The Biophilic Power and Environmental Urgency of Earthen Construction

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Abstract. The built environment must meet the highest demands of human habitation, resource management and community enrichment. To achieve these goals, modern built environments should adopt restorative environmental and biophilic design principles which seek to reconnect the human built environment with nature. In this paper, the biophilic aspects and environmental benefits of earthen construction are assessed and compared to conventional construction in order to demonstrate the tangible and intangible benefits of earthen materials. Specifically, the synergies between biophilic design attributes and earthen construction are elaborated, characterizing the ecological, health, and community collaboration advantages that earthen structures provide. Subsequently, the results of an environmental Life Cycle Assessment (LCA) of earthen building materials from cradle to gate enumerate the environmental preferability of earthen materials over conventional materials.

1. Introduction on the significance of earthen construction

Unsustainable approaches to building materials result in resource depletion, climate change impact, biodiversity loss, and human alienation from the natural world [1,2]. Sustainable solutions build on a restorative environmental approach of energy and resource renewability, and the biophilic design approach of promoting a connection between humans in the built environment and the natural world [3].

In parallel, there has been a revival in natural building techniques, specifically earthen building materials and methods such as cob, rammed earth, light straw clay, adobe, and compressed earth blocks [4,5]. These materials and methods exhibit environmental, social, and economic benefits that attract homeowners and advocates, leading to a growing participation in hands-on building workshops and seminars [6]. Despite this growing interest, earthen architecture is often perceived negatively as being low tech. Although recent research is addressing these perceptions by enumerating the life cycle environmental advantages [6–9], the intangible biophilic effects of earthen construction have thus far not been systematically analysed.

By characterizing the overlaps between biophilic design and earthen construction, as well as enumerating the environmental performance benefits, a new avenue to promote earthen construction unfolds. This paper characterizes the biophilic benefits of earthen architecture, as well as the ecological, aesthetic, and community benefits, including health, well-being, and comfort measures. This paper then addresses the environmental benefits of earthen construction, in comparative life cycle assessment of three types of earthen building materials and methods: cob, rammed earth, and light straw clay.

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2. The intangible benefits and biophilic effects of earthen construction

Biophilia is the inherent human inclination to affiliate with natural systems and processes, especially life and life-like features in the nonhuman environment [10]. Based on the notion that physiological and emotional human development highly depends on cues from the natural world, biophilic design is achieved in practice by integrating critical natural elements and sensory features such as colours, vegetation, light and space, natural shapes and forms, and place-based relationships [3,11]. In *Biophilic Design*, Kellert et al. offers evidence of the enhancement of human functional development and general well-being by both direct and indirect contact with nature [3]. This evidence includes enhanced healing, recovery, coping, and adaptive behaviour in response to nature representation; improved worker performance and motivation due to environmental features in office spaces; and healthy child development and a stronger sense of community due to direct contact with natural settings. The following sections explore the biophilic benefits of earthen architecture towards ensuring future demand for earthen building materials and methods.

2.1. Earthen materiality allows natural light to cascade in, resulting in a soft invitation.

Natural light produces better health, productivity, and well-being in the built environment [12]. Beyond the awareness to orientation throughout the day, the integration of light within spatial harmony can promote a sense of security and curiosity, as well as produce aesthetically appealing shapes and forms through the creative interplay of light and shadow [3]. Natural light in buildings is often brought into the interior space by meeting the features of the surface materiality and its texture. Specifically, earthen structures often incorporate soft edges and textures that produce pleasant light exposure due to their material breathability and sculptural properties. Additionally, earthen walls may integrate various shapes and colours of openings as well as recycled bottles. Due to their required large thickness, earthen and clay-plastered straw bale walls will often incorporate window niches in which a space for sitting is introduced, allowing an enjoyable view of the outside natural elements.

Figure 1: Natural light and earthen materiality celebrated using recycled coloured glass [13], introduced through a thick wall surface [14], and incorporating a sitting niche under the window [15] [16].

