



Designation: E2392/E2392M – 10

Standard Guide for Design of Earthen Wall Building Systems¹

This standard is issued under the fixed designation E2392/E2392M; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ϵ) indicates an editorial change since the last revision or reapproval.

1. Scope

1.1 This standard provides guidance for earthen building systems, also called earthen construction, and addresses both technical requirements and considerations for sustainable development. Earthen building systems include adobe, rammed earth, cob, cast earth, and other earthen building technologies used as structural and non-structural wall systems.

NOTE 1—Other earthen building systems not specifically described in these guidelines, as well as domed, vaulted, and arched earthen structures as are common in many areas, can also make use of these guidelines when consistent with successful local building traditions or engineering judgment.

1.1.1 There are many decisions in the design and construction of a building that can contribute to the maintenance of ecosystem components and functions for future generations. One such decision is the selection of products for use in the building. This guide addresses sustainability issues related to the use of earthen wall building systems.

1.1.2 The considerations for sustainable development relative to earthen wall building systems are categorized as follows: materials (product feedstock), manufacturing process, operational performance (product installed), and indoor environmental quality (IEQ).

1.1.3 The technical requirements for earthen building systems are categorized as follows: design criteria, structural and non-structural systems, and structural and non-structural components.

1.2 Provisions of this guide do not apply to materials and products used in architectural cast stone (see Specification C1364).

1.3 The values stated in either SI units or inch-pound units are to be regarded separately as standard. The values stated in each system may not be exact equivalents; therefore, each system shall be used independently of the other. Combining values from the two systems may result in non-conformance with the standard.

1.4 *This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the*

¹ This guide is under the jurisdiction of ASTM Committee E60 on Sustainability and is the direct responsibility of Subcommittee E60.01 on Buildings and Construction.

Current edition approved Jan. 15, 2010. Published March 2010. Originally approved in 2005. Last previous edition approved in 2005 as E2392 – 05. DOI: 10.1520/E2392-10.

responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.

2. Referenced Documents

2.1 ASTM Standards:²

- C1364 Specification for Architectural Cast Stone
- D2487 Practice for Classification of Soils for Engineering Purposes (Unified Soil Classification System)
- E631 Terminology of Building Constructions
- E2114 Terminology for Sustainability Relative to the Performance of Buildings

2.2 ASCE Standards:³

- ANSI/ASCE 7 Minimum Design Loads for Buildings and Other Structures

2.3 New Zealand Standards:⁴

- NZ97 Engineering Design of Earth Buildings, 1998
- NZ98 Materials and Workmanship for Earth Buildings, 1998
- NZ99 New Zealand Standard, Earth Buildings not requiring Specific Design, 1998 (including amendment #1, December 1999)

3. Terminology

3.1 Definitions:

3.1.1 For terms related to building construction, refer to Terminology E631.

3.1.2 For terms related to sustainability relative to the performance of buildings, refer to Terminology E2114. Some of these terms are reprinted here for ease of use.

3.1.3 *alternative agricultural products, n*—bio-based industrial products (non-food, non-feed) manufactured from agricultural materials and animal by-products.

3.1.4 *biodegradable, adj*—capable of decomposing under natural conditions into elements found in nature.

3.1.5 *biodiversity, n*—the variability among living organisms from all sources including: terrestrial, marine and other

² For referenced ASTM standards, visit the ASTM website, www.astm.org, or contact ASTM Customer Service at service@astm.org. For *Annual Book of ASTM Standards* volume information, refer to the standard's Document Summary page on the ASTM website.

³ Available from American Society of Civil Engineers (ASCE), 1801 Alexander Bell Dr., Reston, VA 20191, http://www.asce.org.

⁴ Available from Standards New Zealand, Radio New Zealand House, Level 10, 155, The Terrace, Wellington 6011, http://www.standards.co.nz.

aquatic ecosystems and the ecological complexes of which they are a part; this includes diversity within species, between species and of ecosystems.

3.1.6 *ecosystem, n*—a community of biological organisms and their physical environment, functioning together as an interdependent unit within a defined area.

3.1.6.1 *Discussion*—For the purposes of this definition, humans, animals, plants, and microorganisms are individually all considered biological organisms.

