# INTEGRATING EARTHEN BUILDING MATERIALS AND METHODS INTO MAINSTREAM CONSTRUCTION

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## ABSTRACT

Earthen Building Materials and Methods (EBMM) exhibit excellent environmental, health, indoor air quality and affordability benefits. Despite these advantages, EBMM are not yet broadly implemented in mainstream construction. The main barriers and gaps to implementing earthen construction are analyzed through 126 survey responses and 10 in-depth interviews of a range of experts and end-users, and possible solutions to overcoming these barriers are presented. Specifically, the research indicates that according to earthen construction experts and potential homeowners, inability or difficulty in obtaining building permits is the strongest barrier to implementation. Additionally, existing technical data and environmental assessments must be synthesized and enumerated in order to support decision makers in advancing earthen building policy.

## KEYWORDS

earthen building materials and methods; innovative renewable building materials; building environmental impact; sustainable building policy

## INTRODUCTION

The majority of modern buildings are constructed from highly processed materials such as chemically treated wood, synthetic insulation and reinforced concrete. Making and processing today's building materials accounts for approximately 15% of global climate change impacts, 20% of global energy demand, and up to 40% of global solid waste (King, 2017). Relying on such conventional building materials at a global level is mostly unsustainable (United Nations Environmental Program, 2009).

To date, the prevalence of unsustainable building materials in modern residential construction is supported by meeting widely accepted building codes and materials standards. Primarily

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developed to ensure safety in the built environment, few construction-related codes or standards address environmental impacts or ecological-based risks to natural systems upon which society's safety and health ultimately depend (Eisenberg & Yost, 2004). As a consequence, additional non-mandatory regulatory and rating systems have been developed to encourage materials and resources considerations in projects (MacDougall, 2008; Shutters, 2015). Examples of these include the [UK] Building Research Establishment's Environmental Assessment Method (BRE Global Ltd, 2015) and the U.S. Green Building Council L.E.E.D certification program (USGBC, 2014)

Parallel to the interests in green rating systems and "sustainable building," there has also been a growing interest in "ecological," and "natural" building materials and methods. These latter concepts have seen a tenfold increase in published research papers when compared to the previous decade (MacDougall, 2008; Pacheco-Torgal & Jalali, 2011). As opposed to "green" or "sustainable" materials and methods, "ecological" and specifically "natural" building materials and methods are defined as minimally processed, low carbon, and locally available materials that complement their local environment, rather than only mitigate negative impacts (Van der Ryn and Cowan, 2007). Examples of natural building materials include natural fibers like straw and hemp, bamboo, and earthen materials like sand and clay.

In contrast to other natural building materials, earthen building materials and methods (EBMM) exhibit various advantages: they provide high thermal inertia and offer adequate structural capacity in compression. As opposed to trees and crops, suitable earth is often abundant in and around the construction site. As compared to cellulose-based natural materials, EBMM have better resistance to fungi, insects and rodents. Furthermore, EBMM allow a diversity of forms and styles, from sculptural monolithic assemblies to modular components (Racusin and McArleton, 2012).

EBMM are among the oldest known to man and still shelter approximately a third of the world's population, particularly in developing regions (Kahn, 1990; Wanek et al., 2002), Nonetheless, EBMM have also been undergoing a renaissance in developed and urban contexts, with dozens of books being published in the last two decades that address implementation of EBMM. A category of natural construction based on earthen materials includes rammed earth (earth compacted in formworks), earthbags (earth compacted in bags), cob (earth and straw mixed and molded), to list a few (Figure 1).

Despite their advantages and rising popularity, EBMM are not yet implemented in mainstream construction industry. Today, earthen construction is primarily developing in a button-up manner, where pioneers and advocates are confronting economic, technological, and regulatory challenges on their way to implement their vision. The mainstream construction community is hesitant to adopt EBMM since many professionals in the conventional building industry are unwilling to embrace techniques that are not broadly used (MacDougall, 2008). Significantly, the contribution of national guidelines for earthen buildings was recently investigated among International Council on Monuments and Sites (ICOMOS) members (Niroumand et al., 2017); although field study that involves both traditional and contemporary EBMM stakeholders from various disciplines is still missing. Therefore, and similarly to emerging research in environmental psychology (e.g., Gosselin et al., 2016; Van Doorn & Verhoef, 2015), there is a need to assess the factors that influence motivations and barriers to the broader use of EBMM among practicing earthen construction experts, as well as earthen houses end users such as homeowners and potential homeowners.

**FIGURE 1.** Rammed earth house in Arizona (The Construction Zone, 2008) (left), earthbag cottage in Utah (Kennedy, 2012) (middle), and Cob house in UK (Maccabe, 2010) (right).

## OBJECTIVES

The objective of the reported research is to catalyze the broader implementation of EBMM within mainstream residential construction. As part of the research programme, the gaps and barriers to the broader implementation of EBMM were identified, and combined with motivating factors, a solution approach was developed to bridging these gaps.

This paper begins with an expanded literature review of the benefits of EBMM in order to build the argument in favor of using EBMM in conventional construction of residential houses, and to demonstrate the necessity of the presented research. The subsequent sections present the field study procedures that were pursued, results that identify the barriers and gaps and a proposed path to broader use of EBMM. Finally, conclusions and required future research are presented.

## THE CASE FOR EARTHEN BUILDING MATERIALS AND METHODS

EBMM are typically viewed as nonconventional or vernacular construction (Fabri & Morel, 2016). While successfully used in this realm, in this era of emerging design technology and structural knowledge, new opportunities are available for the implementation of EBMM in a modern, enhanced manner. In order to be considered in mainstream construction, it is crucial to capture the advantages of EBMM while addressing (or at least recognizing) the limitations. Often cited limitations of EBMM include that they are labor intensive (and thus may be costlier), and are structurally weaker and less stiff than conventional building *materials* (Hall et al., 2012). Even though EBMM materials properties may be weaker, the resulting *structures* are equally as strong and stiff as comparable conventional construction due to the nature of EBMM techniques and scale. While stated limitations will be addressed later, the following sections highlight the environmental, health and social-cultural advantages of EBMM.

