

PAPER • OPEN ACCESS

Integrating Earthen Building Materials and Methods into Mainstream Construction Using Environmental Performance Assessment and Building Policy

To cite this article: L Ben-Alon *et al* 2019 *IOP Conf. Ser.: Earth Environ. Sci.* **323** 012139

View the [article online](#) for updates and enhancements.

You may also like

- [Environmental assessment of the Akmola region territories relative to the exposure to diseases of the population by the signal deviation method](#)
A S Kurmanbayeva, A A Kakabayev, Z E Bayazitova et al.
- [Strategic environmental assessment and monitoring: Arctic key gaps and bridging pathways](#)
Juan Azcárate, Berit Balfors, Arvid Bring et al.
- [Exploring the quality of evidence for complex and contested policy decisions](#)
Jeroen P van der Sluijs, Arthur C Petersen, Peter H M Janssen et al.



ECS
The
Electrochemical
Society
Advancing solid state &
electrochemical science & technology

DISCOVER
how sustainability
intersects with
electrochemistry & solid
state science research

Integrating Earthen Building Materials and Methods into Mainstream Construction Using Environmental Performance Assessment and Building Policy

Ben-Alon L¹, Loftness V¹, Harries K A², Cochran Hameen E¹

¹ School of Architecture, Carnegie Mellon University, Pittsburgh, PA 15217, USA

² Department of Civil and Environ. Engineering, University of Pittsburgh, Pitt, PA 15260, USA

rbenalon@andrew.cmu.edu

Abstract. Earthen building materials offer an environmentally sustainable alternative to conventional materials because they are locally available, minimally processed, and waste-free. However, they have not been comprehensively implemented because their technical data is highly variable, and they are not fully represented in building codes. To address these hurdles, this paper presents an environmental assessment and a policy repair review, including an environmental embodied impact analysis, and a discussion of the regulatory development required for earthen construction. The results of the environmental assessment show that earthen wall assemblies significantly reduce environmental impacts by 62-99% when compared with conventional assemblies such as timber frame and concrete blocks. Additionally, the policy discussion provides recommendations to overcoming materials variability and regulatory organizational collaboration. Overall, this paper highlights the importance of environmental and policy measures that could be used by policy makers and earthen building advocates in their endeavours to catalyse the representation of earthen building materials and methods in mainstream construction.

1. A brief history of unsustainable architecture

Throughout history, human building practices followed the path of building shelters out of locally abundant materials, where the building components were always mined and curated from the nearby environment: earth, stone, trees and grasses. The evolution of these various shelters was developed in different cultures by improving materials, energy, water, and waste solutions, adjusting from generation to generation to meet new needs and opportunities [1,2].

It is only in the last few centuries that our relationship with buildings has changed. Cementitious materials started playing a vital role in the ancient world: the Egyptians obtained cementitious material by burning gypsum; the Greeks used lime by heating limestone; and the Romans developed hydraulic cement by adding crushed volcanic ash to the lime [3]. These techniques were re-developed and patented in western Europe as “Roman —Cement” (in 1794) and “Portland Cement” (in 1824) [2,4].



These last developments, accompanied by the industrial revolution, changed the way building materials were produced and the techniques used for construction. Started as a wave in Western Europe, these highly-processed building materials and methods are still spreading into less-developed parts over the world. Thousands of new building products have been developed and replaced local traditional materials in ways that minimize labor and allow an increase in the pace and amount of construction. Nevertheless, these modern building practices require the extraction, transportation, and heavy processing of (often toxic) building products in ways that contribute to the consumption of large amounts of non-renewable resources, contributing to the deterioration of our global environment [5].

In terms of building materials standardization, conventional modern construction materials, mostly made of steel reinforced concrete, wood, and synthetic insulation, are being implemented in the majority of modern buildings while meeting a wide variety of building codes and standards. Therefore, in light of the environmental impacts specified above, these building codes and standards (that were initially developed to ensure individual safety and public general welfare) are currently neglecting larger, ecologically-based risks to natural systems upon which everyone's safety and health ultimately depend [6]. Nonetheless, due to an increased interest in sustainable and green building practices, additional non-mandatory regulatory and rating systems have been developed that support materials and resources considerations in projects, as shown by the growing numbers of L.E.E.DTM certified projects [7,8].

2. Why earth? The case for earthen building materials and methods

Parallel to the interest in sustainable and green building practices, there has been a growing interest in ecological and natural building materials and methods [8]. These are defined as minimally processed and locally available materials that enhance their local environment and economy, rather than only mitigating negative impacts [9]. Examples of natural building materials include natural fibers like straw and hemp, and earthen materials like sand and clay. Specifically, earthen materials exhibit various advantages; they provide high thermal inertia and offer better structural capacity in compression. As opposed to trees and crops, earth is usually abundant in and around the construction site. As opposed to cellulose-based materials, it has better resistance to fungi, insects and rodents. Furthermore, it allows a diversity of forms and styles, from sculptural monolithic assemblies to modular components [10].