3.1.7 *embodied energy, n*—the energy used through the life cycle of a material or product to extract, refine, process, fabricate, transport, install, commission, utilize, maintain, remove, and ultimately recycle or dispose of the substances comprising the item.

3.1.7.1 *Discussion*—The total energy which a product may be said to “contain” including all energy used in, inter alia, growing, extracting, transporting and manufacturing. The embodied energy of a structure or system includes the embodied energy of its components plus the energy used in construction.

3.1.8 *indoor environmental quality, IEQ, n*—the condition or state of the indoor environment.

3.1.8.1 *Discussion*—Aspects of IEQ include but are not limited to characteristics of the thermal, air, luminous and acoustic environment. Primary areas of concern in considering the IEQ usually relate to the health, comfort and productivity of the occupants within the indoor environment, but may also relate to potential damage to property, such as sensitive equipment or artifacts.

3.1.9 *renewable resource, n*—a resource that is grown, naturally replenished, or cleansed, at a rate which exceeds depletion of the usable supply of that resource.

3.1.9.1 *Discussion*—A renewable resource can be exhausted if improperly managed. However, a renewable resource can last indefinitely with proper stewardship. Examples include: trees in forests, grasses in grasslands, and fertile soil.

3.1.10 *sustainability, n*—the maintenance of ecosystem components and functions for future generations.

3.1.11 *sustainable development, n*—development that meets the needs of the present without compromising the ability of future generations to meet their own needs.

3.1.12 *toxicity, n*—the property of a material, or combination of materials, to adversely affect organisms.

3.2 *Definitions of Terms Specific to This Standard:*

3.2.1 *adobe, n*—(1) (*building product*), unfired masonry units made of soil, water, and sometimes straw or other admixtures;

(2) (*product feedstock*), the soil/straw/admixtures mix that is used to make *adobe* (1), (here also called *earthen building mixtures* or *earthen material*);

(3) (*building product*), the earth plaster used for covering walls or ceilings, or both;

(4) (*structure*), the building that is built of *adobe* (1), (3); and

(5) (*building design*), an architectural style of earthen construction (see also 3.2.9).

3.2.1.1 *Discussion*—The word itself comes from an Arabic word *atob*, which means muck or sticky glob or *atubah* “the brick.” In many other countries, the word “adobe” is meaning-

less, and it is more accurate to say “earthen-brick.” “Adobe architecture” also has different meanings in different places.

3.2.2 *asphalt emulsion, n*—a thick liquid made by combining by-products of crude oil distillation with water and proprietary surfactants.

3.2.3 *cast earth, n*—a construction system utilizing a slurry containing soil plus a chemical binder such as portland cement or calcined gypsum and water, which is sprayed against or poured into forms similar to those used for cast-in-place concrete; also called *poured earth*.

3.2.3.1 *Discussion*—In the sprayed system, modern shotcrete equipment is adapted to spray the wet earth mixture, which is usually stabilized earth.

3.2.4 *clay, n*—inorganic soil with particle sizes less than 0.002 mm (0.00008 in.) having the characteristics of high to very high dry strength and medium to high plasticity.

3.2.4.1 *Discussion*—This size definition for clay, along with those for silt, sand and gravel, is according to Practice D2487. Other standards in the world have slightly different size limitations.

3.2.5 *cob, n*—a construction system utilizing moist earthen material stacked without formwork and lightly tamped into place to form monolithic walls.

3.2.5.1 *Discussion*—Reinforcing is often provided with organic fibrous materials such as straw.

3.2.6 *earth, n*—granular material derived from rock, usually with air voids and often with organic content (humus) (also called *soil*).

3.2.7 *earth, stabilized, n*—earthen building mixtures to which admixtures are added during the manufacturing process to help limit water absorption, stabilize volume, increase strength, and increase durability (see also *stabilization*).

3.2.8 *earth, unstabilized, n*—earthen building mixtures that do not contain admixtures intended to help limit water absorption, stabilize volume, increase strength, and increase durability (see also *stabilization*).

3.2.9 *earthen construction, n*—construction in which walls and partitions are comprised primarily of earth.

