile

Raw earth is considered a fragile material and difficult to standardize

Raw earth presents a very low tensile strength compared with traditional construction materials used in social housing (e.g., clay bricks). Raw-earth construction also presents a very fragile failure mode (Barros & Imhoff, 2010), where its walls can support very small lateral loads and deformations before cracking, which is an important problem in seismic countries such as Chile. Moreover, raw-earth structures need significant wall thickness to achieve adequate stability, leading to heavy structures that are more affected by earthquakes and riskier under collapse than well-designed structures made of traditional materials.

Recent studies (Barros & Imhoff, 2010; Gutiérrez & Manco, 2006) have focused on failure modes of raw-earth construction, identifying three principal reasons that explain the collapse of these structures under seismic loads, which are: (1) Low tensile strength and fragility of the material. (2) Structures with significant mass that increases the effects of earthquakes. (3) Deficient construction techniques that affect the bonding between earth and mortar. Figure 2 presents the common failure modes that raw-earth construction exhibits under seismic loads.

Figure 2. (a) Bending. Seismic forces generate bending (tensile stress) on out-of-plane earth walls, and vertical cracks develop; (b) Shear: Seismic forces generate shear on in-plane-earth walls, and diagonal cracks develop; (c) Overturning: Once separated due to cracking, earth walls behave as independent elements that subjected to seismic forces might fail overturning. Source: self-elaboration.



There is no building code for new raw-earth construction in Chile

Although adobe is recognized as a building system within the OGUC (MINVU, 2016), there is only a recent regulation that applies to the repair of historic buildings in raw earth, but there are no specific building codes that standardize new raw-earth construction in Chile (Soto, M., Personal communication, September 5th, 2013.). In this context, raw-earth construction should be governed primarily by the provisions of the OGUC (MINVU, 2016) and the Chilean Code for Seismic Design of Buildings NCh 433 Of.1996 Mod. 2009 (INN, 2009), which lacks specific indications for raw-earth structures. The (MINVU, 2016) states that the structural peer reviewer must evaluate the project in accordance with the technical standards listed in the document and verify compliance. Additionally, the OGUC declares that "in justified cases where there is no technical standard applicable to the subject, draft structural calculations shall be made on the basis of foreign technical standards, whose application suits the project in the opinion of the structural peer reviewer of the project".

The lack of technical standards for raw-earth construction in Chile discourages the use of these construction techniques and also may increase the costs associated with the structural design of these buildings since the designer does not have any Chilean standard in which he could back up. Moreover, as seen in Table 1, industrialized construction materials in Chile are commercialized by companies that promote and participate in the development of design building codes to provide technical guidance on their use. This is not the case of raw earth, which is a freely accessible material.

Table 1. Main actors of the construction industry involved in the development of Chilean building codes of industrialized construction materials. Source: self-elaboration.