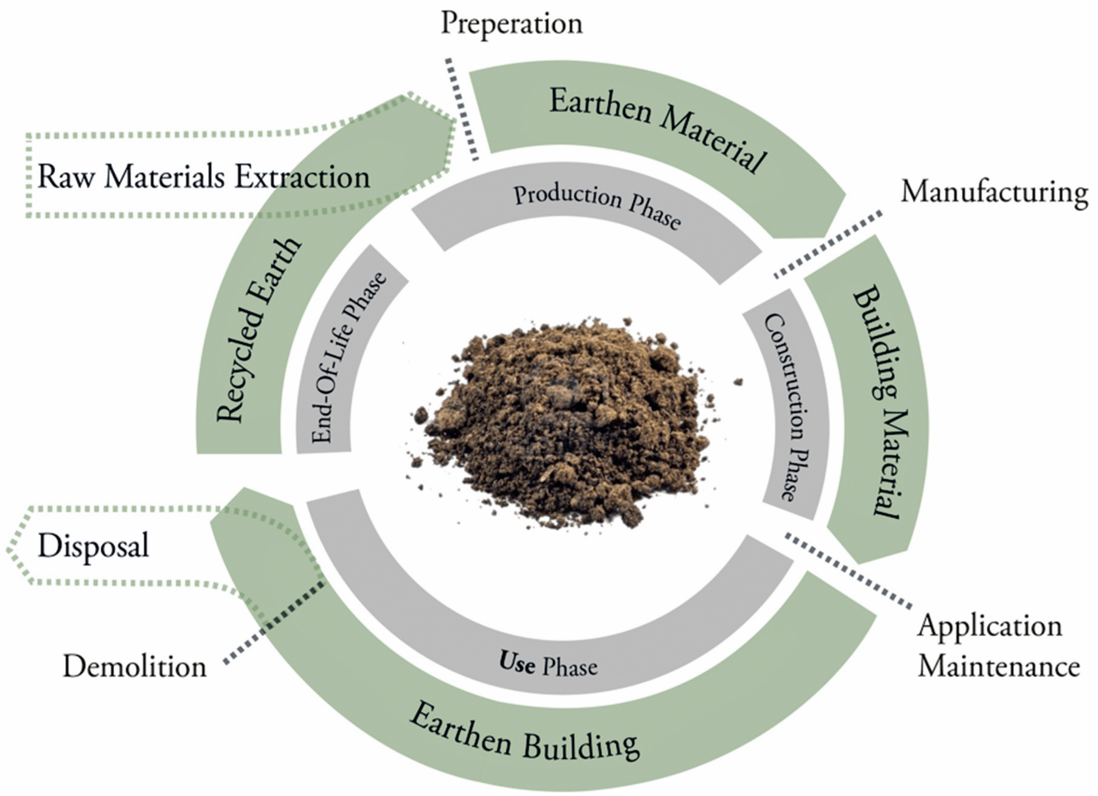
### *Environmental Advantages of Earthen Construction*

Existing environmental Life Cycle Assessment (LCA) studies illustrate that EBMM can potentially require less energy and emit fewer Green House Gasses (GHG) during their life cycle than other comparable construction techniques (Christoforou et al., 2016; Freney, 2014; Treloar et al., 2001). This is due to EBMM's self-sustaining life cycle that begins with the utilization of raw soil, continues with natural processing, and ends with the reuse of recycled earthen materials (Figure 2).

In addition, modern society faces a challenge in regards to material availability. Studies have shown that there is insufficient viable material in the world to continue building in a conventional manner considering growing populations and trends in urban migration (Hendriks, 2001; King, 2017). From a climatic point of view, global climate change studies predict that demand for thermal mass to prevent overheating in buildings may increase (Rubel and Kottek, 2010). To date, the most abundant source of thermal mass (and building material in general) is concrete. Responsible for 6% of anthropogenic global emissions, cement is a construction material that needs to be reinvented (King, 2017).

Because there is insufficient cement-making capacity in the world for the predicted building volume demand (King, 2017), the construction industry can turn to clay which is an abundant natural resource. Clay can be used as a binder to replace cement (in the form of non-stabilized EBMM), or at least to reduce cement content in concrete (as employed in stabilized earthen building materials and in clay-based concrete). Unlike other binders, binding forces in clay are reversible, allowing earthen materials to be plasticized and reused without the use of heating, chemical stripping or mechanical methods of processing.

**FIGURE 2.** EBBM advantages include cradle to cradle advantages as shown in this Life cycle diagram of earth as a building material. Figure adapted from Schroeder (2016).



Given these benefits, EBMM offer an alternative to standard concrete in a world with rising energy costs, material depletion, a growing and migrating population, and an unpredictably changing climate.

### *Health Advantages and Indoor Air Quality of Earthen Construction*

According to a 1984 World Health Organization Committee report, 30% of new and remodeled buildings worldwide are subject to occupants' disorders that are caused due to poor indoor air quality (IAQ). Such poor IAQ can be caused by the chemical contaminants that are found in building materials such as wood products and finishes, as well as by the biological contaminants that result from inadequate ventilation and humidity buffering such as bacteria and molds (US EPA, 1991).

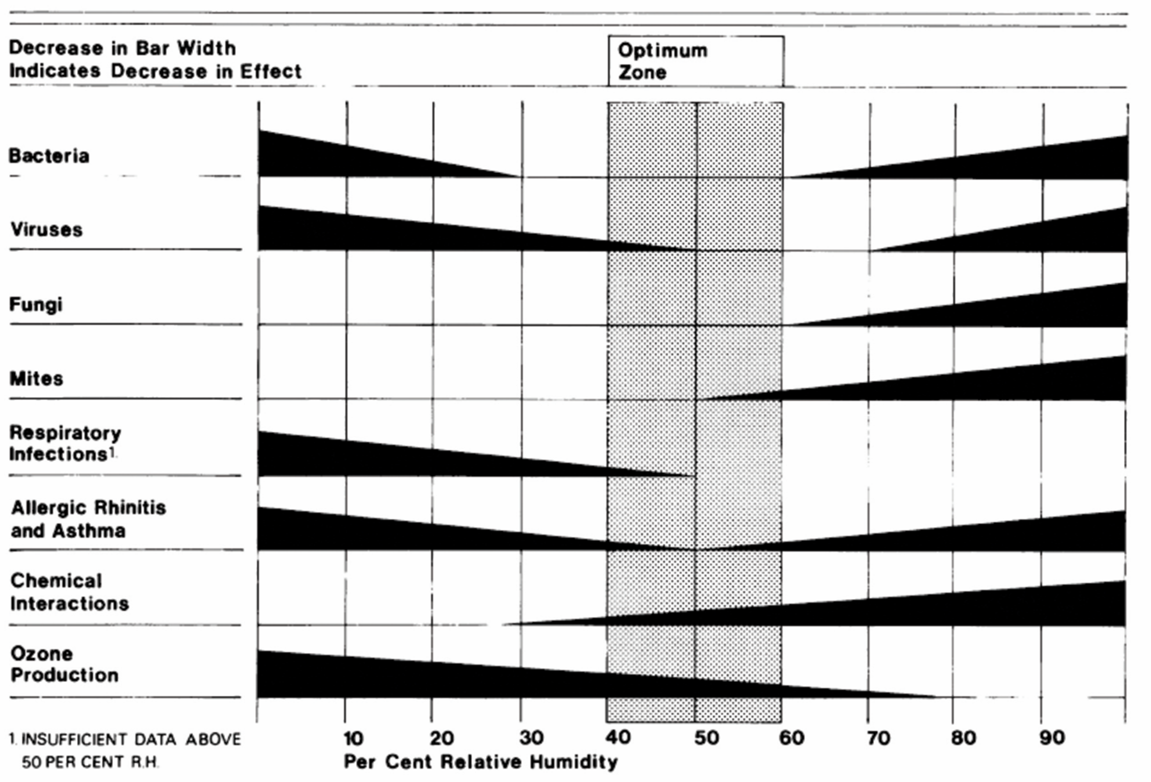
In this context, earthen materials are non-toxic materials that are able to passively preserve indoor temperature and humidity within a comfort and health range, especially in hot climates. Earthen materials were shown to be able to buffer both indoor temperatures and relative humidity, due to their high thermal mass coupled with a high hygric mass (Hall et al., 2012). Insulated earthen materials were shown to perform better than conventional insulating and mass systems. For instance, insulated Compressed Earth Blocks (CEB) were shown to have significantly better indoor temperature stabilization than a standard insulated lightweight frame with respect to internal heat gains. The insulated CEB wall system exhibited 32% more hours within the comfort range (21°C–26°C), as opposed to the standard insulated lightweight frame which overheated beyond 26°C and up to 30°C in tests conducted in summer conditions in Switzerland (Brambilla and Jusselme 2017). Similarly, a rammed earth wall system that was externally insulated with natural wood fiber panels was shown to achieve an 85% increase in thermal stability around the mean temperature of 22°C, and 31% in HVAC energy savings, compared to a conventional double brick wall system, under summer conditions in Spain (Serrano et al., 2016).

