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Integrating earthen building materials and methods using perception surveys and life cycle assessment (LCA)

Much of the current earthen construction advancements are developing in a bottom-up manner, where pioneers and advocates are confronting technical, economic and political constraints (Woolley, 2006). Despite the numerous environmental and social advantages of earthen building materials, the mainstream construction industry is still hesitant to adopt earthen building materials, and many professionals in the conventional building industry are unwilling to embark on what they perceive as non-proven materials and experimental techniques that lack standard approval, certificates and warranties (MacDougall 2016).

This situation leads to lack of earthen building materials integration in the mainstream construction industry, and the reasons behind this comprehensive challenge were not yet thoroughly distilled. Without knowing the mechanism behind the lack of implementation of earthen materials, solutions are hard to develop. For these reasons, it is necessary to acquire more information and regional examples through research.

Additionally, even though the performance of earthen materials has been studied extensively, knowledge is still vast and scattered. Specifically, LCA studies of earthen building materials are mostly focused on inventory analysis, providing a significant first step but are lacking a comparative life cycle impacts assessment of earthen versus conventional assemblies.

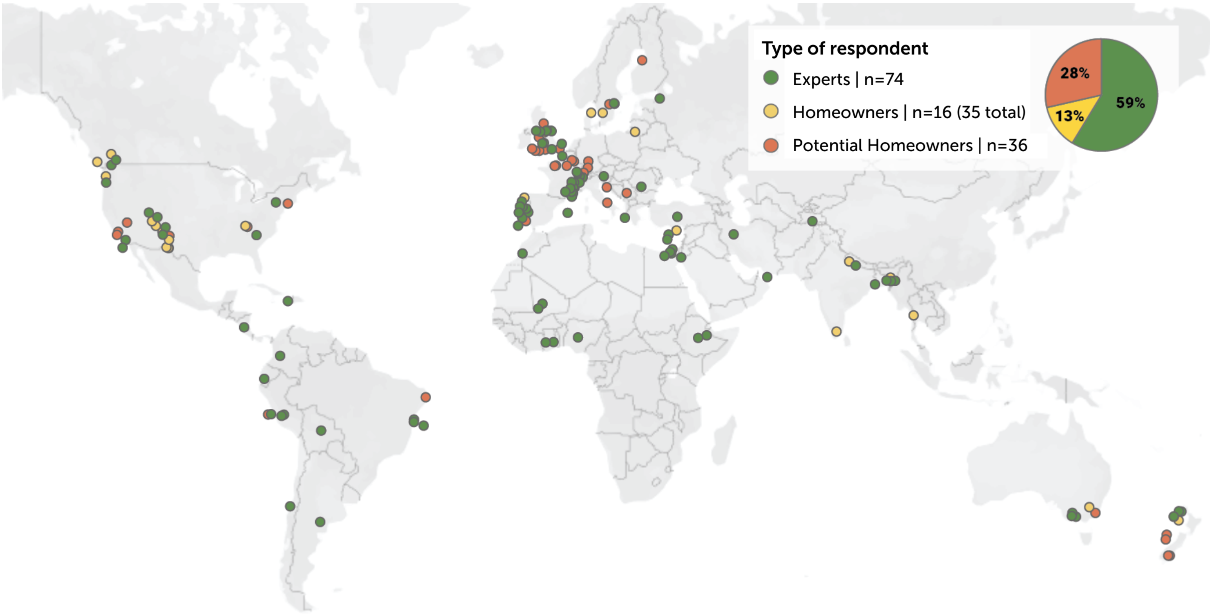
Existing earthen building LCA studies include adobe bricks (Christoforou et al., 2016; Shukla et al., 2009), earth plasters (Melià et al., 2014), earthships (Freney et al., 2012; Kuil, 2012), compressed earth blocks (Fernandes et al., 2019), and earthbags (Cataldo-Born et al., 2017), rammed earth (Morel et al., 2001; Serrano et al., 2013), and cob (Estrada, 2013; Kutarna et al., 2013). These existing studies are mostly focused on individual assemblies that are not readily comparable due to the location-specific and material/process-specific data used in each study, making it hard to extract environmental management recommendations or to determine design change requirements. Finally, many studies use a functional unit of 1 kg of material, which does not allow realistic comparison between various structural systems.