Code	Content	Major Corporations in the Construction Industry	Government and Non-profit	Research Centers and Universities	Private Independent Consultants
NCh 1928. Of 1993 Mod. 2009	Reinforced Masonry - Requirements for the design and calculation	Cámara Chilena de la Construcción; Instituto del Cemento y Hormigón de Chile (Conformada por: Cementos Bío Bío S.A., Cemento Polpaico S.A. y Lafarge Chile S.A.(Cemento Melón)); Ladrillos Princesa; COPRESA; SOPROCAL; Industrias Princesa S.A.; Laymaco Ltda.	Instituto de Ingenieros de Chile, Instituto Nacional de Normalización, Ministerio de Obras Públicas, Servicio de Vivienda y Urbanización, Asociación Chilena de Sismología e Ingeniería Antisísmica, Ministerio de Vivienda y Urbanismo; ENDESA	Pontificia Universidad Católica de Chile, Universidad de Chile, Universidad Técnica Federico Santa María, Universidad de Concepción	G + V Ingenieros; Grau S.A.; INEIN Sociedad Ltda.; PROINCO Ingenieros; Rivera, Balada y Baeza Ingenieros Civiles
NCh 2123. Of 1997 Mod. 2003	Confined Masonry - Design and calculation requirements	ACMA S.A.; Cemento Polpaico S.A.; Cerámica Santiago; Compañía Siderúrgica de Huachipato; COPRESA; Industria Nacional de Cemento S.A (Cementos Bío Bío); Industria Princesa Ltda.	Instituto Nacional de Normalización (INN); Colegio de Arquitectos de Chile; Colegio de Constructores Civiles de Chile; Colegio de Ingenieros de Chile; I. Municipalidad de la Florida; Ministerio de Vivienda y Urbanismo	Pontificia Universidad Católica de Chile; Universidad Católica de Valparaíso; Universidad Católica del Norte; Universidad Central; Universidad de Chile; Universidad de Concepción; Universidad de Santiago; Universidad Técnica Federico Santa María; Universidad Tecnológica Metropolitana	Larraín, Ruiz, Saavedra y Cía. Ltda.; Rivera, Lederer, Baeza Ing. Civiles
NCh 1198. Of 1991 Mod. 2006	Wood - Wood Constructions - Calculation	Corporación Chilena de la Madera (CORMA); TRADEMA Ltda.	Instituto Nacional de Normalización (INN); Colegio de Constructores Civiles; ENDESA; Fundación Chile; IDIEM-Universidad de Chile; Instituto de Ingenieros de Chile; Instituto Forestal; Ministerio de Obras Públicas; Ministerio de Vivienda y Urbanismo; Gobierno Regional V Región	Universidad Católica de Chile; Universidad de Chile; Universidad del Bío-Bío; Colegio de Ingenieros Forestales	INGEWAG
NCh 430. Of.19 61 Mod. 2007	Reinforced Concrete - Design and calculation requirements	Compañía Siderúrgica Huachipato; Gerdau Aza; Instituto Chileno del Acero (ICHA); Instituto del Cemento y del Hormigón de Chile (ICH)	Instituto Nacional de Normalización (INN); Ministerio de Vivienda y Urbanismo; SERVIU Metropolitano	Pontificia Universidad Católica de Chile; Universidad de Chile; Universidad Técnica Federico Santa María	Alfonso Larraín Vial y Asociados; Ara y Worley Parsons; Cade Idepe; DICTUC S.A.; Marcial Baeza S. y Asociados Ltda.; Ruiz, Saavedra y Cía. Ltda.; Sandor Ingenieros; VMB Ingeniería Estructural

Motivations for developing earthbag construction in Chile

Increasing world progress in the development of standards for the use of earth building systems.

According to recent studies (Cid, Mazarrón & Cañas, 2011; Schroeder, 2012) in the last years different countries have been working on the standardization of earth building codes and some examples are the followings. Colombia and Spain with the publication of new standards. Ecuador, Mexico and Nicaragua developing future standards. Peru improving existing documents. New Zealand's regulation, which may be considered the most advanced, involves several standards including: NZS 4297: 1998 - Building Engineering Design of Earth; NZS 4298: 1998 - Materials and Workmanship for Earth Buildings; NZS 4299: 1998 Earth Buildings not Requiring Specific Design. In total, 55 building codes and regulations of different countries over the world are accounted. As recently study (Cid et al., 2011) showed that most of these documents (79%) focuses their content on standardizing a single building system, either adobe, compressed earth block (CEB) or rammed earth.

All international standards use raw-earth walls as structural elements and most of these standards focuses on defining rules of geometrical aspects, limiting the wall height to a maximum two stories that should not exceed 6.5 m in height from the top of the foundation to the top of the earth wall (Tanton, 2008) Since the earthbag building system is relatively

recent compared to traditional raw-earth building systems such as adobe, there are not countries that regulate its use and only in 2010 the American Society for Testing and Materials (ASTM International, 2010) recognized it as a building system. However, it is important to highlight advances in the standardization of traditional systems considering the use of compacted soil-cement, even in seismic countries. Among them, the Peruvian code for adobe NTE E 0.80 and the New Zealand regulations NZS (1998 and 1999) that provide indications for earthquake-resistant design for adobe, rammed earth and CEB.

Traditional earth building systems have been extensively studied and present compacted soil-cement densities of approximately 1.800-2.000 (kg/m³), which is equivalent to the density of compacted soil-cement used in earthbag buildings. For these systems, minimum requirements regarding use, specifications, stability, heights, thickness and loading of elements are established. These requirements have been studied for earthbag buildings (Hunter & Kiffmeyer, 2004) which represents very important advancements for the development of a building code.