Earthen architecture can be defined as building materials and methods in which clay is used as a binder [11]. It is also often referred to as a traditional and/or vernacular building material and method [12]. However, some earthen building techniques were developed in the past few decades (e.g., compressed earth blocks), while others were used traditionally and currently receive a new architectural interpretation (e.g., rammed earth) [13,14]. More specifically, in recent decades, material science has come to know much more about how clay works as a natural binder in building materials. Therefore, earthen building materials are recently suggested to provide a natural concrete alternative, namely a low-carbon, clay-based concrete [11].

Despite their benefits, earthen building materials and methods remain mostly unrealized in the mainstream construction industry from various reasons. First, the literature lacks aggregation of technical data that could quantify the performance of earthen materials for different climate and seismic conditions [15,16]. Second, there is a broad and often mistaken perception of these materials as being low-tech and having poor overall performance [8,17]. Lastly, one of the main barriers that is especially evident in the case of cob and earthbags is the lack of complete and user-friendly codes and regulations that could give rise to the conventional implementation of, for instance, affordable homes [6,18].

These concerns are broadly echoed in the literature. Woolley (2006) concludes that public policy incentives, particularly formal codes and regulations, should be developed for earthen materials, accompanied with financial incentives, in order to give rise to real-estate investments. Similarly, Swan, Rteil, and Lovegrove (2011) suggest that future research should a) aggregate the existing experimental engineering studies; b) provide analytical and numerical insights that could facilitate the design process and allow the inclusion of earthen materials in building codes; and c) provide a life cycle analysis of earthen construction assemblies.

3. Performance-based assessment of earthen building materials vs. conventional assemblies

The performance of a building material describes its functioning in terms of declared characteristic properties. Depicted though levels, classes or short descriptions, these performance parameters can portray the main features of earthen materials as opposed to conventional assemblies.

Table 1. Technical performance of earthen materials as opposed to conventional materials

Performance Parameter		Earthen Building Materials			Timber Frame [19]	Concrete Masonry [20] uninsulated (insulated)
		Cob	Rammed Earth	Light Straw Clay		
Thermal	Thermal Resistance (m²K/W per inch)	0.051 [21] to 0.106 [22]	0.025 [21,23] to 0.06 [24]	0.14 [25] to 0.26 [26]	0.5-0.7 (with fiberglass batt)	0.05 (0.15) [27]
	Thermal capacity (kJ/m³K)	1655 [28]	1830 [29]	400 [26]	10 [26] (25) [30]	170-380, depending on grouting [31]
	Decrement factor time lag (hour)	12 [21]	18.5 [26]	6.5 [26]	9 [26]	14 [26]
	Indoor RH amplitude			13.7% [25]		(22.6%) [25]
Environmental (Sec. 4.	Embodied energy MJ _{eq} /m²	86.4	71.1	65.4	241	226 (uninsulated), 491(insulated)
	Global climate change kgCO² _{eq} /m²	13.2	11.1	10.6	62.7	53.1 - 74.8
	Air acidification kgSO² _{eq} /m²	0.00679	0.00279	0.0125	0.0781	0.061 - 0.142
	Air particulate pollution PM _{2.5eq} /m²	0.00247	0.00145	0.00225	0.0574	0.130 - 0.143
Structural	Compression modulus (N/mm²)	72 [32,33] to 650 [16]	550-960 [34]	Not load bearing	7,000-18,000 along grain [34]	15,000 - 60,000 [34]
	Rupture modulus (N/mm²)	0.17 [32] to 0.98 [33]		Not load bearing		
Others	Sound Transmission Class (STC)		57 [10]		33 [10]	55 [35]
	Fire resistance	Fire resistant [34,36]		Fire retardant [34,36]	Combustible requiring treatment or oversizing (ISO type 1).	Semi Fire Resistive (ISO type 5).

4. Environmental embodied impacts of earthen construction vs. conventional assemblies

Environmental LCA has become a common tool that is used to evaluate building products and processes. It is considered a powerful tool for the evaluation of and contribution to sustainable building development. [37]. However, LCA progress is slower in the building sector than other industries, especially due to buildings' complicated production process. Although the environmental LCA of earthen materials has not been comprehensively studied, it has been argued extensively that earthen materials and methods can potentially require less energy and emit less Green House Gasses (GHG), due to their self-sustaining, socially sustainable, cradle-to-cradle life cycle, as shown in Figure 1 [34].