In terms of moisture buffering, earthen materials have a vapor sorption capacity that far exceeds other building materials. Due to their porosity, earthen materials are considered to be 'breathing' materials, and studies have shown that they are able to maintain the 40–60% levels of relative humidity that are optimal for human health (Allinson and Hall, 2010; Pacheco-Torgal et al., 2011). For instance, stabilized rammed earth exterior walls were shown to be able to maintain 50%-60% indoor relative humidity levels in unconditioned indoor spaces, as opposed to concrete walls with painted plasterboard that showed fluctuations between 40%-80% in warm weather in the UK (Allinson et al., 2010).

Furthermore, indoor air pollution affects occupant comfort. The passive ability of earthen building assemblies to act as a relative humidity buffer results in optimum relative humidity for minimal growth of bacteria, viruses, fungi, respiratory infections, ozone production, etc., as shown in Figure 3. To illustrate this ability, previous study has shown that clay wall coverings led to a 23–51% reduction in ozone concentration, and to a 29–72% reduction in aldehyde concentrations inside a structure containing both ozone and carpet, as opposed to painted gypsum boards (Darling et al., 2012).

'Breathability' also makes earthen materials a good odor regulator. Finally, tests have shown that earthen walls are able to dampen high-frequency electromagnetic fields (emitted from antennas, radars, mobile phones, etc.), much better than other building materials (Röhlen and Ziegert, 2011).

**FIGURE 3.** The hygroscopic qualities of EBBM support optimum relative humidity ranges for minimizing adverse health effects (Arundel et al., 1986).



### *Economic and Sociocultural Advantages of Earthen Construction*

New housing construction is costly and requires lifetime mortgage payments from homeowners. Costly housing construction leads homeowners to seek affordable and self-sustaining construction alternatives (Freney, 2014). Consequently, there is evidence that shows how alternative housing construction was created affordably by incorporating EBMM (Armstrong, 2015; Hardin et al., 2003; Schroder and Ogletree, 2010). EBMM can make housing construction sustainable mainly due to their potential for on-site soil extraction and self-sufficient production processes that in many cases require no additional costs for manufactured products (Hardin et al., 2003; Schroder et al., 2010). Many EBMM require little training and can be assembled by almost anyone, allowing the distribution of construction effort across a community, as shown in Figure 4.

Parallel to this trend, the demand for environmentally responsible building products is increasing, and captures a large share of the eco-marketplace. In North America alone, the Lifestyles of Health and Sustainability (LOHAS) market segment represents approximately 70 million U.S. adult consumers, willing to invest nearly 100 billion USD in green building products, especially in those that improve energy efficiency and reduce toxicity levels (French, 2003; Hall et al., 2012; Natural Marketing Institute, 2017). Overall, there is a demonstrated marketplace for EBMM products that can provide a potential income for EBMM materials product sellers, as well as savings for homeowners.

**FIGURE 4.** EBMM allow community training and engagement throughout the consrtuction process (Koko, 2016).

Alongside their affordability, EBMM are often considered as self-sufficient modes of construction, and many times they are applied as a community engaging activity, while providing local employment opportunities and enhancement of local economies. In this respect, developed countries profoundly influence developing regions, where EBMM are used traditionally. Modern building codes and standards that are based on heavily processed materials have been adopted in developing regions to the [perhaps unintentional] exclusion of vernacular EBMM forms (Hall et al., 2012). Therefore, embracing and enhancing EBMM in developing countries is of significance and might encourage better overall global solutions while preserving local identities (Jackson and Tenorio, 2010).

## DATA COLLECTION METHODS TO ASSESS EBMM PERCEPTION

In order to identify the barriers that hold back EBMM's broader implementation, and to ascertain possible solutions to these barriers, it was necessary to assess the current field situation among primary resources such as practicing professionals and people who live in EBMM houses. To achieve this goal, the research presented in this paper employes surveys and in-depth interviews of EBMM experts and end users, and aims to explore both the factual condition of EBMM in practice, as well as the participants' points of view and experiences. University IRB approval was obtained prior to initiating study procedures.

### *Online Survey Design and Distribution of Participants*

The primary aim of the survey was to gain insights and understanding about patterns of experience that relate to residential construction using EBMM worldwide. Three populations were targeted: (a) professional experts of EBMM (researchers in academia, architects, contractors, etc.), (b) homeowners of EBMM houses, and (c) potential homeowners who are both familiar with and are interested in applying EBMM to the construction of their current/future house. Because of the lack of sampling frame from which to draw a sample from the worldwide EBMM population, a non-probability convenience sample was used. This technique allows researchers to illuminate important information and data, however the results cannot be generalized to a broader population (Nardi, 2018). To this end, the objective was to identify and describe experiences, opinions, and relations in regard to the target populations—admittedly a self-selected and self-defined population of experts and other interested parties.

The recruiting combined two sampling techniques: purposive (i.e., obtaining responses from a selected group) and snowball (i.e., further respondents were obtained from the first group of respondents). The purposive approach was first used by sending a call for respondents to earthen construction experts and homeowners. The snowball approach was then implemented to identify further respondents with similar experiences. A self-selection sample (i.e., posting the survey for a self-selecting group of respondents) was also employed using networking groups, in order to gain more responses and to encourage further potential respondents to take the survey. The online survey questions were developed by the authors and were divided into three main sections: (1) sociodemographic variables, including geographical location, job description, and education; (2) familiarity with EBMM and expertise in different EBMM types; and (3) perceived barriers and motivation factors to implementing EBMM. Additionally, respondents answered a series of questions about EBMM technical performance.

Overall, 126 responses were collected by the online survey. Figure 5 shows the distribution of the surveyed respondents, in terms of their familiarity with EBMM, as well as their geographical region. The distribution of respondents included 59% earthen building experts, 13% homeowners of earthen buildings, and 28% potential homeowners who indicated that they are familiar with EBMM and interested in applying earthen building materials in their current or future homes. The experts, homeowners, and potential homeowners were well distributed geographically. However, 59% of experts provided a geographical region within Europe, 16% within North America, and 25% within other regions. In addition, 64% of potential homeowners reside in Europe.