2.2. Earthen architecture often includes green roofs and other natural ecosystems.

Contact with natural self-sustaining ecosystems that have interconnected plants, animals, water, soil and other geological forms can be especially satisfying to the human experience. One example of such an ecosystem is green roofs that are not only beneficial in terms of energy efficiency, but can also provide landscape as well as an experience of weather conditions [3]. Earthen architecture often introduces green roofs that both act as an observational platform and serve for water collection and absorption elements. In addition, the specific case of earth-sheltered structures that integrate an insulating earth blanket are especially prominent due to their ability to restore and reconnect the ecological fabric of the construction area as well as conserve rainwater, manage runoff, and provide habitat for wildlife.

Figure 2: Earthen architecture often incorporates earth blankets, living roofs, and roof gardens. Photos: [17] [18] (can you notice the below-grade level?) [19] [20].

2.3. Earthen structures are often heated using superefficient rocket mass heaters made of clay

Fire was used in the built environment for thousands of years for heating and cooking, and it is therefore associated with comfort and civilization [3]. Clay mass heaters and rocket stoves are frequently introduced into the interiors of earthen structures, allowing increased efficiency and reduction of air emissions as opposed to a conventional fireplace [21]. These heaters often incorporate horizontal ducting embedded within interior mass elements such as cob benches and earthen walls, which "store" and gradually release heat during, for instance, a cold night.

Figure 3: Earthen rocket mass heaters, an energy superefficient heating system that often includes heated benches and other interior elements. Photos: [22], [22], [23].

2.4. Natural and locally available materials are the essence of earthen architecture

One of the strongest biophilic features of earthen architecture lies in its use of natural materials curated from the local environment. Natural materials can reflect the dynamic properties of organic matter through their adaptive response to time, allowing positive sensory responses [3]. In addition, contact between the human body and earth (e.g., through an earthen floor) is believed to improve hormonal regulation, sleep dysfunction, pain, and stress [24]. Lastly, earthen materials are pleasant to both eye and touch, providing a breathable and soft, yet sturdy mass building material.

2.5. Earthen building materials provide natural colours and tones

The effective biophilic use of natural colour in the built environment favours muted earthen tones of soil and plants, emphasizing appealing natural forms. This interaction between colour and light, from cool coloured walls and lamp shades, to warm coloured walls (and floors) and sunlight, can shape the mood of a space [3]. While the commonly used white colour can feel calming, pure and clean, it can also feel sterile and jarring. In this context, earthen architecture introduces a tonal variety of natural colours, that even when applied with a natural white pigment, can achieve a warm off-white that is more calming and pleasant than vibrant white. Additionally, earthen plaster and natural paints, made from finely sifted clay soil or powdered potter's clay, are non-toxic and breathable finish materials that can be celebrated with colourful richness when added with natural pigments.

Figure 4: Natural colours of earthen building materials include warm off-whites [25], earthy tones [26], warm earthen floors [27], and colours that can be achieved by natural pigments [28].

2.6. Earthen structures offer natural shapes, textures, and information richness

Naturalistic shapes often represent adaptive flows and responses to nature's forces. Natural forms arise, to some extent, out of the load carrying ability of the material (e.g., the inverted catenary dome shape). Earthen building materials and methods employ a myriad of natural shapes and forms due to their sculptural capability, from rounded edges, to curved walls, arches, vaults, and domes. In addition, earthen surfaces are easily finished with naturalistic textures, decorations and ornaments including sculpted furniture and niches. Even unfinished, earthen materials such as rammed earth exhibit rich natural textures and colours that mimic sedimentary layers.