Only a few studies have enumerated the environmental impacts of earthen building materials, including the LCA of adobe bricks [38,39], rammed earth [40,41], and earthen plasters [42,43]. Though

significant, these studies are not comparable with conventional assemblies, due to the location and process-specific data used. To address this limitation, this study compares the environmental impacts of different earthen construction techniques to benchmark conventional techniques.

The presented LCA was implemented following the ISO Standard 14040 and 14044 format and methodology [44,45], using the SimaPro software [46], the US-LCI database [47] where possible, and EcoInvent [48] processes that are globally applicable otherwise (i.e., RoW processes). Six wall assemblies are compared: 3 earthen walls (cob, rammed earth, and light straw clay) and 3 conventional walls (timber frame, insulated and uninsulated concrete block). The functional unit used is 1 square meter of a single-family housing wall, located in warm-hot climates in the US, defined as IECC climate zones 1 through 4 [49]. The system boundaries consider embodied environmental impacts from cradle to construction site, including the extraction and processing of raw materials, manufacturing, storage, and transporting to the construction site.



Figure 1: Cradle to cradle life cycle diagram of earth as a building material (edited from Schroeder, 2016)

The Life Cycle Impact Assessment (LCIA) includes embodied energy demand, global climate change impacts, air acidification, and human health (HH) air particulate pollution. The impacts were assessed using CED (Cumulative Energy Demand) factors for fuels and sources of energy [50] and the TRACI (Tool for Reduction and Assessment of Chemicals and Other Environmental Impacts) for inventory emissions [51]. Weight distribution was calculated for each of the earthen wall components: straw, sand, clay-rich soil, and clay plaster. The cob and rammed earth walls were assumed to have an average 460 mm thickness [52,53], and the light straw clay wall a 300 mm thickness [54]. Clay-rich soil was assumed to contain 50% clay and the study accounts for a scenario in which this soil is not available on site and thus is processed and transported from a quarry. The LCA of the benchmark wall assemblies was assessed using existing LCI results. Specifically, the wood frame LCI incorporated lumber [55], plywood sheathing [56,57], gypsum board [58], and fiberglass batt. The concrete LCI incorporated concrete blocks [61], rigid polystyrene insulation [59], and Portland cement stucco [60]. These LCIs were selected according to their corresponding system boundaries of cradle to gate and geographical context of North America.

The impact assessment results, shown in

Figure 2, illustrate that all earthen wall systems have significantly lower environmental impacts as opposed to the benchmark wood and concrete block assemblies. Embodied energy demand of earthen walls is reduced 62-71% from that of conventional construction; embodied global climate change impacts are reduced 85-91%; embodied air acidification is reduced 79-95%; and embodied particulate pollution is virtually eliminated. These comparative results depict the environmental urgency of using earthen materials.

Specifically, transportation distances and amount of straw have the strongest effect on the environmental impacts of the different earthen walls. Among the earthen walls, light straw clay accounts for the least energy demand and global climate change impacts, due to its smaller thickness, as well as the absence of the sand and soil that require truck transportation. The rammed earth wall, with the same thickness as cob, results in fewer environmental impacts than cob for all impact categories due to its absence of straw that requires large amounts of chemicals for production. For the same reason, light straw clay has the highest impacts in terms of air acidification, following by cob, due to the straw production-stage emissions of methane (CH₄), sulphur dioxide (SO₂), and nitrogen oxides (NO_x), associated with the use of pesticides and fertilizers.