As per EBMM expertise, most experts had previous experience in construction of residential projects using clay plaster, adobe, rammed earth, and cob, as shown in Figure 6. Additionally, as illustrated in Figure 7, the majority of surveyed experts are experienced in using earthen building codes throughout their projects, and most experts mentioned using the German Earth

**FIGURE 5.** Distribution of respondents according to their familiarity with EBMM and mapping of their geographical location.

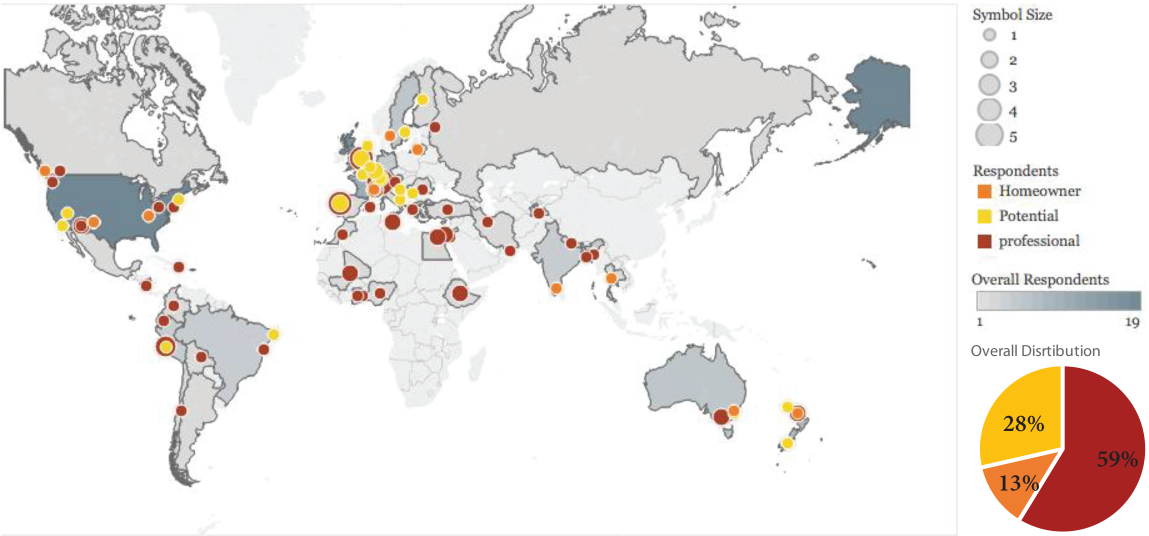


**FIGURE 6.** The majority of expert participants are experienced in residential construction of clay plaster, adobe, rammed earth, and cob.

Building Regulations (Dachverband Lehm, 2008), New-Zealand Standards (New Zealand Standards, 1998a, 1998b, 1998c), and New-Mexico Earthen Building Materials Code (NMAC, 2015).

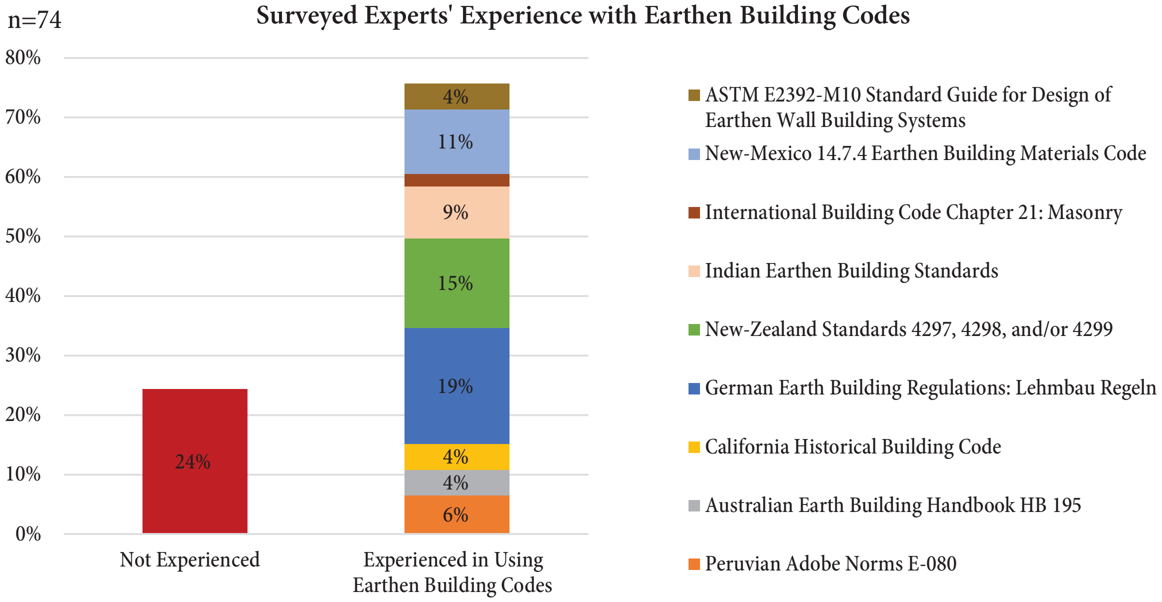
Six professions related to the construction industry were identified among participating experts. Researchers in academia made up the majority of experts with 37%, following by 31% architects/designers, 15% builders/contactors, 8% building project managers, 5% teachers, and 4% structural engineers. The high portion of responses gathered from academia could be interpreted as a result of the purposive survey distribution, which was initially realized using a call for respondents from within academia.

### *In-Depth Interviews with EBMM Experts*

The second part of the field study included in-depth interviews with the aim to obtain a rich understanding of perceptions, motivations, and views related to the application of EBMM in practice in the US. Subsequently, EBMM experts were recruited from earthen building network groups as the target audience because they possess the most comprehensive knowledge of the building procedures. Specifically, experts based in the US who have incorporated EBMM in their professional practice for the past ten years or more were interviewed, including engineering, design, and regulatory experts, as detailed in Table 1.

The 60–120 min phone in-depth interviews included a guiding questionnaire with open-ended questions. Additioanlly, prompts were used to expand discussion and to further elicit the views and experiences of the participants (Creswell & Creswell, 2017). Each expert was asked about the following subjects: (1) current barriers to implementing EBMM in construction

**FIGURE 7.** The majority of surveyed experts are familiar with earthen building codes, particularly German Earthen Building Regulations, New Zealand Standards, and New-Mexico Earthen Building Codes.



projects, (2) the role of each barrier among the other existing barriers, (3) suggestions to overcoming these barriers, (4) the conditions that have made previous EBMM projects successful, and (5) suggestions for required contribution, especially from research in academia. The in-depth interviews were recorded, transcribed by a transription software, and analyzed by employing matrices as an analytical and organizational tool.