The work presented in this paper provides an in-depth assessment of the earthen building situation at the field, obtained from earthen building professionals and end users. Additionally, a comparative LCA of a suite of earthen and conventional residential building assemblies is presented. Using a functional unit of 1 m^2 of a typical one- or two-story wall system, this study allows for future comparison as well as future analyses that account for operational considerations of other typical wall assemblies.

Perception study: Earthen building experts and homeowners surveys

Survey design and respondents distribution

An online survey of earthen building experts and end users explored both the factual condition of earthen building in practice, as well as the participants' points of view, perceptions and experiences in building with earth. A non-probability convenience sample was used to illuminate important information and data. While this type of sampling technique does not allow results to be generalised to a broader population, it makes it possible to identify and describe experiences, opinions, and relations with regard to the target populations. The recruiting combined two sampling techniques: purposive (i.e. obtaining responses from selected professional groups) and snowball (i.e. further respondents were obtained from the first group



01 Geographical distribution of respondents according to their familiarity with earthen building

of respondents). In total, 126 individuals responded to the online survey from January to July of 2018.

All targeted populations were asked about their perceived motivation and barriers to using earthen building materials. Additionally, experts were also asked about their professional experience, and their perception of codes for earthen building. Homeowners were asked to answer a series of design and performance questions related to their earthen house.

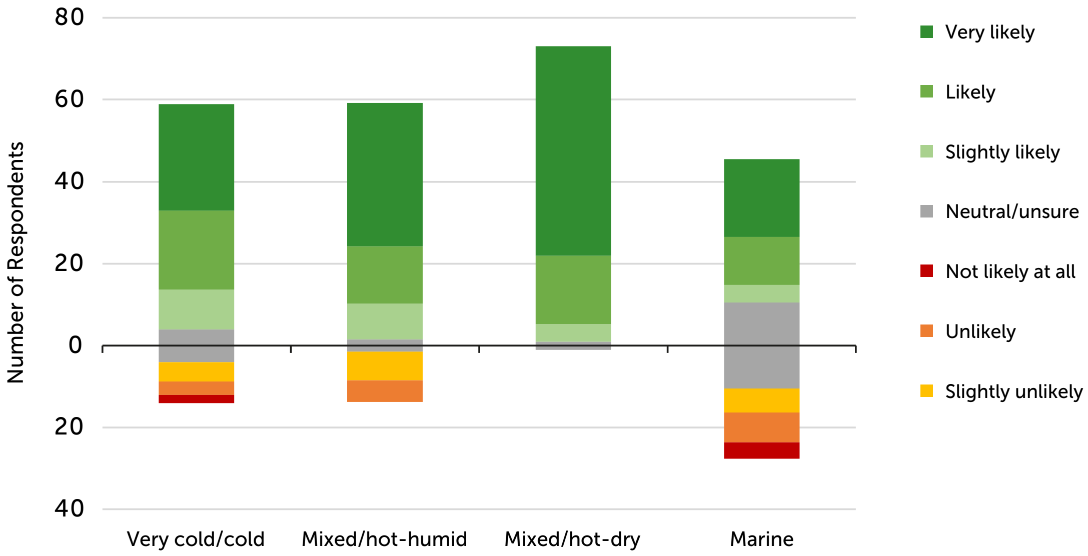
Figure 1 shows the geographical distribution of respondents that were well distributed geographically, with a bias towards European locations, due a Call for Participants distribution from an academic institution in the EU. In addition to the 16 homeowners respondents, 26% (n = 19) of the experts indicated that they also live in an earthen structure, increasing the total number of complete homeowners questionnaires to 35.

Survey results: Experts

Researchers in academia made up the majority of experts with 37% (n=27), following by 31% (n=23) architects/designers, 15% (n=11) builders/contractors, 8% (n=6) building project managers, 5% (n=4) teachers, and 4% (n=3) structural engineers. Experts were asked about the likelihood that they would recommend using earthen materials and methods for four broad climate zones. As depicted in Figure 2, experts reported a trend towards generally recommending earthen building materials in all climates, whereas the climate that received the least positive responses is Marine, probably due to the expected combination of precipitation and salt, both of which are regarded as major earthen building erosion factors.