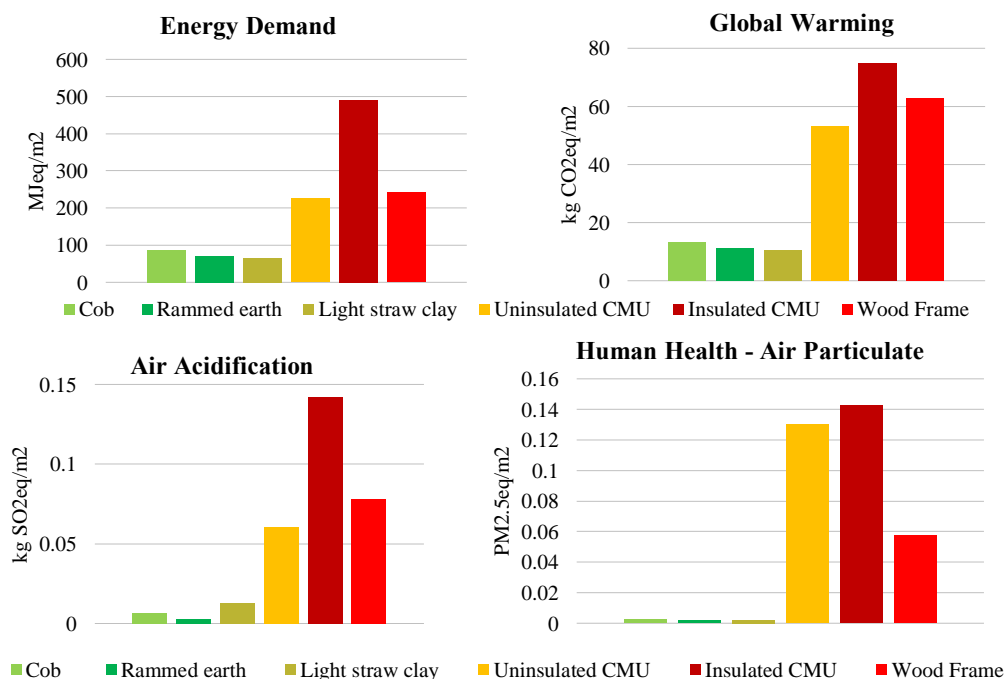


Figure 2: Environmental embodied impacts comparison among the different wall systems: cob, rammed earth, light straw clay, uninsulated Concrete Masonry Unit (CMU) blocks, insulated CMU, and wood frame (Source: authors)

5. Required Improvements to Earthen Building Policy

5.1. The Importance of Earthen Codes and Standards

The importance of earthen building materials standardization lies in both technical and sociocultural realms. In terms of their technical significance, standards for earthen materials gather accurate design values as well as provide a common frame of reference for the user community – a lingua franca of sorts. Technical performance tests could be compiled to obtain a more reliable understanding of the material's properties based on a statistical analysis which can lead to the refinement of, and confidence in, design values. This, in turn, could lead to a broader integration of the material in the construction community. Such integration, coupled with advocacy, can lead to broader social acceptance of what was previously considered a marginalized vernacular construction method [62]. While approximately a third of the world population lives in earthen structures, in both developing and developed countries, the existence of appropriate codes is of importance. However, current building codes are based on heavily processed materials such as concrete and steel products, earthen techniques that cannot fulfil heavy load bearing and high insulation requirements were excluded [63].

5.2. Challenges and Suggested Solutions to the Development of Earthen Codes and Standards

In order to embed earthen building materials in building standards and codes, their performance should be assessed through the work of universities, laboratories and professional organizations. To date, earthen building materials and methods are still considered nonconventional and their standardization is in its earliest stages; design, construction, testing protocols and technical terminology, even among experts, is fragmented and requires further evolution. However, in this context, even conventional construction materials such as steel, timber, and reinforced concrete were once unconventional and unproven materials and their acceptance was achieved through decades of testing, analysis, and experience. Codes and standards development has been described as “a long and onerous” process (Mottram 2017). Particularly for materials having few existing precedents, the task is daunting and meets resistance at many steps. The following lists many of the challenges and possible strategies to overcoming these.

5.2.1. Overcoming Materials Variability. One of the main challenges to the emergence of earthen materials standards is their high variability and reliance on local construction methods. Additionally, earthen materials are often locally sourced and processed or mixed on site. Such variation effects both the construction process (e.g., workability, drying time) and the performance of the building outcome (e.g., structural, thermal, durability). For instance, in an experimental study of cob technical performance, specimens were collected from local builders, resulting in a high coefficient of variation among the different mixtures [32]. In terms of building standards, this high variability could reduce characteristic strength values that could result in inefficient utilization of the material. This, in turn, could potentially lead to unrealistic required building element dimensions and higher environmental and monetary costs. Furthermore, due to their variability, and in order to verify their code compliance and desired performance, natural materials require frequent field tests.

The challenge of material variation could be addressed by various strategies. By using wood as an example for a natural building material with large variability, we can identify the ways in which we developed both prescriptive and performance standards for timber. While the number of wood species is great, the main strategy used in timber standardization is to group species according to their structural properties and appearances, prescribing uniform grade-use data for each group. Similar to timber codes and standards, a homogenization approach grouping different species or ‘classes’ of clay materials should be developed for earthen materials to ensure adherence with format and objectives of conventional standards.



Figure 3: Homogenized soil classification, assessed in accordance with Australian Standard [64]

5.2.2. Establishing Collaborative Standardisation Framework to Overcome Financial Challenges. Earthen building materials are non-commodified systems that have no ‘industry association’. Often, they cannot be developed into products and cannot be patented. This leads to a lack of financial support and advocacy of nonconventional and vernacular materials at code and standards organizations and committees, whereas established conventional building materials representation is often compensated by their organization [65]. Additionally, national standard-writing organizations with limited resources and volunteer committees have little incentive to address technology that is often considered marginal.

