Integrating Earthen Building Materials and Methods into Mainstream Housing Projects throughout Design, Construction, and Commissioning Stages

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Abstract

Earthen building materials and methods offer a low-impact, truly sustainable alternative to conventional materials and methods currently used in mainstream construction of residential homes. However, the absence of adequate codes and standards for these methods is a barrier to broader implementation in mainstream construction practice. This paper analyzes this regulatory gap, and suggests an approach for developing policy repair that could bridge the interests of decision makers and grassroots advocates during the process of developing earthen building codes. A preliminary demonstration of this approach is explored for the specific case of cob construction, including (1) in-depth interviews to analyze the regulatory barrier, (2) environmental impact analysis in the form of a Life-Cycle Assessment (LCA), (3) a summary of the engineering properties of cob, and (4) a discussion of the regulatory development needed for cob.

1 Introduction

In the US, approximately 750,000 new homes are consistently constructed each year, of which 95% are 1 or 2 stories (US Census Bureau, 2015). These homes are mostly constructed of wood, synthetic insulation, concrete, bricks, and steel, while depleting large amounts of natural resources and increasing waste production and pollution (Ochoa et al. 2002; Treloar et al. 2003).

Although the building standards used for permitting these homes were developed to ensure safety and public welfare, these standards are currently neglecting larger, ecologically-based risks to natural systems, upon which public safety and health ultimately depend (Eisenberg & Yost, 2004). To improve environmental conditions resulting from current construction materials, the residential construction industry should strive to incorporate natural materials that are minimally processed and locally abundant (Melià et al. 2014; Pacheco-Torgal & Jalali, 2011). Examples of natural building materials and methods include straw-bale, hemp, bamboo, and earth (Harries & Sharma, 2016).

Earthen materials are among the oldest building materials used on the planet and continue to shelter approximately one third of the world's population (Wanek et al. 2002; Kahn 1990). Nevertheless, earthen building materials and methods are currently undergoing a new Renaissance (Easton, 2007; Evans et al., 2002; Minke, 2012, to list a few.)

From an environmental point of view, the broader implementation of earthen building materials and methods could result in lower embodied energy and fewer Greenhouse Gas (GHG) emissions than conventional building materials (MacDougall 2008; Morel et al. 2007). In most cases, earthen building methods tend to incorporate waste materials or byproducts that have excellent properties. Other benefits include their ability to passively regulate humidity in a building, and their low toxicity levels, high thermal mass, and biodegradability at the end of life which allows a cradle-to-cradle supply chain (Morel, et al. 2007; Pacheco-Torgal and Jalali 2011). In light of these environmental benefits, earthen construction methods require justification, demonstration, and code permission possibilities. However, despite the environmental benefits and bottom up attempts to implement them, many barriers and unrealized opportunities remain for earthen materials and methods in the mainstream construction industry.

2 Identification of Key Implementation Gaps

Not only does the current regulation exclude many earthen building methods, but it also contributes to forming a broader cycle of key implementation gaps, as shown in Figure 1.

2.1 Research Gap – Engineering Data is Insufficient and Disaggregated

While there is a growing body of research into the engineering properties of earthen building materials and methods, this research has not yet been efficiently aggregated. It is therefore difficult to address the variability and accuracy of these results, as well as to quantify earthen buildings' true performance for different climate and hazard conditions (Miccoli et al. 2014; Swan et al. 2011; Woolley 2006).

2.2 Perception Gap – Negative Perception Results from Lack of Knowledge

Research has shown that experts perceive natural building materials as 'low-tech' and poor in performance (MacDougall, 2008). Nevertheless, experts' skeptical attitudes toward natural building materials is caused by a) lack of knowledge, b) lack of experience, and c) cultural bias (Bristow, 2015; MacDougall, 2008; Spišáková & Mačková, 2015).