Figure 3 shows the distribution of experts' familiarity with existing earthen building codes and guides. 24% (n=18) of surveyed experts reported to be generally unexperienced in using building codes whereas 76% (n=56) of experts reported using building codes for their earthen projects. Of the experts who use building codes, 27% (n=15) had been applying conventional material codes to their earthen building projects. The remaining experts reported to be mostly using earthen codes from Germany (e.g. Dachverband Lehm, 2008; NABau, 2013), New-Zealand (New Zealand Standards, 1998a, 1998b, 1998c), or New-Mexico (New Mexico Regulation & Licensing Department & NMAC, 2015). These results suggest that within the earthen building community, building codes are often unfamiliar or not applied. No dominant earthen code/standard/guide was identified.

Experts rated the quality of the earthen building code/standard/guide they used. Figure 4 shows that, according to experts, earthen building codes are generally representative of the various earthen techniques in a user-friendly manner, with highest ratings given to the New-Zealand Earthen Building Standards (New Zealand Standards, 1998c, 1998a, 1998b). However, experts indicated that using earthen building codes/standards results in a costlier and longer



02 Experts are most likely to recommend earthen building materials in mixed hot and dry climates

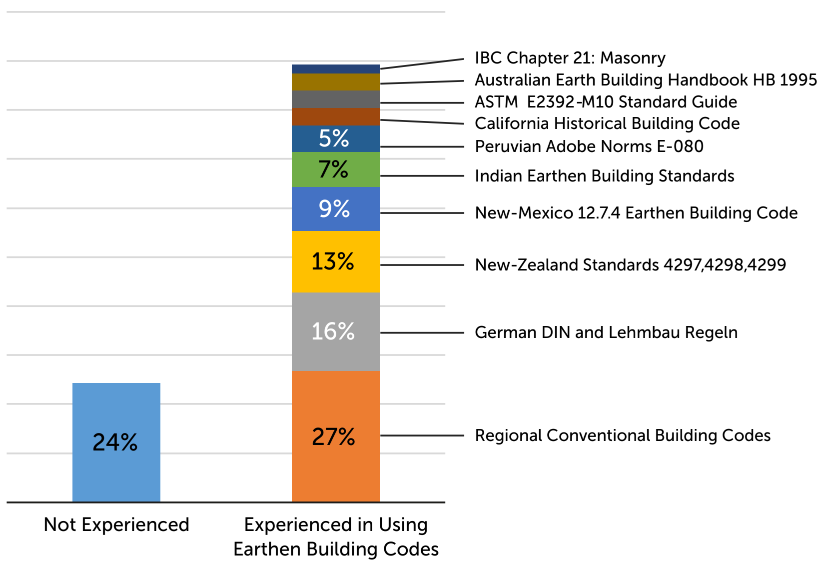
permitting process compared to conventional building projects, with the greatest impact stemming from the use US-based earthen codes/standards, specifically the NM code (New Mexico Regulation & Licensing Department et al., 2015). This observation may be less a function of the code documents themselves, and more a reflection of the permitting environment in the United States.

Furthermore, experts stated that, in general, building officials are unfamiliar with earthen building codes/standards. Specifically, the German Earth Building Regulations were rated as the least familiar to building officials (indeed, at the time of writing this paper, they are available in only German), followed by the New-Zealand Earthen Building Standards. Experts often reported a different geographical location from the code country of origin; for instance, for the German Earth Building Regulations, out of 9 surveyed end users, 7 reported to be from outside Germany.