**TABLE 1.** Interviewees' profession, primary EBMM experience, and projects locations within the US.

| | Profession | EBMM experience | Projects locations within the US |
|---|---|---|---|
| 1 | Civil engineer of natural buildings | Various | All over the US |
| 2 | Civil engineer of EBMM | Cob | CA, AL, CO, HI, NM, OR, WA |
| 3 | Architect of natural homes | Various | PA and MD |
| 4 | Architect of EBMM | Cob | CA |
| 5 | Architect of EBMM | Various | VT |
| 6 | Builder and teacher | Earthbags | CA |
| 7 | Builder and teacher | Various | OH |
| 8 | Builder and teacher | Various | CA and OR |
| 9 | Regulatory expert | Various | All over the US |
| 10 | Architect of EBMM | Adobe | CA and NM |

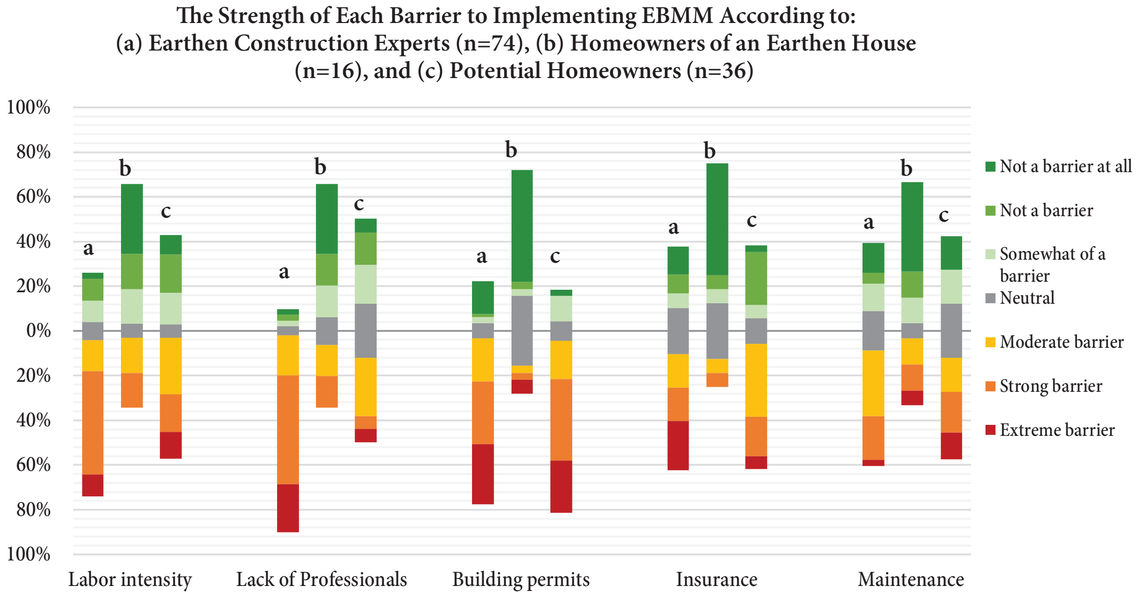
## CAPTURED BARRIERS AND GAPS TO THE BROADER IMPLEMENTATION OF EBMM

Five basic immediate barriers to the implementation of EBMM in mainstream construction were formulated from the analysis of the in-depth interviews: (1) labor intensity of the EBMM construction process, (2) lack of contractors and/or EBMM professionals and unexpected costs, (3) challenge in issuing building permits for an earthen structure, (4) difficulty in finding an insurance company to insure an earthen house, and (5) required high maintenance. Using the surveys, the perceived extent of each barrier was obtained from both end-users (homeowners and potential homeowners) and experts.

Figure 8 illustrates the extent of each barrier in a comparative manner. Potential homeowners rated obtaining building permits as the greatest barrier to EBMM implementation. Homeowners, on the other hand, rated building permits as the least significant barrier. These latter participants perceived maintenance as the greatest barrier to EBMM implementation. This might result from the fact that participants who are homeowners have already built their house from EBMM, successfully permitting their structure, and are currently involved in ongoing maintenance, whereas potential homeowners might experience current building permit challenges.

According to experts, the most significant barrier to implementing EBMM is the lack of EBMM professionals and contractors, following by building permits. Each expert had the option to leave a comment about the barriers that were specified in the survey, as well as to elaborate about any additional unspecified barriers. Twenty-six experts provided such comments. For instance, a researcher in academia who deals with rammed earth mentioned that "the absolute worst barrier to adoption is a lack of construction standards or official guidance. Without that, all structures must be assessed by Structural Engineers, i.e. incurring a much

**FIGURE 8.** Experts and potential homeowners are mostly challenged by obtaining building permits, as opposed to homeowners who are mostly challenged by labor intensity and maintenance.



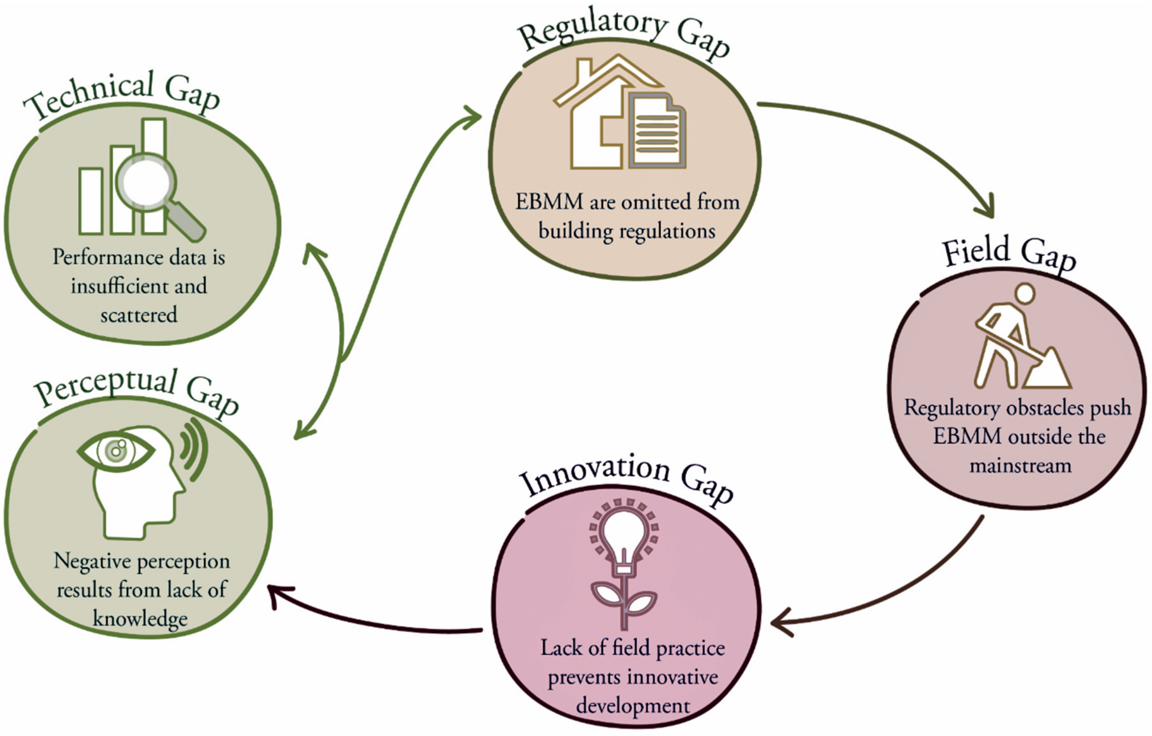
higher cost than an equivalent masonry building. However, for maintenance, if the material is stabilized then evidence suggests that maintenance isn't too great a concern."