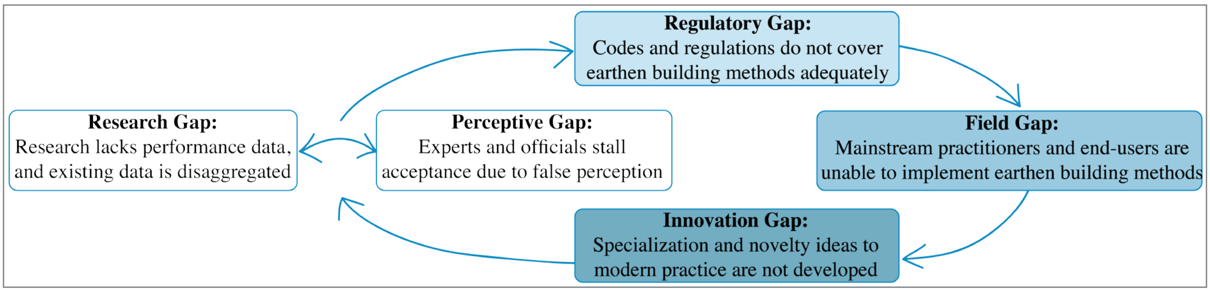

Figure 1. The Cycle of Key Implementation Gaps of Earthen Building Materials.

2.3 Regulatory Gap – Research and Perception Gaps Lead to a Regulatory Gap

Insufficient engineering data and negative perceptions have led experts to resist codes and regulations for earthen building methods (Bristow, 2015). In addition, despite their numerous environmental benefits, earthen building materials and methods are non-commodified systems and therefore lack financial support for expert representation in regulary committees (Eisenberg & Persram, 2009). The regulatory gap is especially evident in methods such as cob and earthbags, in contrast to adobe, earth bricks and rammed earth, which are represented in few limited local codes in regions where they have a cultural tradition (e.g., Pima County Arizona and New Mexico). Adobe is also represented in the International Building Code (IBC) masonry chapter, however minimally (Swan et al. 2011; Pullen and Scholz 2011) but, interestingly not in the International Residential Code (IRC). While not regulatory in nature, ASTM E2392 *Standard Guide for Design of Earthen Wall Building Systems*, provides guidance in terms of both technical and sustainability considerations for earthen construction. ASTM E2392 provides empirical design and minimum detailing guidance in non-mandatory language (thus, this document cannot be cited in a building code.)

2.4 Field Gap – Regulatory Obstacles Push Earth Methods Outside the Mainstream

Representations in building codes are insufficient and standard permits are hard to achieve, leading to a lack of experience by the mainstream construction industry in using earthen building methods (MacDougall, 2008; Swan et al., 2011). The exclusion of earthen building methods from the mainstream construction industry leaves these methods to either ownerbuilders and community efforts, or to wealthy households.

2.5 Innovation Gap – Lack of Field Practice Prevents Innovative Solutions

Finally, the demand for earthen building practice is not realized, thus leading to the lack of educated experts who might innovate the traditional techniques (Woolley, 2006). For instance, there is a need to find new ways to reinforce earthen structures because earthen structures in the USA are limited to one- and two-story structures in low seismic areas (ICC, 2015; NMAC, 2015; Pima County Development Services, 2013).

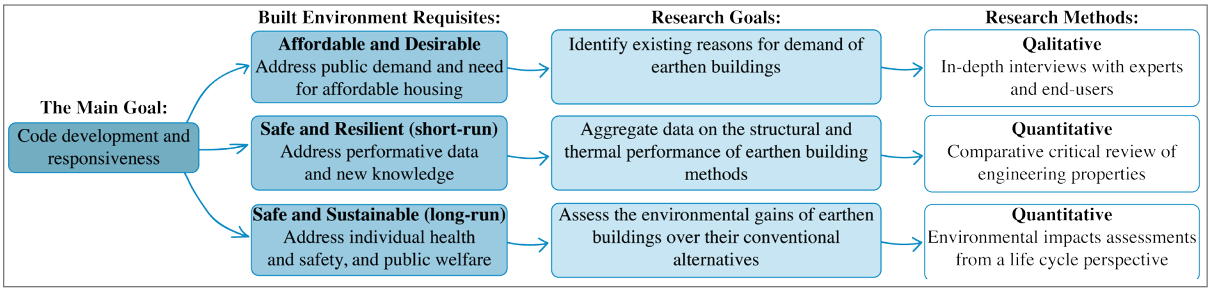

Figure 2. The proposed research approach to fulfill the main goal of earthen building code development.