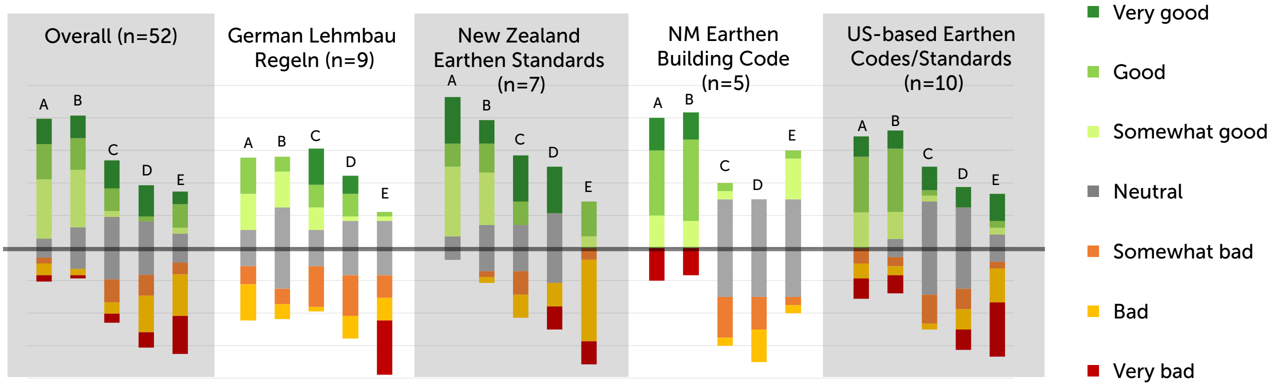
Survey results: Homeowners

35 homeowners questionnaires aimed at investigating some design aspects of earthen homes including walls, floors, roof, and other envelope materials and dimensions. Of the earthen homeowners, 31% (n=11) reported having adobe in the exterior walls of their home. Other houses included a wide variety of tech-

03 Experts are mostly experienced in using conventional building codes for earthen building projects



A Representation
B User-friendliness
C Cost to permit
D Time to permit
E Familiarity among building officials