Figure 5: Natural shapes and textures of earthen surfaces. Photos: [29] [30] [31]

2.7. Earthen structures offer community connections and a spirit of place

The notion of cherishing the environment through collaborative effort and a human touch goes hand in hand with the utilization of local and indigenous skills that both reduce environmental impacts and enhance local culture and identity. In this context, earthen construction is amenable to high levels of craft and can be built with simple skill-sets, making it optimal for design-build and community efforts, where everyone can participate in the building activity, even children. Earthen structures that incorporate community collaboration and hand-crafting can therefore give rise to a sense of belonging, ownership, care, and appreciation. Studies have shown that earthen construction incentivizes community participation throughout the design and construction that enhances local economies, leading to better maintenance and conservation of the built environment by its users [32,33].

Figure 6: Earthen construction often incorporates community collaboration and hand craft of the occupants. Photos: [34] [35] [36]

3. The tangible life cycle environmental benefits of earthen construction

Environmental LCA has become a common tool in the building sector to evaluate sustainable building development [37]. However, only a few studies have examined the environmental impacts of earthen construction techniques, including the LCA of adobe bricks [38,39], rammed earth [40,41], and earthen plasters [42,43]. Though significant, these studies are not broadly applicable or comparable, due to the location and process-specific data used. To address this limitation, a new study is introduced comparing the environmental impacts of different earthen construction techniques to benchmark assemblies.

The LCA presented in this paper was implemented based on the environmental Life Cycle Assessment methodology described in the ISO 14040 series of standards [44,45], using the *SimaPro* software [46], the US-LCI database [47] where possible, and EcoInvent [48] processes that are globally applicable otherwise. The goal of the study was to comparatively enumerate the energy demand and air emissions of load bearing cob, rammed earth, and light straw clay walls of a single-family housing dwelling located in warm-hot climates in the continental US, defined as IECC climate zones 1 through 4 [49]. Using a functional unit of 1 square meter of a wall system, this study aims to provide the basis for a future comparison among other typical wall assemblies. The system boundaries, shown in Figure 7, consider embodied environmental impacts, including the extraction and processing of raw materials, manufacturing, storage, and transporting to the construction site.

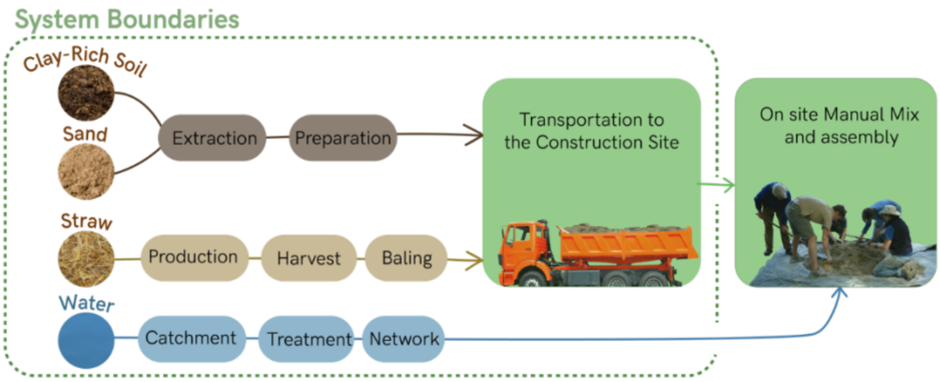

Figure 7: The system boundaries of the developed LCA (Ben-Alon 2018)

The Life Cycle Impact Assessment (LCIA) was conducted using the CED (Cumulative Energy Demand) impact 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]. The cob and rammed earth walls were assumed to have an average 460 mm thickness [52,53], and the light straw clay wall a 305 mm thickness [54]. The wall details are all typical and comparable in terms of building performance. 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 purchased from a quarry.