Maintenance was least perceived to be a barrier among experts and potential homeowners. As a reinforcement, some experts associated high maintenance demands to inappropriate construction techniques. For instance, a rammed earth and earthbag building project manager mentioned that he "do[es] not agree with high maintenance, it happens if the job was poorly done," a cob and CEB architect commented that "earthen materials do not require high maintenance at all if well designed." However, these observations might be a result of the nature of the building expertise, which might be focused on the initial processes of design and construction, rather than on the ongoing commissioning and maintenance of the building project.

This part of the survey allowed respondents to add other barriers that were not specified in the survey questions. As part of this option, experts repeatedly mentioned that poor perception and lack of awareness to EBMM benefits are a significant barrier. Specifically, experts mentioned that a significant barrier is "public poor perception" and "people's aversion to dirt." Experts also elaborated on the relation between poor perception and socioeconomic prejudice, for instance: an architect of rammed earth and adobe from a seismically active region mentioned that "unfortunately, most people feel unsafe and poor in earth buildings"; and an architect of adobe, earthbags, and clay plaster from South East Asia added that "people do not treat earthen building as a permanent and standard building; they think only the poor use earth as a building material." Lastly, some experts mentioned that another barrier is the lack of available technical data, and "lack of information on new developments and recent good examples."

The mechanism behind each barrier was further investigated using in-depth interviews with experts. This part of the field study was done in order to gain a more fundamental understanding

**FIGURE 9.** The cycle of EBMM key implementation gaps.



of the gaps that need to be overcome. In addition, the way in which the gaps form a cycle of non-implementation of EBMM was observed and depicted. The following subsections detail each gap, as described by experts, finalizing in the description of how these gaps coalesce to form a cycle, of sorts, as illustrated in Figure 9.

### *Perceptual Gap—EBMM are Gaining Popularity but Still Perceived as being "Dirty"*

According to experts, earthen construction is gaining popularity, and there have been an increasing number of workshops and seminars to building with various EBMM, targeted for individuals and communities. However, EBMM are still often perceived by both clients and contractors as being unreliable and "dirty." For instance, according to an interviewed structural engineer, homeowners are often skeptical in regard to EBMM durability and ask to incorporate Portland cement for stabilization, "even if just a pinch." According to an interviewed builder, many projects that take place within US Indian reservations specify the use of CEB (that have an appearance similar to conventional bricks) due to their ability to provide both a sense of connection to earth by using earthen materials, and a sense of pride by living in a structure that resembles a "conventional American house."

### *Technical Gap—Scattered Engineering Data Makes It Challenging for EBMM Advocacy that is Grassroots with Low Funding*

Many interviewed experts highlighted the need for accessible, synthesized engineering data, which is currently scattered. While technical justification requires time and money resources, as well as technical expertise, advocacy for EBMM regulations becomes challenging. For instance, some of the interviewees who deal with cob described their main challenge as the justification of cob in code amendment meetings. This task requires advocates to synthesize existing performance data on cob, as well as to conduct and support tests to fill-in missing data that could validate cob, especially in earthquake zones.

Even more, EBMM construction is often organized by NGOs and volunteers, making it challenging in respects to entrenched interests of other regulatory representatives of commodified building materials. For example, interviewees reported that they were surprised to attend a code meeting in which the IRC subsection for adobe, located within the masonry chapter (ICC, 2015), was claimed to be unnecessary, and could have been cancelled unless EBMM advocacy was present in the meeting.

Related to the often less-formal EBMM construction industry and its adoption into building codes, an additional barrier was identified by an earthen structures researcher in Europe: "[EBMM] enthusiasts resist standards development as a threat to [their] craft-based industry; taking work away from experienced practitioners." Taking such an approach runs counter to establishing sufficient inertia to ensure the acceptance of EBMM (or indeed any sustainable 'alternative materials') into mainstream construction practices.

### *Regulatory Gap—EBMM Can Be Affordable but its Omission from Building Regulations Make It More Expensive.*

According to the in-depth interviews, EBMM can and should be affordable, however, omission from building codes (and from mandatory or at least code-compliant standards) inflate engineering and regulatory costs and therefore construction duration due to the required back-and-forth between a structural engineer who specializes in EBMM, and local code officials.

As a result, EBMM in a residential context is currently implemented by either single-family rural owner-builder, or high-income families. Interviewees also affirmed that these conflicts may result in bypassing regulations and compromised design. Examples include: integrating steel reinforcement within clay walls (structurally ineffectual and a durability concern), placing earthen materials within a structural frame (although EBMM can be used as a thermal mass, it should be structurally isolated from an enclosing frame), and intentionally designing structures to a size that will not require code approval.

### *Field Gap—Lack of EBMM Contractors and Educated Professionals*

Due to lack of inclusion in building codes and standards, there is a lack of experience by the mainstream construction industry in using EBMM. According to interviewees, lack of experienced and trained professionals lead homeowners who are interested in EBMM to either use other, more conventional materials, or to an independent construction path as owner-builders. Several interviewees highlighted that the conditions that made successful EBMM projects were good collaborations among professionals, and specifically with the local code officials; regions with code officials who were knowledgeable or sympathetic to using EBMM, made very successful projects.

It is also recognized that code officials in many—particularly smaller, less well-funded jurisdictions—are often not construction professionals themselves. In such cases, the officials are reliant on a clearly delineated code in order to make compliance decisions (a 'checklist' as it were). Ironically, such jurisdictions are exactly those were EBMM may be expected to most appropriate and attractive.