3.2.9.1 *Discussion*—Roofs and other framing may be wholly or partly of wood or other materials. Common earthen construction systems go by many names, which sometimes connote minor variations. Some of those names are:

adobe, or mud brick, earthen brick, banco, butabu, brique de terre
cast earth, or poured earth, earthcrete, sprayed earth
cob, or zabur, puddled mud, puddled earth
extruded earth block
pressed brick, or compressed earth brick/block (CEB)
rammed earth, or pisé, tapial
sod, or turf, fale and divet
tire houses, also earth bags, earth tubes
wattle and daub, or quincha, jacal, barjareque, nyumba yo mata

3.2.10 *energy efficient, adj*—refers to a product that requires less energy to manufacture or uses less energy when operating in comparison with a benchmark for energy use, or both.

3.2.10.1 *Discussion*—For example, the product may meet a recognized benchmark, such as the EPA’s Energy Star Program standards.

3.2.11 *gravel, n*—inorganic soil with particle sizes greater than 4.75 mm (0.187 in.).

3.2.12 *horizon, n*—distinctive layer of in situ soil having uniform qualities of color, texture, organic material, and obliteration of original rock material.

3.2.12.1 *Discussion*—In *World Reference Base for Soil Resources*, by the Food and Agriculture Organization of the United Nations, seven master horizons are recognized – H, O, A, E, B, C, and R.

3.2.13 *loam, n*—soil with a high percentage of organic material, particles are predominately silt size but range from clay size to sand size.

3.2.13.1 *Discussion*—Loams are usually good agricultural soils due to their nutritional organic content and their ability to hold water. Loams should be avoided in earthen construction, as the organic content is subject to biological decay and volume change. Note that the word “loam” derives from the German “lehm.” In Europe, “loam” and “lehm” usually have an opposite meaning; that is, they connote earth with a very low organic content, ideal for building but not for agriculture.

3.2.14 *material (product feedstock), n*—refers to the substances that are required for the manufacture or fabrication, or both, of a building product.

3.2.14.1 *Discussion*—Material resources include raw materials and recycled content materials.

3.2.15 *moisture wicking*—the capillary uptake of water from foundation soil or precipitation.

3.2.15.1 *Discussion*—Moisture wicking can result in saturation of adobe with an accompanying decrease in strength and durability.

3.2.16 *operational performance, n*—refers to the functionality of a product during its service life.

3.2.16.1 *Discussion*—Specific measures of operational performance will vary depending upon the product. Aspects of operational performance include: structural strength, durability, energy efficiency, and water efficiency.

3.2.17 *poured earth, n*—see *cast earth*.

3.2.18 *pressed block, n*—a block (or brick, or the construction system using those blocks) that consists of earthen materials formed in a block mold by the mechanical compaction of lightly moistened earth into a dense mass (also called *compressed earth block, CEB*).

3.2.19 *rammed earth, n*—a construction system that consists of walls made from moist, sandy soil, or chemically stabilized soil, which is tamped into forms (mechanically stabilized).

3.2.20 *sand, n*—inorganic soil with particle sizes ranging from 0.75 to 4.75 mm (0.03 to 0.19 in.).

3.2.21 *silt, n*—inorganic soil with particle sizes ranging from 0.002 to 0.75 mm (0.00008 to 0.03 in.) having the characteristics of low dry strength, low plasticity, and little dilatancy.

3.2.22 *soil, n*—see *earth*,

3.2.23 *stabilization, n*—modification of soils to limit water absorption, stabilize volume, increase strength, and increase durability, or some combination of these.

3.2.23.1 *Discussion*—For the purposes of this guide, reference to “stabilization” or “stabilized” means chemical stabilization or chemically stabilized. Chemical stabilization is achieved by the intermixture of cement, lime, gypsum, asphalt

emulsion, or other materials with the soil before emplacement, and curing as appropriate for the stabilizer and chemical reaction. Mechanical stabilization is achieved by compacting or compressing a plastic earth mixture, or containing earth in permanent forms such as bags.

3.2.24 *straw, n*—an agricultural waste product that is the dry stems of cereal grains, or sometimes native grasses, after the seed heads have been removed.

3.2.25 *straw-clay, n*—a construction system that consists of clay slip mixed with straw, of which straw makes up a high percentage by volume.

3.2.25.1 *Discussion*—Other fibers such as wood shavings or paper are sometimes used. This system is well suited for manufacturing blocks and in situ insulating wall panels.