3 The Proposed Approach

To address the research and regulatory gaps, the presented approach proposes an incorporation of both qualitative and quantitative studies, as described in Figure 2, and in the following sections.

3.1 Qualitative Study – The qualitative study includes in-depth interviews with experts and end-users. The main goal of the interviews is to describe both the factual situation and the story behind the interviewees' experience regarding the demand and the barriers to the implementation of earthen building materials and methods.

3.2 Quantitative Study – The quantitative study includes performance-based assessments and critical engineering data collection of earthen building materials and methods. The main goal of the performance-based assessment is to compare the environmental impacts of earthen building materials and methods against their conventional alternatives. The main goal of the critical engineering data collection is to enumerate engineering properties that could be used for code development.

4 Preliminary Qualitative and Quantitative Analysis of Cob

The earthen material and method chosen to demonstrate the research approach is cob, since it is becoming popular but lacks representation in USA building codes (Pullen et al., 2011.) Cob is an earthen building method that combines earth, natural fibers such as straw, and water. This mixture is produced in a plastic state and implemented wet to build monolithic and load bearing or freestanding walls. Cob is sometimes referred to as monolithic adobe, and has many other names worldwide, such as bauge (France), lehmweller (Germany), pasha (Turkey), and zabour (Yemen) (Hamard et al. 2016.)

4.1 Qualitative Study of Demand and Barriers of Cob Construction

In-depth interviews were conducted with six professionals with expertise in architecture, structural engineering, construction, and regulatory provisions of earthen building methods. Each interview included 5-7 open-ended questions, was conducted by telephone, recorded and transcribed, and ranged in duration from 60-120 minutes. Three main observations were derived from these preliminary interviews:

4.1.1 There is an Increasing Demand for Building with Cob

At present in the USA there are numerous attempts to build homes from cob, in a vernacular (and mostly extra regulatory) manner. According to the interview data, people are attracted to cob due to its affordability, sustainable nature, ecological and indoor air quality features, as well as simplicity of construction that can be easily implemented by a community.

4.1.2 The Regulatory Environment is the Main Barrier to Building with Cob

While cob technique is labor intensive, this is less of a barrier than permitting cob structures. According to the interviews, once the cob technique is chosen, the labor is embraced and in some cases even produces jobs for community members. However, the most challenging barrier faced by experts and end-users throughout the country is the structural justification of cob structures that could lead to the acknowledgment and code compliance of cob building technique.

Designers and engineers are required to provide evidence to local authorities for each building project to show that cob adheres to individual aspects of the building code - thermal, fire, seismic and more. Officials that are unfamiliar with earthen methods and (justifiably) do not want to bear the responsibility, set inflated requirements for the project permit. Not only do these requirements increase project costs and complexity, but also, in many cases, defy the nature and features of the incorporated earthen building technique. For instance, in order to avoid cob over-reinforcement, required by code officials in California, engineers have been adapting New Zealand Standard (NZS 4297) for earthen buildings to address issues of high seismic activity areas which are absent from any earthen US code.

4.1.3 Advocates are Organizing to Influence Existing Codes

In summary, the interviews showed that specialized earthen material experts have been lobbying the code governing bodies, and grassroots advocates (organized in NGOs such as CRI, Earth Builders Guild, CAL-EARTH) have been organizing to provide the technical information required for code inclusion. However, progress toward these goals has been slow. The main challenges for these efforts is the lack of engineering analysis and demonstration, as well as the time consuming and costly process of summarizing the engineering properties of cob. Interviewees consistently described the importance of aggregating the prior research and conducting tests in laboratories and field projects to influence existing codes.

4.2 Quantitative Study of Cob's Environmental Benefits and Engineering Properties

Environmental impact assessments from a life cycle perspective and quantification of a full set of engineering properties relative to code compliance were processed for cob.