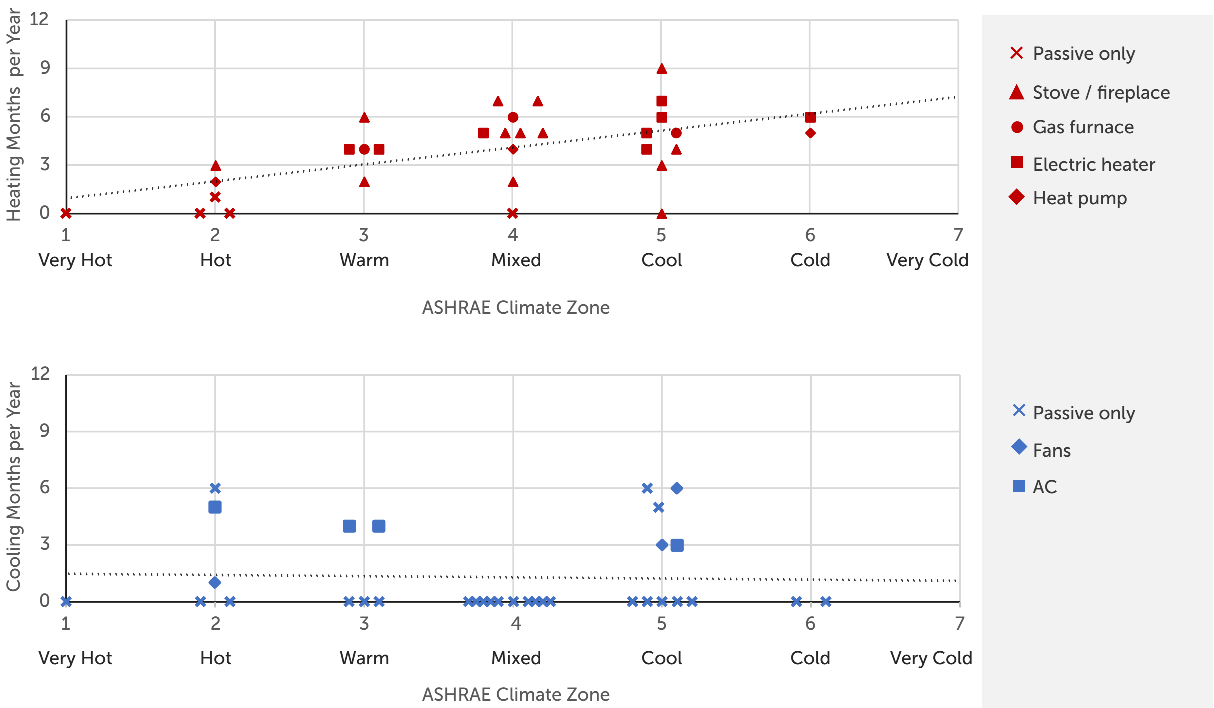


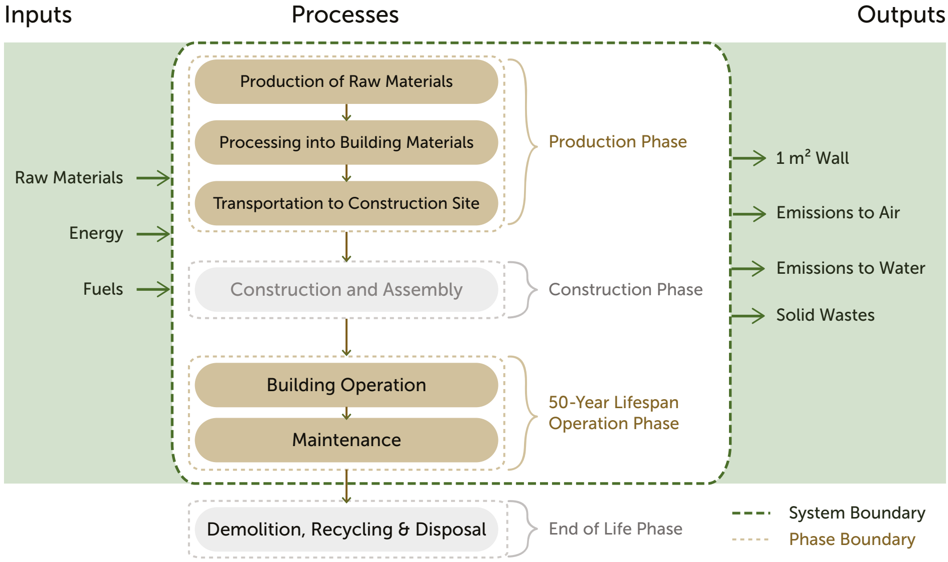
04 According to experts, building officials are unfamiliar with earthen building codes/standards

niques: cob, hybrid straw bale and earthen mass, clay plaster on top of different surfaces, rammed earth, light straw clay, and compressed earth bricks. 55% (n=18) of the homes were reported to have no supplemental insulation. Insulated homes reported straw bales, light straw clay, blown cellulose, and sheep's wool. None of the homeowners reported synthetic insulation in their earthen home.

58% (n=19) of the homeowners reported building their home on a concrete footing, whereas other homeowners used either stone, gravel, or stabilised earth foundations. Most homes had a modest floor area, with 67% (n=20) reporting a home within the range of 270-1470 ft^2 (~25-135 m^2) floor area. 83% (n=29) of responses indicated that they used manual labour techniques to construct their home and only 17% (n=6) reported using a combination of manual techniques and machines. Homeowners specified the following machinery: mechanical mixers, block compressing machines, tractors, rammers and excavators for site levelling.

05 According to homeowners interviewed, their earthen homes reduce the need for cooling, for all climates





06 The system boundaries diagram of the LCA study. The phases included are the production and operation from cradle to end of life.

Respondents provided their country and city, comfort levels in each season of the year, heating and cooling system types, as well as their usage pattern during the day and throughout the year. This series of questions allowed for the analysis of thermal performance of the earthen houses for both heating and cooling seasons according to ASHRAE climate zone. As shown in Figure 5, 75% (n=26) of homeowners reported that their house has no cooling system. These results might indicate that earthen homes reduce the need for cooling, for all climate zones. A few passive cooling systems were indicated to be "activated" (manually) by the owners for several months per year. Passive cooling strategies included shading and open windows. Among the passive heating strategies, homeowners indicated using solar air heaters, earth air tubes for tempered ventilation, trombe walls and sunlight.