4. Summary of Practice

4.1 This guide identifies the principles of sustainability associated with earthen building systems. Additionally, it outlines technical issues associated with earthen building systems, identifying those that are similar to construction that is commonly used in the marketplace.

4.2 This guide is intended for use in framing decisions for individual projects.

4.3 This guide is intended for use in development of standards and building codes for earthen building systems.

5. Significance and Use

5.1 *Historical Overview*—Earthen building systems have been used throughout the world for thousands of years. Adobe construction dates back to the walls of Jericho which was built around 8300 B.C. Many extant earthen structures have been functioning for hundreds of years. However, with the development of newer building materials, earthen building systems have fallen into disfavor in parts of the world where they were once commonly used. At the same time, earthen construction is experiencing a revival in the industrialized world, driven by a number of factors.

5.2 *Sustainability*—As world population continues to rise and people continue to address basic shelter requirements, it becomes increasingly necessary to promote construction techniques with less life cycle impact on the earth. Earthen building systems are one type of technique that may have a favorable life cycle impact.

5.3 *Building Code Impact*—Earthen building systems have historically not been engineered, but as of the late 20th Century it is for the first time in history possible to reliably apply rational structural design methods to earthen construction. A large number of earthen building codes, guidelines and standards have appeared around the world over the past few decades, based upon a considerable amount of research and field observations regarding the seismic, thermal and moisture durability performance of earthen structures. Some of those standards are:

- Australian Earth Building Handbook
- California Historical Building Code
- Chinese Building Standards
- Ecuadorian Earthen Building Standards
- German Earthen Building Standards
- Indian Earthen Building Standards
- International Building Code / provisions for adobe construction

New Mexico Earthen Building Materials Code
New Zealand Earthen Building Standards
Peruvian Earthen Building Standards

This guide draws from those documents and the global experience to date in providing guidance on earthen construction to engineers, building officials, and regulatory agencies.

5.4 *Audience*—There are two primary and sometimes overlapping markets for earthen construction and for this guide:

5.4.1 *Areas with Historical or Indigenous Earthen Building Traditions*—In places where earthen architecture is embedded in the culture, or there is little practical or economical access to other building systems, this guide can set a framework for increasing life safety and building durability.

5.4.2 *Areas with a Nascent or Reviving Interest in Earthen Architecture*—In places where earth is sometimes chosen over other options as the primary structural material, this guide provides a framework for codification and engineering design.

6. Considerations for Sustainable Development and Durability

6.1 *Materials (Product Feedstock)*—Materials of earthen building systems include clay soil and inorganic or organic tempering materials. Silt, sand, and gravel are commonly used inorganic tempers and straw, hair, and chaff are commonly used organic tempers. Soils may be stabilized, using such materials as cement, asphalt emulsion, calcined gypsum or cactus juice, or may be unstabilized. Systems may be finished with plaster or left unfinished.

6.1.1 *Soil*—Soils for earthen building systems are a mixture of a binder (clay), and temper soils of silt, sand, and gravel. These mixtures may be naturally occurring local soils or engineered by mixing different soils. Sources for the soils include on-site horizons, by-products of sand and gravel quarrying, and alluvial deposits. Some clays are highly expansive (montmorillonites) or moderately expansive (illites) when wetted, and thus problematic for earthen construction. Ideally, a non-expansive kaolinite clay should be used. The intermixture of small amounts of lime, bitumen, or cement will negate the expansive properties of swelling clays, but by the same chemical mechanism negate the binding and other beneficial properties of the clay. Stabilizing binders should thus generally be used only when there is no other viable strategy for meeting the project requirements. Care should be taken to avoid adverse effects on the capacity for food production when considering the use of loams and other soils that are suitable for agricultural purposes.

6.1.2 *Straw*—Straw, being dry and having no seed heads is more durable in earthen building systems than hay which contains seed heads. Straw is an agricultural waste product that is typically not used for productive end use; therefore, it is considered an alternative agricultural product and a renewable resource when used in earthen building systems.

6.1.3 *Plaster*—“Plaster” is a material applied to the exposed surfaces of earthen building systems to improve durability and modify appearance.