Benefits of living in earth buildings.

Earth buildings provide good acoustic and thermal insulation and they can also help in regulating the indoor humidity, especially when used in bathrooms, where they can reduce condensation and fungal growth (Little & Morton, 2001) Earth is a non-allergenic material that provides a safe, healthy and comfortable indoor environment for the occupants of earth buildings (Sameh, 2014).

The earth itself is the most reliable temperature controller of nature (Cal-Earth Institute, 2013), and, therefore, stabilized earth walls perform as an absorbent mass capable of storing heat and radiate it back into the living space as the mass is cooled. This fluctuation of temperature is known as thermal mass effect (Pacheco-Torgal & Jalali, 2012). A recent study concerning to biomimetics of stabilized earth (Reddi, Jain, Yun & Reddi, 2012) applied thermoregulatory concepts of biological systems to show that the use of stabilized earth in construction can provide thermal regulation for dwellings, similar to what a skin does to regulate the body temperature in humans and animals. Therefore, earth structures provide cool internal environments in hot climates such as the Atacama Desert, and warm internal environments in winter in hillside places such as southern Chile. Earth sheltered buildings has the best potential for energy savings due to the lower temperature differences between the exterior surrounding soil and the interior space (Carpenter, 1994).

Earthbag walls present good acoustic isolation due to the high density (2,000 kg/m³) of compacted soil-cement. A 40 cm thick earthen wall provides acoustic isolation varying from 49 to 70 dB, as a result of the different densities achieved. Its compliance with current acoustic isolation regulations is equivalent to other conventional materials (Bestraten, Hormías & Altemir, 2011; Little & Morton, 2001).

Earthbag walls are fireproof, do not propagate fire and emit no toxic gases. The fire resistance of earth walls having thickness of 15 cm or greater is equivalent to the resistance of conventional materials (Bestraten et al., 2011). Moreover, earth building materials have good fire resistance properties unless they contain significant amounts of fiber. According to the German Building Standards, earth, even with a high straw content, is “not combustible” if the density is higher than 1,700 (kg/m³) (Little & Morton, 2001). Additionally, studies of The University of Kassel’s Building Research Institute showed that earth is better than any other building material protecting human beings from electromagnetic radiations (Little & Morton, 2001).

Enhanced mechanical stabilization and structural testing of earthbag buildings

Unlike traditional raw-earth building systems, earthbags system implements a set of mechanical stabilizing elements for an improved structural performance. The use of polypropylene bags brings the required support to hold the soil-cement mix in a fixed position. They help preventing erosion and maintaining cohesion and shape of the structure, even under conditions of extreme humidity (Cal-Earth Institute, 2013).

Implementation of barbed wire between rows of bags, adds tensile strength, which is very important to make the stacked bags behave as a single element. Additionally, the incorporation of wire mesh gives more support to retain the plasters, both internally and externally, providing further enhanced cohesion and shear strength to the walls (Croft, 2011). Moreover, the earthbag building system uses simple geometries and symmetrical plants, and promotes the use of catenary domes as base structure, since catenary domes better distribute seismic lateral loads (Huerta Fernández, 2003). However, its use also extends to designs of cylindrical and rectangular structures with vertical walls, which must

incorporate seismic-resistant elements as buttresses or reinforced concrete elements on top of the walls, among other things that provide greater stability to structures.

Regarding structural testing of the earthbag system, there have been several studies showing the enhanced structural behavior of earthbag construction compared to traditional raw-earth construction. Daigle (2008) performed compression tests over stabilized earthbag walls, whose strengths were similar to steel frames which evidences the good behavior of earthbags under axial loads. Pelly (2009) studied the plastic limit of earthbag arches that showed significant plastic deformation and rotation before collapsing, which is an excellent behavior especially in seismic areas. Croft (2011) studied the structural behavior of earthbag houses under lateral loads (in-plane and out-of-plane) showing an enhanced resistance to bending and shear compared to traditional raw-earth construction.

Soil-cement: Chemical stabilization opens a new era for earth buildings

The dependence on the quality and dosage of clay on raw-earth mixes has implied that traditional practices begin to disappear. Recent studies (Barros & Imhoff, 2010; Hall, Najim & Keikhaei Dehdezi, 2012; Little & Morton, 2001; Toirac-Corral, 2008) proposed compacted soil-cement as an alternative that has a significantly better mechanical behavior compared to traditional raw-earth material.