Technical study: Life cycle assessment (LCA) of earthen vs. conventional assemblies

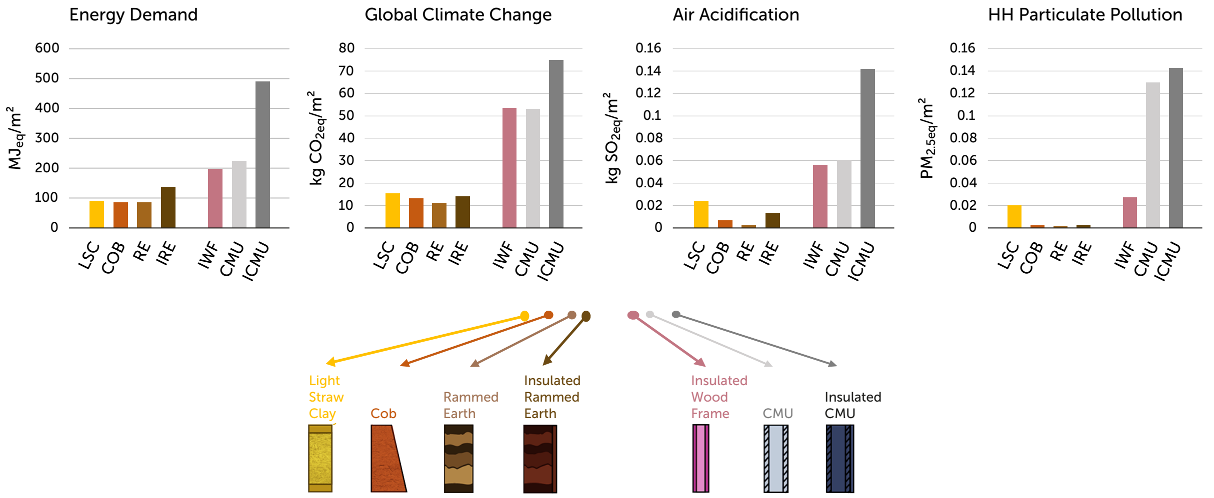
LCA goals, scope, and methods

The main goal of the presented LCA was to enumerate the potential environmental impacts of building and living in an earthen structure compared to various conventionally built homes. The study considers four earthen wall assemblies (cob, light straw clay, insulated and uninsulated rammed earth) and three conventional assemblies (light timber frame, insulated and uninsulated concrete masonry). This LCA follows the environmental Life Cycle Assessment methodology, as defined by the ISO series of LCA standards (ISO, 2006a, 2006b)version 2006. SimaPro software (Pre Consultants, 2017) was used to model inventory data that is relevant to North America.

The environmental impacts included energy savings and emissions reductions for a single-family housing unit in warm-hot climates in the US as defined by ASHRAE (ICC, 2018): warm-hot climate zones 2B (e.g., Tucson, AZ), 3B (e.g., El Paso, TX), 3C (e.g., Los-Angeles, CA), 4B (e.g., Albuquerque, NM), 4C (e.g., Portland, OR) and 5B (e.g., Denver, CO). EnergyPlus version 9.2.0 (US Department of Energy, 2019) and DesignBuilder version 6.1.3 (DesignBuilder, 2019) were used to model the thermal performance of both the earthen and conventional assemblies.

The LCA system boundary accounts for a cradle to end-of-life phases, including the extraction and processing of raw materials, manufacture of building materials, transportation of the building materials to the construction site, operation of HVAC for space conditioning and maintenance for a 50-year lifespan. On-site construction as well as demolition and disposal energy and emissions are beyond the system boundaries, as shown in Figure 6.

The various wall assemblies were designed with different constituent materials and the inventory analysis for each constituent material was developed as a first step for this work as detailed in (Ben-Alon et al., 2019) low carbon, and locally available alternative to conventional building materials and methods. This paper provides a framework for a comparative Life Cycle Assessment (LCA). Each of the light straw



07 Environmental embodied impacts comparison overview for each wall system

clay, cob, and rammed earth wall systems incorporate clay-rich soil. Depending on the assembly, gravel, sand, fibres and water were included in the mixture. Cob and light straw clay also included a layer of clay plaster. Additionally, light straw clay included a lightweight timber frame.