4.2.1 Life Cycle Assessment (LCA) of Cob Versus Conventional Mater*ials*

As opposed to previous LCA studies of natural building materials (such as Christoforou et al., 2016; Melià et al., 2014; Prétot et al., 2014), this study's main goal is to extensively compare earthen and conventional building materials. This section presents summary results of a cob LCA cradle-to-site study that follows the methodology defined by ISO 14040. The aim of the study was to evaluate the embodied energy and carbon for cob in comparison to conventional materials. The system boundaries include the extraction, preparation, and transportation to the construction site of the required materials (clay sand and straw) for a 1kg dry cob mixture functional unit. Onsite mixing and assembly of the cob is beyond the system boundaries. As part of the study, a hybrid EIO-LCA and process-based LCA was developed, using financial-based allocations (Ben-Alon et al., 2017.)

The environmental impacts were assessed using Cumulative Energy Demand (CED) indicators, which measure the direct and indirect energy use over the entire life cycle of a product, and TRACI indicators which were used for embodied carbon estimation. The results of the cob mixture for embodied energy and carbon show that cob has significantly lower embodied energy and carbon, as opposed to other building materials (Table 1).

Table 1. Embodied energy and carbon per kg of cob in comparison to other building materials (from Jones and Hammond 2008)

Material	Cob	Brick	Limestone Brick	Cement	Soil Cement	Steel	Timber
embodied energy: MJ-eq/kg	0.065	3	0.85	4.6	0.85	24.4	8.5
embodied carbon: kgC/kg	0.036	0.06	--	0.23	0.038	0.48	0.12

4.2.2 Engineering Properties

Comparative analyses of engineering properties and failure mechanisms of cob are limited, and the results are considerably scattered as might be expected of such a material (Table 2). Material property tests results depend not only on factors such as workmanship and weathering, but also on the testing procedure. Specifically, tests using small prisms or cylinders adapted from concrete test procedures such as ASTM C39 ASTM C78, or ASTM C293 result in lower values than small wall specimens. This may be partially explained by the larger scale required for long straw stalks to fully affect the strength of cob specimens. Additionally, it is important that results from different test procedures not be compared directly. Standard test specimens for compression (ASTM C39) or flexure (ASTM C78 and C293) are intended to establish characteristic material properties and are conventionally based on reduced scale tests – such results comprise a lingua franca, of sorts, for engineers. Tests of multiple component wall units (“wallettes”) (ASTM E519 and DIN 1052-1) are conducted at “full-scale” and provide system- and material-specific design properties of assemblies and thus capture additional effects such as workmanship.

Certainly, for materials such as cob, which are expected to demonstrate considerable scale effects associated with the embedded straw, full scale component testing is preferred. A limitation therefore becomes cost. Standard tests are well-established, easily conducted almost anywhere in the world and require relatively inexpensive specimens (allowing a larger sample size) and test apparatus. Components tests are larger, more expensive (few samples) and require special test apparatuses (for example, ASTM E519).

Table 2. Engineering Properties of Cob, as Recorded by Laboratory Tests

Parameter	Source	Test Method	Condition	n	Strength	Modulus
Compression Strength & Modulus	Pullen et al., 2011	ASTM C39		6	102 psi	11,000 psi
	Rizza & Bottger, 2015	10 x 8 x 5 in. prisms tested parallel to long axis	conventional	4	76 psi	10,400 psi
			long straw added	4	88 psi	9,400 psi
			chopped straw added	4	41 psi	5,400 psi
	Miccoli et al., 2014	DIN EN 1052-1		1 Wallette	231 psi	94,400 psi
	Saxton, 1995	ASTM C39		24	145 psi	-
	Kleinfelder, 2005	ASTM C39		6	120 psi	
	Summit, 2016	ASTM C39		12	193 psi	
Modulus of Rupture	Pullen et al., 2011	ASTM C78		6	-	25 psi
	Rizza et al., 2015	Mid-span flexure of 2 x 2 x 6 in. beams	conventional	4	-	142 psi
			long straw added	6		78 psi
			chopped straw added	6		115 psi
	Kleinfelder, 2005	ASTM C293		6	105 psi	
Shear Strength & Modulus	Miccoli et al., 2014	ASTM E519		1 Wallette	145 psi	60,900 psi