6.1.3.1 *Earth (or clay) Plaster*—Earth plaster is a mixture of clay, silt, sand, and water. Fibrous tempering materials are typically added.

6.1.3.2 *Cement Plaster*—Cement plaster is a mixture of cement, sand and water; the mixture may also include pozzolans, lime, pigments, glass fibers, and proprietary admixtures. Cement plaster, which is considerably less vapor-permeable than earthen plaster, can trap moisture, resulting in saturation and deterioration of unstabilized earth wall systems. For this reason, the use of cement plaster over unstabilized earth is strongly discouraged.

6.1.3.3 *Lime Plaster*—Lime plaster is a mixture of hydrated lime and sand that is much more compatible with unstabilized earth than cement plaster in terms of vapor permeability, coefficient of temperature change, and stiffness. Lime plaster has a long and successful history of use over indigenous earthen building systems in various cultures. Successful application of lime plaster over unstabilized earth does require some manner of mechanical locking, such as by scoring the earth surface, and careful application of the lime in progressive layers.

6.2 Manufacturing Process:

6.2.1 *Manufacturing*—The manufacturing process of creating a building product includes not only the process to produce manufacturing, but also fabrication and distribution procedures. The manufacture of unstabilized earthen building materials is substantially more energy efficient per unit volume than the manufacture of fired-clay masonry like brick, terra-cotta or structural clay tile, or the manufacture of cement-based systems like concrete masonry, precast concrete, or cast-in-place concrete. Stabilized earthen materials that use Portland cement, lime, asphalt emulsion or calcined gypsum are less energy efficient to manufacture per unit volume than similar unstabilized materials, but are generally more energy efficient to manufacture than cement-based concrete materials.

6.2.2 *Fabrication*—In the fabrication of earthen construction a clay binder is tempered with inorganic or organic materials, or both, to reduce shrinkage and cracking, and to increase strength and workability. Soils may be unstabilized or may be stabilized. Stabilizing is done to increase durability and strength. Placement of adobe and pressed-block systems is similar to the placement of fired-clay and concrete masonry units systems in that manufactured units are hand stacked upon one another to produce structures. Where the fabrication of these systems differs is in the mortar used to bond the manufactured units, or the firing of the units, or both. Fired-clay and concrete masonry systems use mortars containing Portland cement, proprietary masonry cements, and mortar cements, and lime putty which use substantially more energy in their manufacturing processes than unstabilized earthen building mortars and, to a lesser degree, stabilized earthen building mortars. Fabrication of rammed earth is similar to the fabrication of cast-in-place concrete systems in that formwork is required. Formwork is usually temporary wood, steel, fiberglass or earth construction built to give the desired shape and size to the completed structure. The formwork is removed before full curing of the material and can be reused or recycled depending upon the material used. Where the systems differ is in the amount of labor required to place the materials in the formwork. Cast-in-place concrete, which is continuously poured into place until the desired height or thickness is

obtained, requires less onsite labor than rammed earth, which is placed into the form in short layers called lifts and compacted after each lift. Fabrication by the cob method involves placement of the material directly into its final position without using forms.

6.2.2.1 *Energy Use*—Because of the additional steps and energy input required for transport and fabrication, fired-clay, concrete masonry, steel, and most wood systems use more embodied energy in their manufacturing processes than unstabilized earthen building systems. Stabilized earthen building systems use slightly more embodied energy because of the use of small amounts of cement or other admixtures in their fabrication. Embodied energy involved in the formwork is equal for all methods requiring temporary formwork.

6.2.3 *Distribution Procedures*—Distribution procedures for earthen building systems range from on-site extraction, manufacturing and fabrication of individual buildings by their owners to regional multi-party systems involving off-site quarries, masonry manufacturers, and building contractors.

6.3 *Operational Performance (Product Installed)*—The need for stabilization will vary from project to project and professional judgment is required.

6.3.1 *Discussion*—There are historic, multi-story apartment buildings made with unstabilized earth that have provided hundreds of years of useful service (for example Taos Pueblo, United States, and Shibam, Yemen), demonstrating that unstabilized earthen construction can be much more durable than is generally thought. In order to minimize financial costs to building owners, complication and waste during construction, and pollution costs to the ecosystem, stabilization by cement, lime or gypsum should only be used where other strength and durability measures (such as roof overhangs, reinforcing, renewable plasters, or thicker walls) cannot achieve the same strength and durability goals.