The practice with soil-cement assumes that there are different types of soil. However, some researchers have identified which soil types have better results for chemical stabilizers as well as the optimum percentages of stabilizer and humidity for the soil-cement mixture (Barros & Imhoff, 2010; Minke, 2006; Toirac-Corral, 2008). Therefore, the priority is given to characterize the soil from each site to determine the dosage of chemical stabilizers to use with earth adequately (Minke, 2006). Moreover, the addition of sand or clay is needed for an adequate mixture. Adding a chemical stabilizer such as cement in the filling mixture, significantly improves the mechanical behavior of earthbag buildings, increasing the tensile strength of the material and providing a more predictable structural behavior.

Case study: Comparative sustainable performance indicators results between earthbag social house and reinforced brick masonry social house

Main characteristics of the houses evaluated

In this section an earthbag social house and a brick reinforced masonry social house are compared in terms of energy, CO₂ emissions and costs. The main characteristics of the buildings can be seen in Table 2. Figure 3 shows the proposed plans for the reinforced brick masonry social house and the earthbag social house.

Sustainable performance results: Costs, energy and CO₂ emissions.

Table 3 summarizes the main results of both alternatives in terms of CO₂ emissions, energy and costs per habitable m².

Table 2. Main characteristics of the houses evaluated. Source: self-elaboration.

	Earthbag house	Reinforced brick masonry house
Building system	Earthbags	Reinforced masonry
Wall materials	Compacted soil-cement 70% sand, 15% clay, 5% loam, 10% cement	Ceramic clay bricks
Roofing material	Wooden structure Onduline roofing system (organic fibers with bitumen)	Steel structure Zinc roofing system
Thermal insulation	According to thermal zone 4 of Chile	According to thermal zone 4 of Chile
Spaces	Living room, kitchen, bathroom, 2 bedrooms	Living room, kitchen, bathroom, 2 bedrooms
Habitable area	50.35 m ²	50.70 m ²
% Glazed surface	7.48%	7.00%
Energy requirements for heating and cooling	301.32 MJ/m ² /year	383.76 MJ/m ² /year

Figure 3. (a) Reinforced brick masonry social house plan; (b) Earthbag social house plan. Source: self-elaboration.

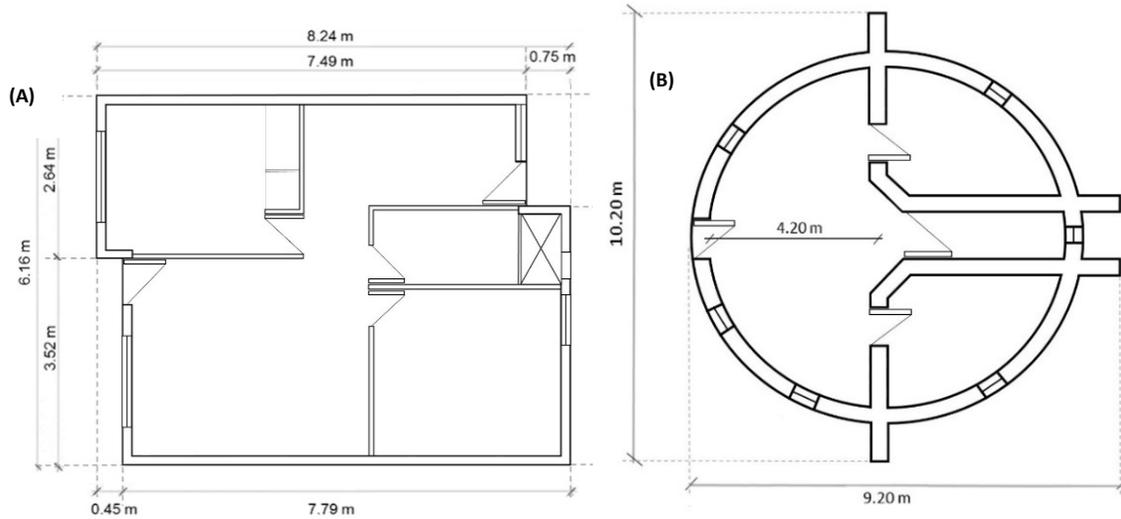
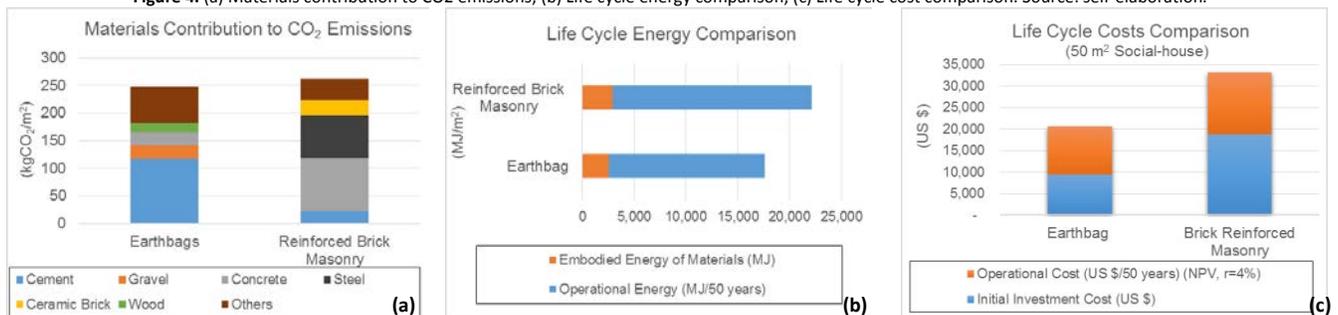