5 Conclusions and Future Research

The study presented in this paper aims to identify both the research and regulatory gaps of earthen building materials and methods implementation. Using cob as an initial demonstration, the research approach includes both a qualitative study that identifies the demands and barriers to implementation, and a quantitative study that enumerates the environmental gains and engineering properties of earthen building methods. In-depth interviews with experts show that there is an increasing demand to build with cob; however, this demand faces a strong regulatory barrier that advocates are trying to overcome. The environmental impacts of cob from a life cycle perspective show that the embodied energy and carbon of cob is significantly lower than of the other conventional materials. Finally, the engineering properties of cob are varied and highly dependent on the selected test method. Specifically, standard concrete tests might not be adequate for cob testing, which should be tested in larger specimens to capture the woven straw mixture properties. Regulatory development of cob requires defining these test procedures that should be adapted to cob's unique construction practices and mixture properties. The presented work is a preliminary summary of larger scale research conducted by the authors, which will include additional earthen methods.

References

ASTM C39/C39M-17a *Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens*, ASTM International, West Conshohocken PA.

ASTM C78/C78M-16 *Standard Test Method for Flexural Strength of Concrete (Using Simple Beam with Third-Point Loading)*, ASTM International, West Conshohocken PA.

ASTM C293/C293M-16 *Standard Test Method for Flexural Strength of Concrete (Using Simple Beam with Center-Point Loading)*, ASTM International, West Conshohocken PA.

ASTM E519/E519M-15 *Standard Test Method for Diagonal Tension (Shear) in Masonry Assemblages*, ASTM International, West Conshohocken PA.

ASTM E2392/E2392M-10(2016) *Standard Guide for Design of Earthen Wall Building Systems*, ASTM International, West Conshohocken PA.

Ben-Alon, L., Carre, M., Tschofen, P., He, Y., Liu, Y. (2017). *A Comparative LCA of Fiberglass and Straw Bale Insulation*. (Unpublished Course Project). Carnegie Mellon University. Pittsburgh, PA.

Bristow, C. (2015). *Identifying barriers to the use of natural building materials in mainstream construction in Ireland.* University of Bath.

Christoforou, E., Kylili, A., & Fokaides, P. (2016). Cradle to site Life Cycle Assessment (LCA) of adobe bricks. *Journal of Cleaner Production*, 112, 443-452.

Ciancio, D., & Beckett, C. (Eds.). (2015). *Rammed earth construction : cutting-edge research on traditional and modern rammed earth.* CRC Press.

Easton, D. (2007). *The rammed earth house*. Chelsea Green Publishing.

Eisenberg, D., & Persram, S. (2009). Code, Regulatory and Systemic Barriers Affecting Living Building Projects. Retrieved from https://living-future.org/wpcontent/uploads/2016/11/Code-Regulatory-Systemic-Barriers-Affecting-LB-Projects.pdf

Eisenberg, D., & Yost, P. (2004). Sustainability and building codes. *The Sustainable Urban Development Reader*, 193–198.

Evans, I., Smith, M., & Smiley, L. (2002). *The hand sculpted house*. US Chelsea Green Pub.

Hamard, E., Cazacliu, B., Razakamanantsoa, A., & Morel, J.-C. (2016). Cob, a vernacular earth construction process in the context of modern sustainable building. *Building and Environment*, 106, 103–119.

Harries, K., & Sharma, B. (2016). *Nonconventional and Vernacular Construction Materials: Characterisation, Properties and Applications. Elsevier.* Woodhead Publishing.

Hart, K. (2015). *Earthbag architecture: building your dream with bags.* Hartworks.

Hunter, K., & Kiffmeyer, D. (2002). *Earthbag building: the tools, tricks and techniques*. New society publishers.

ICC. (2015). *International Building Code Chapter 21: Masonry.* Washington, DC.

Jones, C. I., & Hammond, G. P. (2008). Embodied energy and carbon in construction materials. *Proceeding of the Institution of Civil Engineers - Energy*, 161(2), 87–98.