One way to overcome this situation is to have existing experts organize in a way that can produce valuable exchange of experience and technical documents. For instance, in the case of the New Zealand earth building standards, the Earth Building Association of New Zealand (EBANZ), with the

participation of local engineers and architects, first developed a set of guidelines in 1991. Thereafter, New Zealand Standards (NZS) took responsibility for the project and joined together with Standards Australia in 1993 to develop a joint standard with an enlarged committee [66]. The collaboration was discontinued in 1997 mainly due differences in seismic requirements, yet the exchange of information and expertise was valuable. One year later, NZS published the New Zealand earth building standards (NZS 4297, NZS 4298, NZS 4299), which comply with the local Building Code. Simultaneously, Standards Australia developed *The Australian Earth Building Handbook* (HB-195 2002) and the Earth Building Association of Australia (EBAA) developed the *Building with Earth Bricks and Rammed Earth in Australia* (EBAA 1997). The hybrid approach of Standards and non-standards bodies' development of construction guidance for earthen material is summarized in Figure 4.

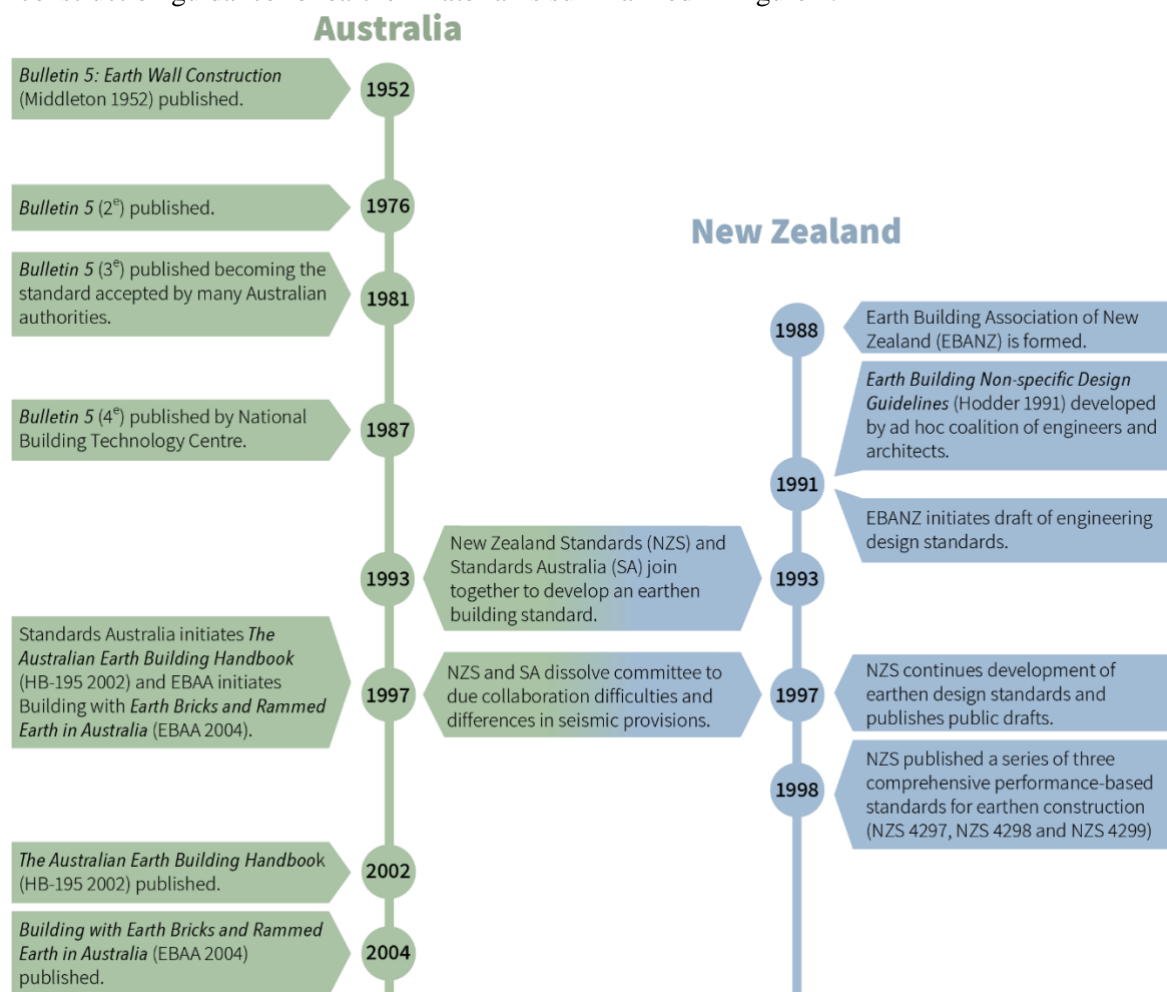


Figure 4: Timeline of New Zealand and Australia Earth Building Standards development process (Source: authors)

Additionally, using verb form is crucial to earthen building regulatory development. Similarly to NZS, Code-compliant mandatory language could allow reference from within building codes. Enacting documents or clauses – those that represent a legal obligation – are conventionally required to provide unequivocal and imperative requirements: “shall”. Recommendations (“should”) and permissive language (“may”) are relegated to non-mandatory appendices or documents and are legally unenforceable, such as in the case of ASTM E2392.