The impact assessment results, shown in Figure 9 and

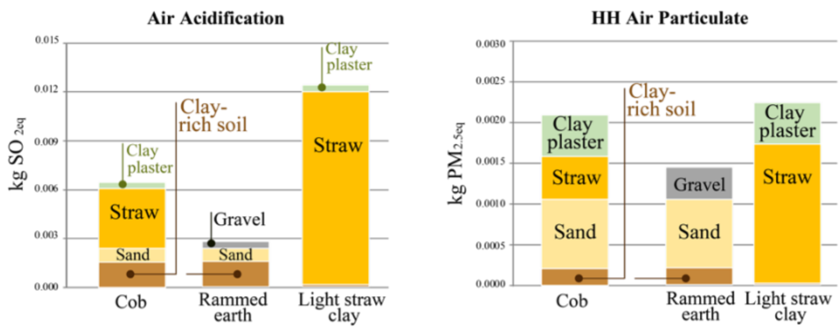

Figure 10, illustrate the differences between the earthen walls systems. The light straw clay accounts for the least energy demand and global climate change impacts, due to its smaller thickness, as well as the absence of the sand and soil that require truck transportation. The rammed earth wall, with 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 its production. For the same reason, light straw clay has the highest environmental impacts in terms of air acidification, following by cob, due to the straw production-stage emissions of Methane (CH_4), Sulphur Dioxide (SO_2), and Nitrogen Oxides (NO_x), associated with the use of pesticides and fertilizers.

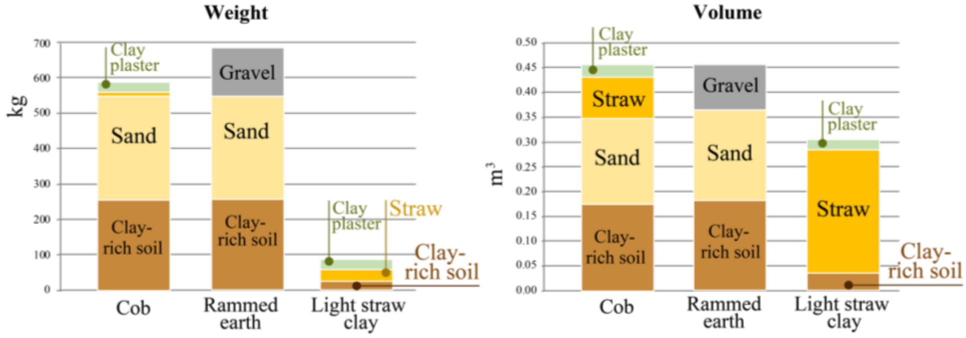

Figure 8: The weight and volume of the constituent materials for each wall system (Ben-Alon 2018)

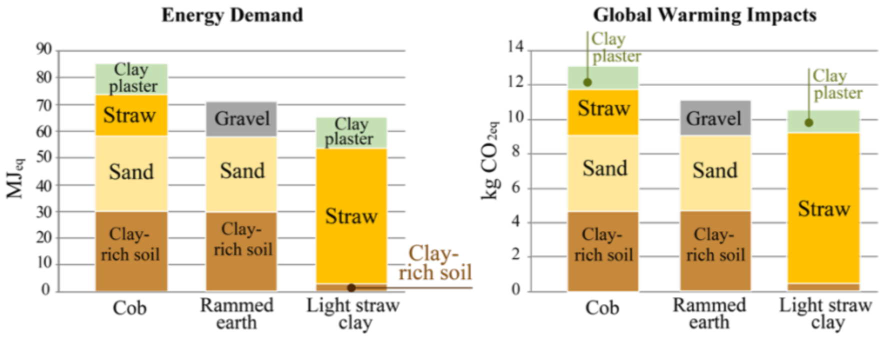

Figure 9: Comparative energy demand (left) and (right) global climate change impacts assessment of cob, rammed earth, and light straw clay wall systems (Ben-Alon 2018)

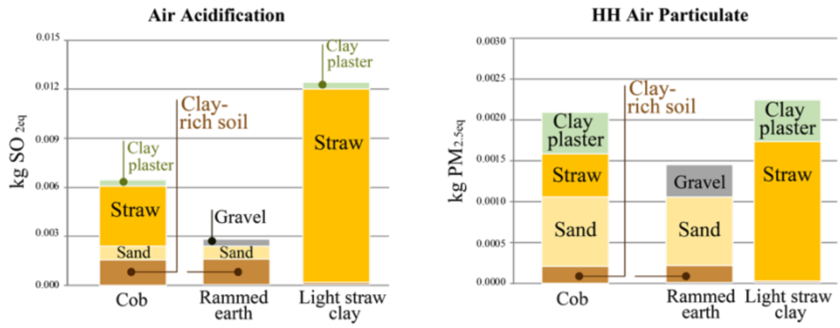

Figure 10: Comparative air acidification (left) and human health air particulate (right) impacts assessment of cob, rammed earth, and light straw clay wall systems (Ben-Alon 2018)