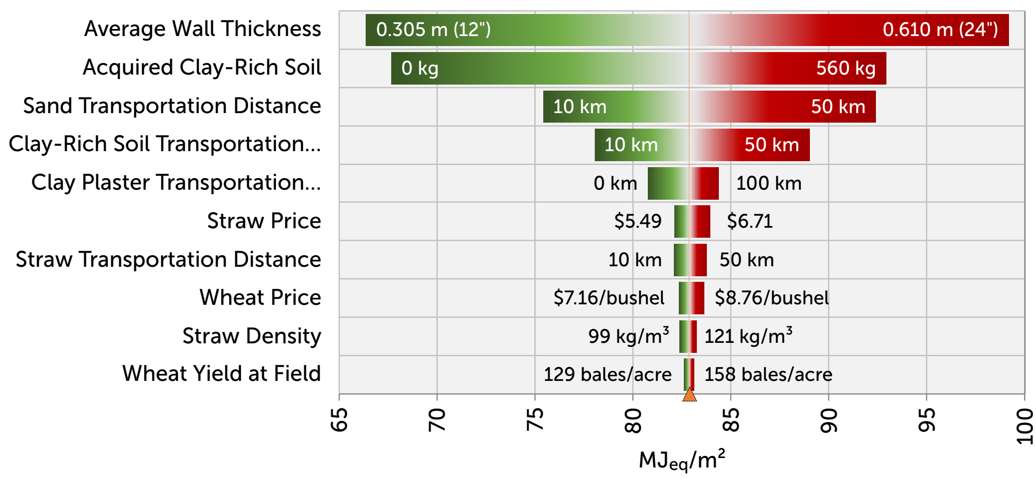
Embodied and operational life cycle impact assessment (LCIA)

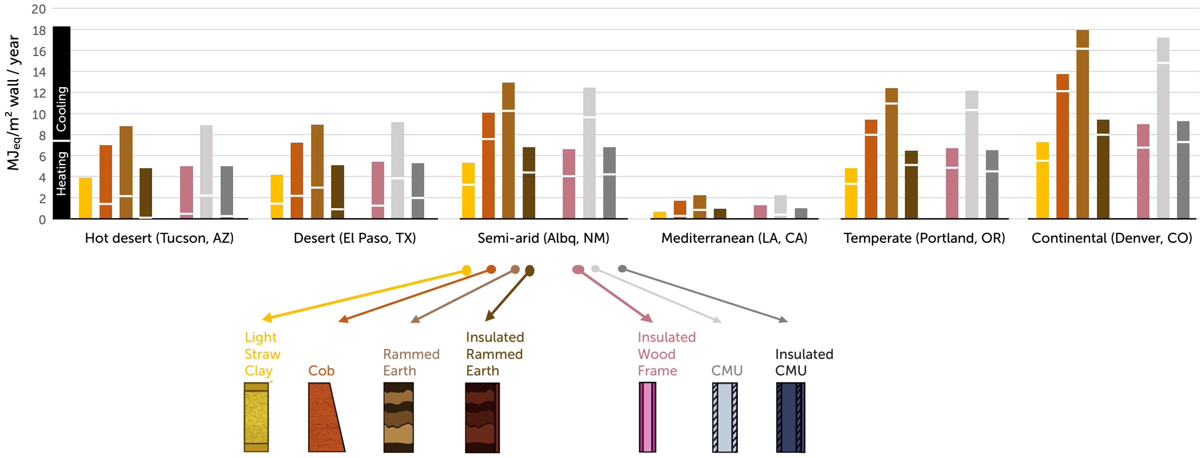
The comparison of the embodied environmental impacts among all six wall systems is shown in Figure 7. The results show that the earthen wall systems exhibit significantly better embodied environmental performance than the conventional insulated wood frame and concrete masonry unit (CMU) wall systems, for all impact categories. Earthen assemblies are shown to reduce embodied energy demand by 62-68%, climate change potential by 83-86%, air acidification by 58-95%, and particulate pollution by 84-99%.

For a more detailed comparison, a sensitivity study was conducted to demonstrate the effect of all the various assumptions included in the embodied impacts. Using triangular input distributions and modelled over 1000 iterations, the sensitivity analysis illustrates the effects of transportation distances, wheat grain and straw market prices, average wall thickness, amount of clay-rich soil required, straw density and average wheat yield at field. The analysis was conducted using the @Risk software and uses a model that resides in excel (Palisade, 2009).