5.2.3. Enriching traditional techniques with modern knowledge. Experience from previous generations that is well preserved in local tradition and dutifully transmitted to people living today can be the basis of an informal, non-codified “standard”. For instance, bamboo standards consider the use of traditional practices as those constituting an “old and pure tradition” or treated as “general wisdom” within a community. The application of such traditional expertise is limited to similar scenarios and may not be extrapolated in terms of dimensional scale or locale [67].

Codes and standards reflect state-of-practice rather than the state-of-the-art. Therefore, the development of a sound ‘engineering judgement’ is an iterative process of continuous improvement and is reflected in the maintenance of standards worldwide. For this reason, standard development for earthen materials must begin with synthesis of the existing engineering data, as well as documentation and enhancement of local practices. Such synthesis requires using consistent test procedures in materials test studies, as well as proper documentation and analysis of results. To date, researchers studying earthen materials have adopted different established test methods – some for concrete materials, others for masonry units, and even others for masonry assemblies – and their attendant specimen geometries. These result in a considerable range of reported data that cannot be directly compared. In some cases, test method selection results in a bias in reported properties. For example, it has been shown that different studies report the compression modulus of cob material to vary by an order of magnitude depending on the test method used [68].

5.2.4. Establishing Clarity and User Friendliness in Earthen Building Codes. “Usability” of a standard, as the word implies, must be based on the needs and expectations of the user. An alternative to presenting design examples is to develop navigation flow charts for design standard provisions or typical design cases (for instance, as provided in [69]). These serve to improve ease of navigation but are also a tool the standard authors can use to ensure clarity and completeness. Development of a design work flow chart can identify provisions which are incomplete, lead to ‘dead ends’, or result in complex iterative procedures.

Additionally, the purpose of the code or standard should be clearly defined in order to reduce complexity and to refine its scope. For instance, a very specific scope statement is included in the New Zealand Earth Building Standards: *The objective of this Standard is to provide for the structural and durability design of earth buildings. The Standard is intended to be approved as a means of compliance with clauses B1 and B2 of the New Zealand Building Code (NZS 4297).* A more general suggested example may be an object *to codify existing knowledge in order to ensure structural safety, as well as to address common design situations while providing means of compliance with building codes and supporting innovative design.*

When considering earthen materials that are often nonconventional and vernacular, the user community might be further removed from the standards development process, increasing the risk of misinterpretation. This might lead to the standards simply not being applied at all. On one hand, the opportunity afforded by nonconventional materials for starting with a “blank page” when developing standards should be used to mitigate unnecessary complexity. On the other hand, existing codes and standards as well as committee constitutions that prove successful should be used as exemplars to avoid excessive complexity that results from “re-inventing the wheel”.

6. Conclusions and Required Future Steps

Earthen building materials and methods offer a prominent solution to conventional highly processed materials. However, despite their advantages, earthen materials and methods have not been comprehensively implemented because their technical data is inconsistent, and they are not comprehensively represented in building codes. To address these hurdles, this paper begins with a comparative synthesis of the technical performance of earthen materials as opposed to conventional assemblies. Thereafter, the paper presents an environmental LCA that enumerate the environmental urgency of earthen materials, showing that the earthen walls save 62-71% of embodied energy demand, reduce 85-91% of embodied global climate change impacts, 79-95% of embodied air acidification and

98-99% embodied particulate pollution. Lastly, a discussion of the regulatory development required for earthen construction is presented, including main challenges and recommendations to overcoming these, including ways to overcome challenges of materials variability, collaborate between advocates and organizations, integrate traditional expertise with state-of-the-art knowledge, and establish language and scope clarity. Future studies on the environmental and policy measures should incorporate a full LCA that takes into account operational impacts, as well as develop inventories for a complete set of earthen and natural wall assemblies that could be used against inventories of benchmark wall assemblies.