Kahn, L. (1990). *Shelter*. Shelter Publications.

Kleinfelder. (2005). *Report of Cob Laboratory Tests*. Stockton, CA.

MacDougall, C. (2008). Natural Building Materials in Mainstream Construction: Lessons from the U. K. *Journal of Green Building, 3*(3), 1–14.

Melià, P., Ruggieri, G., Sabbadini, S., & Dotelli, G. (2014). Environmental impacts of natural and conventional building materials: a case study on earth plasters. *Journal of Cleaner Production*, 80, 179–186.

Miccoli, L., Müller, U., & Fontana, P. (2014). Mechanical behaviour of earthen materials: A comparison between earth block masonry, rammed earth and cob. *Construction and Building Materials*, 61, 327–339.

Minke, G. (2012). *Building with earth: design and technology of a sustainable architecture*. Walter de Gruyter.

Morel, J.-C., Pkla, A., & Walker, P. (2007). Compressive strength testing of compressed earth blocks. *Construction and Building Materials*, 21(2), 303–309.

NMAC. (2015). *2015 New Mexico Earthen Building Materials Code*.

Ochoa, L., Hendrickson, C., & Matthews, H. S. (2002). Economic Input-output Life-cycle Assessment of U.S. Residential Buildings. *Journal of Infrastructure Systems*, 3(4), 132–138.

Pacheco-Torgal, F., & Jalali, S. (2011). Earth construction: Lessons from the past for future eco-efficient construction. *Construction and Building Materials, 25*(1), 512–519.

Pima County Development Services. (2013). *Section 2114: Earthen Structures*. Tucson, AZ.

Prétot, S., Collet, F., & Garnier, C. (2014). Life cycle assessment of a hemp concrete wall: Impact of thickness and coating. *Building and Environment 72*, 223-231.

Pullen, Q., & Scholz, T. (2011). Index and Engineering Properties of Oregon Cob. *Journal of Green Building, 6*(2), 88–106.

Rizza, M., & Böttger, H. (2015). Effect of Straw Length and Quantity on Mechanical Properties of Cob. In *The 16th Non-Conventional Materials and Technologi*es. Winnipeg, CA.

Saxton, R. H. (1995). Performance of cob as a building material. *Structural Engineer, 73*(7), 111–115.

Snell, C., & Callahan, T. (2009). *Building green: a complete how-to guide to alternative building methods: earth plaster, straw bale, cordwood, cob, living roofs*. Sterling Publishing Company, Inc.

Spišáková, M., & Mačková, D. (2015). The use potential of traditional building materials for the realization of structures by modern methods of construction. *Selected Scientific Papers-Journal of Civil Engineering, 10*(2), 127–138.

Summit. (2016). *Report of Cob Compression Tests*. Hillsborough, CA.

Swan, A. J., Rteil, A., & Lovegrove, G. (2011). Sustainable Earthen and Straw Bale Construction in North American Buildings: Codes and Practice. *Journal of Materials in Civil Engineering, 23*(6), 866–872.

Treloar, G. J., Gupta, H., Love, P. E. D., & Nguyen, B. (2003). An analysis of factors influencing waste minimisation and use of recycled materials for the construction of residential buildings. *Management of Environmental Quality: An International Journal,14*(1), 134–145.

US Census Bureau. (2015). *Characteristics of New Housing*.

Walker, P., Keable, R., Martin, J., & Maniatidis, V. (2005). *Rammed earth: design and construction guidelines*. Watford: BRE Bookshop.

Wanek, C., Smith, M., & Kennedy, J. (Eds.). (2002). *The Art of Natural Building: Design, Construction, Resources*. New Society Publishers.

Weismann, A., & Bryce, K. (2006). *Building with cob*. Green Books, London.

Wojciechowska, P. (2001). *Building with earth: A guide to flexible-form earthbag construction*. Chelsea Green Pub. Co.

Woolley, T. (2006). *Natural Building: A Guide to Materials and Techniques*. Crowood Press.