Table 3. Sustainable performance indicators between earthbag social-house and reinforced brick masonry social house. Source: self-elaboration.

Sustainable performance indicator	Earthbag habitable m ²	Reinforced brick masonry habitable m ²
Embodied CO ₂ emissions of materials (kgCO ₂)	247	262
Operational CO ₂ emissions (kgCO ₂)	0	0
Life cycle CO₂ emissions (kgCO₂)	247	262
Embodied energy of materials (MJ)	2,561	2,916
Operational energy (MJ/50 years)	15,066	19,188
Life cycle energy (MJ/50 years)	17,627	22,104
Initial investment cost (US \$)	187	370
Operational cost (US \$/50 years) (NPV, r=4%)	223	284
Life cycle cost (US\$ NPV, r=4%)	410	654

As seen in Figure 4(a), both alternatives present a similar performance in terms of life cycle CO₂ emissions, but it is important to notice that the emissions of the earthbag house were mainly due to industrialized materials such as cement. The earthbag house has a superior performance, compared to the reinforced brick masonry house, in terms of energy exhibiting savings of 12% for embodied energy of materials and 20% for the overall life cycle energy, as seen in Figure 4(b). These savings in energy are associated with the better thermal performance of the earthbag house. Furthermore, it is noticed that about 90% of the life cycle energy, corresponds to operational energy due to heating and cooling. This indicates that it might be important to improve housing thermal insulation in order to achieve greater energy and costs savings. Finally, the most important benefit of the earthbags house can be found in economic terms, as shown in Figure 4(c), where the earthbag house presents savings of 50% in initial investment costs and 38% in life cycle costs compared to the brick reinforced masonry house.

Figure 4. (a) Materials contribution to CO₂ emissions; (b) Life cycle energy comparison; (c) Life cycle cost comparison. Source: self-elaboration.



Earthbag construction integrates benefits of traditional raw-earth construction with benefits of modern construction, such as stabilization, using industrialized materials to obtain buildings with enhanced performance in structural, thermal, acoustic, and economic terms compared to traditional building systems, such as reinforced brick masonry, commonly used for social housing.

Although there have been an increasing number of investigations evaluating the satisfactory structural performance of earthbag building systems, and consequently, the implementation of these projects has increased worldwide, Chile still lacks a building code that normalizes the use of this technique which might disincentive its use. A case study was presented herein to analyze and compare the LCA and life cycle cost of an earthbag social house to a reinforced brick masonry social house. Results show that the earthbag alternative generates a 20% of energy saving in life cycle terms and a 50% saving in initial investment and savings of 38% over the life cycle cost as compared to the conventional brick reinforced masonry social house, which incentives the further study of this alternative for social houses in Chile.

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