References

- [1] Kahn L 1990 *Shelter* (Shelter Publications)
- [2] Wanek C, Smith M and Kennedy J 2002 *The Art of Natural Building: Design, Construction, Resources* (New Societ Publishers)
- [3] Lechtman H N and Hobbs L W 1986 Roman concrete and the Roman architectural revolution ed W D Kingery *High-technology Ceram. past, Present. Futur. Nat. Innov. Chang. Ceram. Technol.* **3** 81–128
- [4] Peter C H 2006 *Lea Chemistry of Cement and Concrete* (Elsevier Butterworth- Heinemann)
- [5] United Nations Environmental Program 2009 *Buildings and Climate C hange*
- [6] Eisenberg D and Yost P 2004 Sustainability and building codes *Sustain. Urban Dev. Read.* 193–8
- [7] Shutters C 2015 New Study Finds Green Construction is Major U.S. Economic Driver *U.S. Green Build. Counc.*
- [8] MacDougall C 2008 Natural Building Materials in Mainstream Construction: Lessons from the U. K. *J. Green Build.* **3** 1–14
- [9] Van der Ryn S and Cowan S 2007 *Ecological design* (Island Press)
- [10] Racusin J and McArleton A 2012 *The Natural Building Companion: A Comprehensive Guide to Integrative Design and Construction*
- [11] King B 2017 *The New Carbon Architecture: Building to Cool the Planet.* (New Society Pub)
- [12] Niroumand H, Kibert C J, Antonio Barcelo J and Saaly M 2017 Contribution of national guidelines in industry growth of earth architecture and earth buildings as a vernacular architecture *Renew. Sustain. Energy Rev.* **74** 1108–18
- [13] Serrano S, De Gracia A and Cabeza L F 2016 Adaptation of rammed earth to modern construction systems: Comparative study of thermal behavior under summer conditions *Appl. Energy* **175** 180–8
- [14] Ciancio D and Beckett C 2015 *Rammed earth construction : cutting-edge research on traditional and modern rammed earth* (CRC Press)
- [15] Woolley T 2006 *Natural Building: A Guide to Materials and Techniques* (Crowood Press)
- [16] Miccoli L, Müller U and Fontana P 2014 Mechanical behaviour of earthen materials: A comparison between earth block masonry, rammed earth and cob *Constr. Build. Mater.* **61** 327–39
- [17] Spišáková M and Mačková D 2015 The use potential of traditional building materials for the realization of structures by modern methods of construction *Sel. Sci. Pap. Civ. Eng.* **10** 127–38
- [18] Swan A J, Rteil A and Lovegrove G 2011 Sustainable Earthen and Straw Bale Construction in North American Buildings: Codes and Practice *J. Mater. Civ. Eng.* **23** 866–72
- [19] AF&PA 2001 *Details for Conventional Wood Frame Construction*
- [20] Farny J, Melander J and Panarese W 2008 *Concrete Masonry Handbook for Architects, Engineers, Builders*
- [21] Heathcote K 2011 The Thermal Performance of Earth Buildings *Inf. la Construcción* **63** 117–26
- [22] Goodvin C, Baird G and Baird A 2011 Cob Home Performance Report
- [23] Röhlen U and Ziegert C 2011 *Earth Building Practice: Planning - Design - Building* (Beuth Verlag GmbH)