### *Innovative Gap—Lack of Research, Higher Education, and Technology Development*

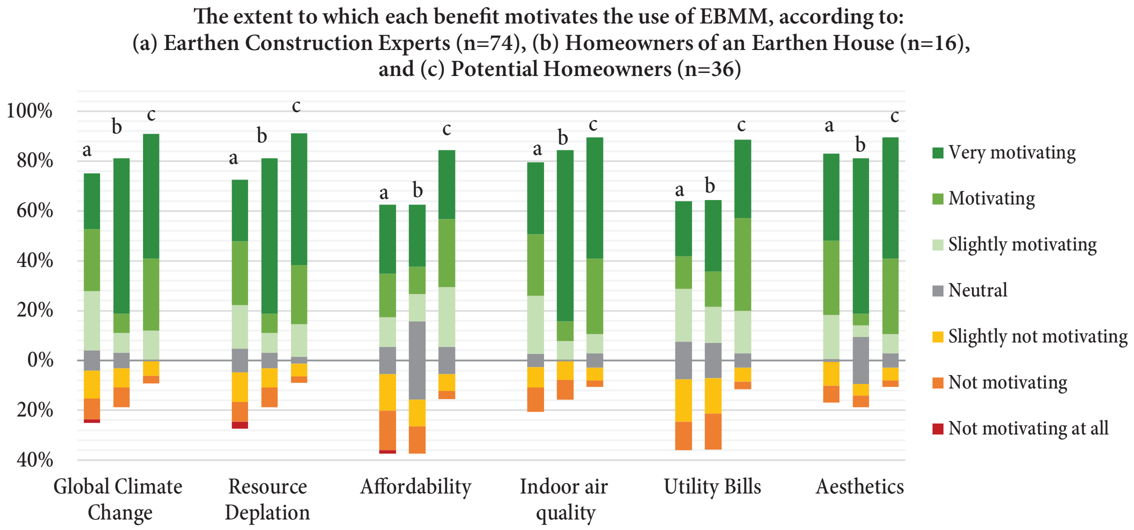
According to the in-depth interviews, EBMM is constrained within a "traditional" niche, and in order to evolve, earthen construction requires more academic research about structural, durability, and construction methods enhancement using innovative technology such as 3D printing, incorporating BIM and machinery throughout the construction process, innovative ways to test soils and to naturally provide mixtures with added strength or stability.

Following the in-depth interviews, the interdependency among the above gaps was observed and depicted in Figure 9. Accordingly, the technical and perceptual gaps are inter-reliant. Lack of technical data leads to a poor reputation of EBMM, and vice versa. Negative perception results in fewer technical tests, and less research conducted on EBMM. In turn, insufficient engineering data and negative perceptions lead to omission from building codes by experts, as well as to challenging building permits for EBMM by code officials. As a consequence, standard permitted structures are hard to achieve, leading to lack of experienced building professionals. Finally, demand for EBMM is not realized, leading to the lack of educated experts who might innovate the traditional building techniques and products.

## MOTIVATING FACTORS FOR USING EBMM

As part of the survey, participants were asked to rate the various benefits of EBMM. Experts were asked to rate the extent to which each benefit motivates homeowners. Additionally, homeowners and potential homeowners were asked to rate their own motivation factors. Figure 10 illustrates

**FIGURE 10.** Homeowners and potential homeowners are motivated mostly by indoor air quality to choosing EBMM in the construction of their house, whereas affordability is the least motivating factor.



in a comparative manner the results according to homeowners (as perceived by experts), homeowners (as perceived by themselves), and potential homeowners.

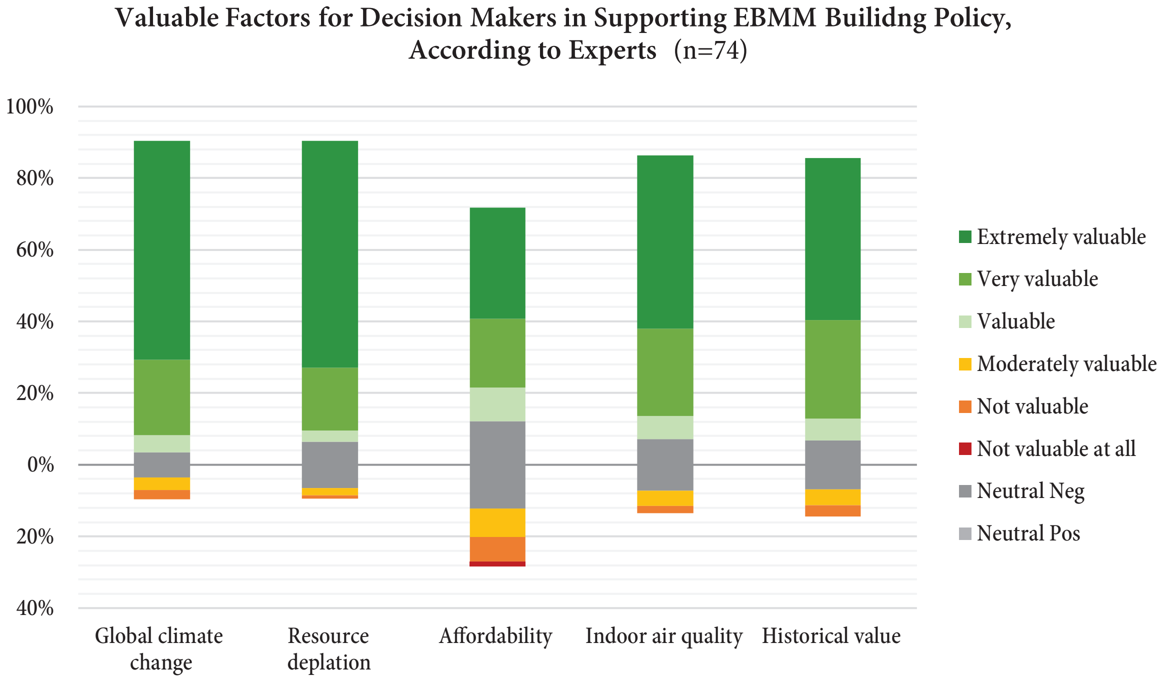
Subsequently, according to experts, the most significant factors for homeowners in their choice for using EBMM are aesthetics and indoor air quality. This result corresponds with the answers of homeowners themselves, who rated indoor air quality, following by environmental factors (global climate change and resource depletion) as the most significant motivating factors for their choice of EBMM. Although potential homeowners' perceptions were distributed in a more uniform manner among the various EBMM benefits, results still show that in a similar manner, a majority of attention was given to environmental sustainability factors, following by indoor air quality and aesthetics. In contrast, the least significant factors to motivate homeowners (according to both experts and homeowners) in choosing EBMM are affordability and [reduced] utility bills.

Furthermore, experts were asked to rate the extent to which each EBMM benefit is of value to decision makers in supporting earthen building policy. As depicted in Figure 11, the most important factors for decision makers are global climate and resource depletion while the least significant was affordability.

These results indicate that economic factors are least significant as motivating factors when applying EBMM, while environmental sustainability, health and aesthetics might represent the most attractive and valuable benefits of EBMM. In addition, the results indicate that in order to promote EBMM among decision makers, environmental sustainability factors should be addressed.

As part of the survey, experts were given the option to add comments regarding any further benefits of EBMM. Almost one-third of the participating experts (n=22) added a benefit that correlates with the ability to self-build and to engage local communities in the building process in a way that enhances local economies. For instance, in three responses from European

**FIGURE 11.** According to experts, environmental factors (global climate change and resource depletion) are the most valuable for decision makers in supporting EBMM building policy.



professionals, a rammed earth and adobe contractor commented that "it is the peoples' building-material. Everybody is able to handle it and it is of great value that people can use their hands for practical purpose"; an EBMM architect added that a valuable benefit of EBMM is the "participation of communities on construction site"; and an CEB and rammed earth architect commented that EBMM is capable of "giving a new competence to local communities, for new construction and for repair of existing construction . . . good for local economy."