When compared to a conventional wall assembly of concrete masonry blocks (CMU), all earthen wall assemblies considered show significantly lower environmental impacts (Figure 11). The benchmark conventional CMU wall incorporates LCI data for uninsulated and unreinforced 1400 kg/m CMU blocks [55], gypsum board [56] and Portland cement stucco [57]. The comparative results depict the environmental urgency of earthen materials, showing that walls made of cob, rammed earth, or light straw clay can reduce approximately 62-71% of embodied energy demand and 85-91% of embodied global climate change impacts when compared with a conventional CMU wall. Additionally, earthen materials reduce 79-95% embodied air acidification and 98-99% embodied particulate pollution.

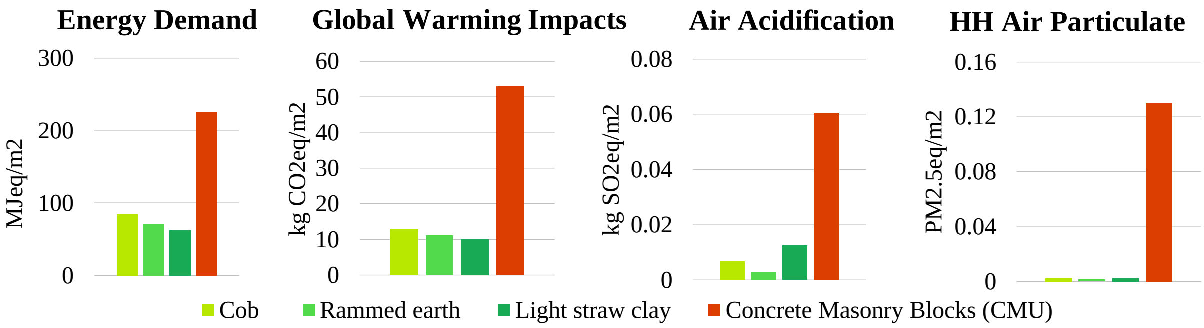

Figure 11: Comparative energy demand, global climate change acidification and particulate impact assessments of earthen wall systems and CMU conventional wall system (Ben-Alon 2018)

4. Conclusions, discussion, and required future research on earthen construction

Earthen building materials and methods offer an environmentally sustainable alternative to conventional highly processed materials currently used in mainstream construction. However, despite their advantages, earthen building products have not been implemented comprehensively because they are mistakenly perceived as and lacking synthesized technical and environmental data that could be used for regulatory purposes. To address these hurdles, this paper demonstrates the intangible and tangible benefits of earthen buildings from biophilic and environmental restoration approaches.

The results of the paper show the direct and indirect experience of nature that earthen buildings facilitate. Earthen buildings provide qualities that are experienced through a variety of human senses including sight, touch, smell, time, and motion. These multisensory encounters with nature in the built environment should be encouraged because they can greatly contribute to comfort, satisfaction, enjoyment, and cognitive performance.

In terms of their environmental performance, the results presented in this paper demonstrate the environmental urgency of earthen construction from an embodied impacts perspectives of energy demand, global climate change, acidification of air, and human health impacts of air particulates. The impact assessment of light straw clay is shown to be minimal among all three earthen wall sections for most of the impact parameters. Lastly, when compared with a conventional section of concrete masonry blocks, the earthen walls prove to save up to 71% of embodied energy demand and reduce up to 91% of global climate change potential, 95% of air acidification, and 99% of particulate pollution.

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