- [24] Walker P and Standards Australia 2001 The Australian Earth Building Handbook HB 195-2002
- [25] Labat M, Magniont C, Oudhof N and Aubert J E 2016 From the experimental characterization of the hygrothermal properties of straw-clay mixtures to the numerical assessment of their buffering potential *Build. Environ.* **97** 69–81
- [26] Goodhew S and Griffiths R 2005 Sustainable earth walls to meet the building regulations *Energy Build.* **37** 451–9
- [27] National Concrete Masonry Association E 2014 *R-VALUES AND U-FACTORS OF SINGLE WYTHE CONCRETE MASONRY WALLS*
- [28] Michael S and Goodhew R 2000 THE THERMAL PROPERTIES OF COB BUILDINGS OF DEVON
- [29] Houben H, Guillaud H, CRAterre. and Intermediate Technology Publications. 1994 *Earth construction : a comprehensive guide* (Intermediate Technology Publications)
- [30] Rüdiger D 2015 Thermal transmittance and dynamic performance (thermal mass) of a timber-frame wall *HTflux Hygric Therm. Simul.*
- [31] National Concrete Masonry Association, Atlas Block N T 2008 *HEAT CAPACITY (HC) VALUES FOR CONCRETE MASONRY WALLS*
- [32] Pullen Q M and Scholz T V 2011 Index and Engineering Properties of Oregon Cob *J. Green Build.* **6** 88–106
- [33] Rizza M and Böttger H 2015 Effect of Straw Length and Quantity on Mechanical Properties of Cob *The 16th Non-Conventional Materials and Technologies* (Winnipeg, CA)
- [34] Schroeder H 2016 *Sustainable Building with Earth* (Springer)
- [35] DuPree R 1980 Catalog of STC and IIC ratings for wall and floor/ceiling assemblies
- [36] DIN 4102-4 2016 *Fire behaviour of building materials and building components - Part 4: Synopsis and application of classified building materials, components and special components*
- [37] Khasreen M M, Banfill P F G and Menzies G F 2009 Life-Cycle Assessment and the Environmental Impact of Buildings: A Review *Sustainability* **1** 674–701
- [38] Christoforou E, Kylili A and Fokaides P 2016 Cradle to site LCA of adobe bricks *J. Clean. Prod.* **112** 443–52
- [39] Shukla A, Tiwari G N and Sodha M S 2009 Embodied energy analysis of adobe house *Renew. Energy* **34** 755–61
- [40] Serrano S, Barreneche C, Rincón L, Boer D and Cabeza L F 2012 Stabilized rammed earth incorporating PCM: Optimization and improvement of thermal properties and LCA *Energy Procedia* **30** 461–70
- [41] Treloar G J, Owen C and Fay R 2001 Environmental assessment of rammed earth construction systems *Struct. Surv.* **19** 99–106
- [42] Melià P, Ruggieri G, Sabbadini S and Dotelli G 2014 Environmental impacts of natural and conventional building materials: a case study on earth plasters *J. Clean. Prod.* **80** 179–86
- [43] Morela J C, Mesbaha A, Oggerob M and Walker P 2001 Building houses with local materials: means to drastically reduce environmental impact of construction *Build. Environ.* **36** 1119–26
- [44] ISO 2006 *14044:2006 Environmental management - LCA Requirements and guidelines*
- [45] ISO 2006 *14040:2006 Environmental Management - LCA Principles and framework*
- [46] Pre Consultants 2017 SimaPro Life Cycle Analysis version 8 (software)
- [47] NREL 2012 *US LCI database for Simapro*
- [48] Wernet G, Bauer C, Steubing B, Reinhard J, Moreno-Ruiz E and Weidema B 2016 The ecoinvent database version 3: overview and methodology. *Int. J. Life Cycle Assess.* **21** 1218–30
- [49] ICC 2018 Chapter 4 [RE] Residential Energy Efficiency *IECC*
- [50] Frischknecht R, Wyss F, Knöpfel S B, Lützkendorf T and Balouktsi M 2015 Cumulative energy demand in LCA: the energy harvested approach *Int. J. Life Cycle Assess.* **20** 957–969
- [51] Bare J C 2012 *Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts (TRACI) TRACI version 2.1 - User's Manual*

- [52] Tolles E L, Kimbro E E and Ginell W S 2002 *Planning and Engineering Guidelines for the Seismic Retrofitting of Historic Adobe Structures*
- [53] NMAC 2015 *2015 New Mexico Earthen Building Materials Code*
- [54] IRC 2015 *Appendix R Light Straw-Clay Construction*
- [55] Puettmann M, Consultants W E and Oneil E 2013 Cradle to Gate Life Cycle Assessment of Softwood Lumber Production from the Pacific Northwest 1–35
- [56] Matthews S A 2011 *A Life Cycle Comparison of Light-Frame Wood and Insulated Concrete Form Building Envelopes : Energy Use and Green House Gases*
- [57] NREL 2012 U.S. Life Cycle Inventory Database
- [58] Athena 1997 *Life Cycle Analysis of Gypsum Board and Associated Finishing Products*
- [59] Athena 1999 *Life Cycle Inventory Analyses of Building Envelope Materials: Update and Expansion*
- [60] Athena 2001 *Cradle-To-Gate Life Cycle Inventory for Exterior Stucco Finishes* (Ottawa)
- [61] Nisbet M a, Marceau M L and Vangeem M G 2002 LCI of Portland Cement Concrete *Cycle*
- [62] Harries K A, Sharma B and Richard M 2012 Structural Use of Full Culm Bamboo: The Path to Standardization *Int. J. Archit. Eng. Constr.* **1** 66–75
- [63] Hall M R, Lindsay R and Krayenhoff M 2012 *Modern earth buildings : materials, engineering, construction and applications* (Woodhead Publishing)
- [64] MJM Consulting engineers 2017 Residential Soil Classification Report
- [65] Eisenberg D and Persram S 2009 Code, Regulatory and Systemic Barriers Affecting Living Building Projects 95
- [66] Walker R and Morris H 1998 Development of new performance based standards for earth building *Proc. Australas. Struct. Eng.*
- [67] ISO 22156 2004 *Bamboo-Structural design*
- [68] Ben-alon L, Loftness V, Harries K A and Hameen E C 2017 Integrating Earthen Building Materials and Methods into Mainstream Housing ... *Stages Earth USA 2017* (Santa Fe, NM)
- [69] AASHTO LRFD 2017 *Bridge Design Specifications* (Washington, DC: American Association of State Highway and Transportation Officials)