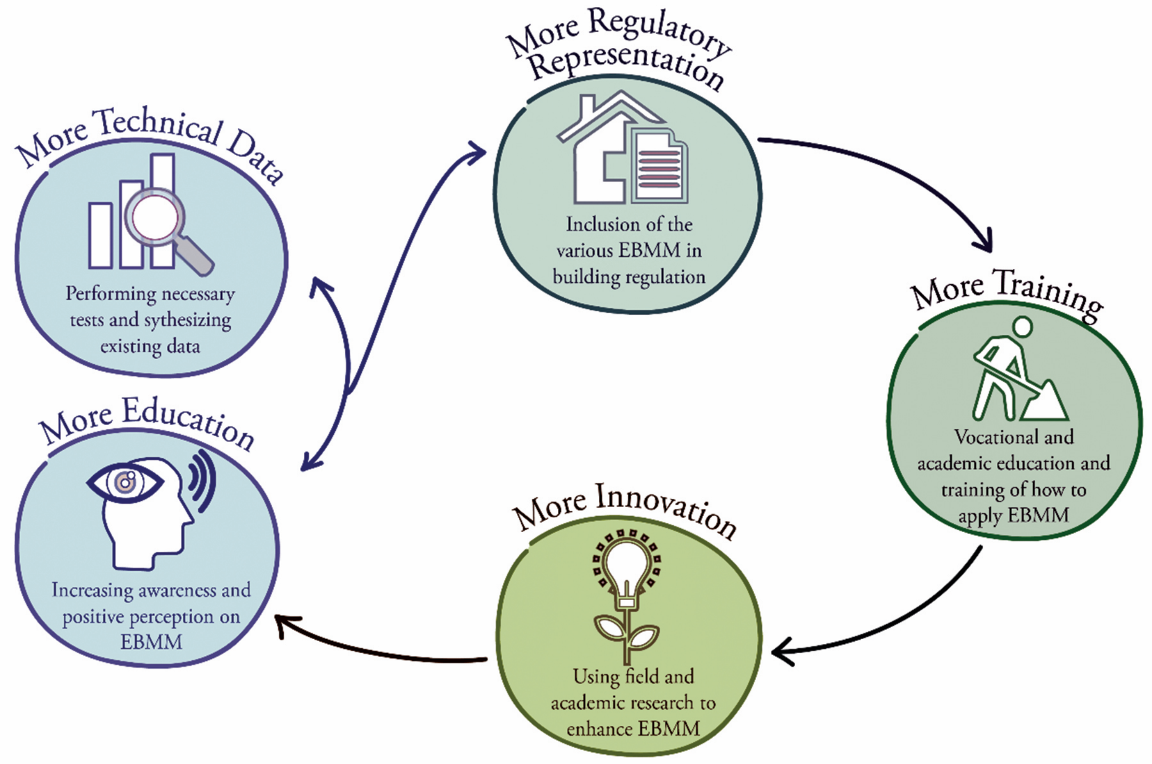
## CRITICAL STEPS TO ADVANCING EBMM GIVEN CAPTURED PERCEPTION

The mechanism behind each benefit as well as the factors that motivate stakeholders were analyzed further. Using both the survey data as well as the in-depth interviews, the following recommendations and possible solutions (Figure 12) were formulated:

### *More Education—Increasing Awareness and Knowledge about EBMM*

Mistaken negative perception of EBMM could be replaced by both increasing the awareness of EBMM features, as well as exposure and familiarity with EBMM projects. These goals could be pursued by means of education, both bottom-up within communities, as well as top down within higher education of building professional communities. In addition, raising awareness of the benefits of EBMM should be targeted to populations that perceive EBMM as being poor alternatives, illustrating EBMM's ability to be built to conventional utility with improved performance.

**FIGURE 12.** EBMM critical implementation solution steps.



### *More Technical Data—Conducting Tests and Synthesizing EBMM Technical and Environmental Performance Data*

While the quantity of EBMM performance data have been increasing, there are still areas of missing data, as well as a need to synthesize existing technical data. Appropriate test standards and reporting protocols are key to permitting such synthesis and are lacking in the EBMM field (Harries et al., 2019). A long-term goal should include the production of a white technical paper for each EBMM with a complete technical profile for each technique, as well as case studies and design examples.

### *More Regulatory Representation—Including the Various EBMM in an International and User-Friendly Building Regulation*

Using synthesized technical data and successful examples of specific EBMM building codes from other countries, proposal for the inclusion of EBMM types that are currently omitted from international codes and standards should be made. In addition, EBMM standards that are written to comply with codes in a mandatory framework might provide better guidance for code-compliant projects. (Harries et al., 2019), on the other hand, make an argument for developing 'user friendly' routes to code-compliance that incorporate permissive (rather than mandatory) language as a means of including materials such as EBMM.

### *More Training—Educating Building Professionals to Using EBMM*

According to the in-depth interviews, education of building code officials and other experts made EBMM projects successful. Therefore, training and education for architects and engineers, and especially for local building officials should take place. Vocational education, internships, and professional training for builders and contractors should also be developed to provide practical guidance in existing EBMM design guides, standards, and building codes. Additionally, earthen material products should be produced and marketed for builders.

### More Innovation—Using Research to Enhance EBMM

There is a need to develop innovative ways of using EBMM that can enhance construction operations and durability of EBMM. Advanced methods of implementing earthen materials could be developed in field and academia endeavors. For this purpose, research grants and funding opportunities should be made available for research projects that deal with technological development and structural enhancement of EBMM.

## CONCLUSIONS

Earthen Building Materials and Methods (EBMM) exhibit excellent environmental, health, indoor air quality and affordability benefits. Despite their advantages, EBMM are not yet broadly implemented in mainstream residential construction. This paper summarizes 126 detailed survey responses and 10 in-depth interviews from a range of experts and end-users to identify the main barriers and gaps to implementing EBMM. The results show that potential homeowners perceive the process of building permitting as the most extreme challenge to using EBMM in the construction of their home. Similarly, experts are mostly challenged by the lack of professionals followed by the process of building permitting. Not surprisingly, existing EBMM homeowners find maintenance and labor intensity to be the strongest barriers.

The presented results show the relevance of environmental sustainability as well as co-benefits as motivators for implementing EBMM in modern construction. Specifically, existing homeowners are mostly motivated by indoor air quality in using EBMM for the construction of their home. Potential homeowners and experts voted mostly for environmental factors such as resource depletion and global climate change as motivating benefits and as valuable factors for decision makers. Lastly, experts added to self-sufficiency and community engagement as significant benefits that enhances local economies. These results are consistent with previously established findings in environmental psychology on the relevance of environmental co-benefits, highlighting the positive social and health outcomes to motivate pro-sustainable behaviors (Bain et al., 2016; Moser & L, 2007; Thibodeau et al., 2017).

The mechanism behind the barriers and motivating factors was furtherly analyzed using in-depth interviews of field experts, and five critical steps to overcoming these barriers are proposed: (1) increasing education and awareness about EBMM, (2) synthesizing technical data about EBMM performance, (3) including the various EBMM in building codes, (4) training professionals to properly use EBMM, and (5) innovating and enhancing traditional EBMM.

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