The sensitivity results for cob are shown in Figure 8, representing an "average" between the rammed earth and light straw clay assemblies due to its inclusion of both geological and biological materials. The high dependence of the environmental impacts of cob on the amount of acquired clay-rich soil demonstrates the benefits of using on-site subsoil, which can be

08 Sensitivity analysis of the energy demand of cob production, ranked by the input effect on output mean.
(Straw price: Input 4,64€, Output 5,68€ | Wheat price: Input 6,06€ – Output 7,41€)





09 Annual operational energy demand impacts for heating and cooling for each assembly in each of the six tested locations. Divided by a white line, the lower bars signify heating impacts and upper bars signify cooling impacts.

made available from foundation excavation, or from nearby excavation projects. This scenario adds the benefit of avoiding the transportation or re-grading impacts of otherwise unused excavated soils. For example, the sensitivity analysis shows that use of on-site clay soil may reduce up to 20% energy requirements from 83 MJ_{eq}/m^2 to 66 MJ_{eq}/m^2. The effect of the wall thickness on the embodied impacts of cob may encourage research and field efforts towards an optimal mixture that could provide a wall thickness that is as minimal as possible. Increasing the R-value of cob might also allow a smaller thickness.

For the operational impacts, a full year heat balance was simulated using a virtual chamber in each of the tested climates. The energy loads for each climate were then used to estimate the operational environmental impacts from a life cycle perspective.

Figure 9 details the simulation heating and cooling energy demand results, showing that the light straw clay outperforms the other assemblies in the majority of instances. Insulated rammed earth is shown to result in similar energy requirements as conventional assemblies, with fewer heating loads for arid and temperate climates. It is only in the mildest conditions that the complete suite of earthen assemblies performs best. This is evident for Los Angeles summer cooling loads, although due to its mild climate, the overall loads for this location are lower and less significant compared to other locations.

The trade-offs between the embodied impacts and the operational life cycle impacts for space heating and cooling for a 50-year building life show that embodied phase can dominate for the earthen assemblies, and provide a significant advantage over conventional construction, even with 50 years of operational energy use.

For all climates except the mildest, light straw clay is shown to achieve the best performance as opposed to conventional assemblies, for both embodied and operational impacts. Insulated rammed earth is shown to reduce energy demand mostly for hot desert and arid climates. Cob is shown to be most advantageous in hot desert and Mediterranean climates, outperforming non-insulated CMU assemblies that are prevalent in these climates worldwide, however, cob is outperformed by insulated wood frame construction and insulated CMU in semi-arid, temperate and continental climates.

Conclusions and discussion

This paper presents critical steps to integrating earthen materials into mainstream construction using perception surveys and environmental Life Cycle Assessment.

126 perception surveys investigated the regulatory barriers and comfort measures as perceived by earthen building experts and homeowners. The results of the surveys show that within the earthen building community, building codes are often unfamiliar or not applied. Additionally, according to experts, local building officials are unfamiliar with regional earthen building codes/standards. Lastly, according to homeowners, earthen homes reduce the need for cooling, for all climate zones.

For the LCA, the environmental urgency of earthen building materials is illuminated, taking into account the trade-offs between the embodied and operational energy demand and emissions. The LCA shows that light straw clay outperforms conventional assemblies, for both embodied and operational impacts, for the majority of climates. Insulated earth is shown to outperform uninsulated mass as well as conventional assemblies. These results suggest that locating earthen mass and insulating fibre in the different parts of the building might result in optimal comfort levels as opposed to conventional insulation assemblies, providing the basis for hygrothermal, mass, and thermal conductivity consideration in indoor comfort and challenging current international energy requirements.

The work presented in this paper contributes to the development of environmental and policy measures that could be used to advance earthen building implementation in mainstream construction. Future research should address how environmental impacts such as energy demand and climate change effect societal impacts such as access to materials resources and circular economy. Additionally, future work should focus on evaluating and minimising the discrepancies between zero-carbon bio-based materials research and mainstream construction practices. This can be achieved by bridging the gap between policymakers, product developers, and field practitioners, and by providing policy and environmental measures that can be used for Environmental Product Declarations (EPDs).

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