6.3.2 *Durability*—Moisture can degrade unstabilized earthen building systems. Therefore, they should be protected with some combination of foundations raised above the level of rain splash or potential flood, protective coating such as renewable earthen or lime plaster, or overhangs of sufficient size to deflect wind-driven rain. Various factors may affect durability and rate of erosion; therefore, specific site and climate conditions should be carefully evaluated. Demolished, unstabilized adobe can disintegrate and return to the soil without negative impact on the ecosystem. Materials used to stabilize earthen building systems, such as asphalt emulsion and cement, can greatly increase strength and durability, but alter soils and their suitability for agricultural uses.

6.3.2.1 Standard construction materials tests such as dry compressive strength, wet compressive strength, modulus of rupture, percent absorption, moisture content, spray and drip erosion, field density, and dry density can be used to assess the probable durability of earthen building systems. In many areas with a tradition of earthen construction, some criteria, based on these tests but modified to reflect the unique characteristics of earthen materials, are already in place for determining moisture susceptibility and load resistance.

6.3.3 *Energy Efficiency*—Earthen building systems provide thermal storage capacity (specific heat) but little insulation

(R-value). In climates where the desired indoor temperature is between the maximum and minimum daily outdoor temperatures, exterior walls of earthen building systems can dampen thermal transfer and help stabilize indoor temperatures. In climates where both the maximum and minimum daily temperatures are above or below the desired indoor temperatures for several consecutive days, weeks or months, exterior walls of earthen building systems may reduce thermal comfort by increasing conducted heat. In these climates, earthen building systems can improve energy efficiency only if insulation is installed to isolate the earthen construction from outdoor temperature changes, or limiting earthen construction to interior walls.

6.4 *Indoor Environmental Quality (IEQ)*—IEQ for earthen building systems is generally good. Possible sources of indoor pollution from earthen construction are VOC outgassing associated with asphalt stabilization and dusting from unstabilized systems.

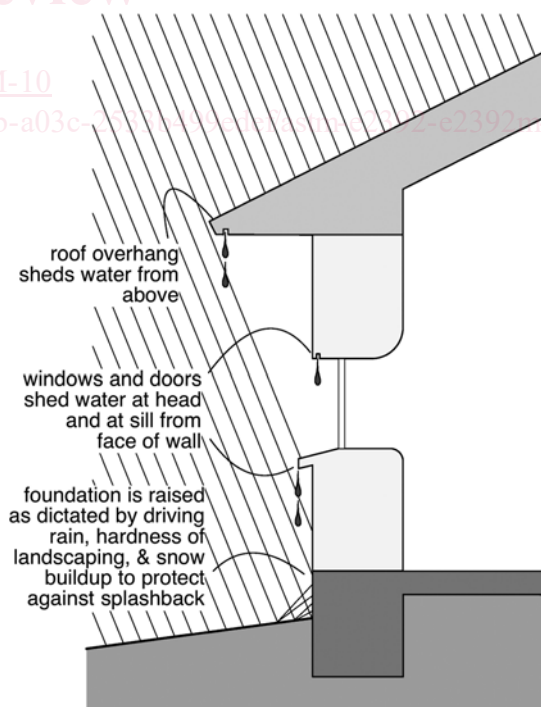
7. Technical Requirements

7.1 Structural Engineering Design:

7.1.1 Engineered design of unstabilized earthen walls can make use these New Zealand Standards: **NZ97**, **NZ98**, and **NZ99**.

7.1.2 Stabilized earth, especially cement-stabilized earth, belongs more under the purview of existing standards for concrete and concrete masonry construction (see also 7.1.6).

7.1.2.1 *Discussion*—Cement-stabilized earth, especially pressed brick and rammed earth which are mechanically compacted, often achieves compressive strengths comparable



NOTE 1—Unstabilized earthen walls should be protected by every means possible from rain, driving or splashing rain, snow, and other sources of moisture and erosion.

FIG. 1 Moisture Protection Strategies

to ordinary concrete. Engineers in many parts of the world have used locally-accepted design procedures for concrete and concrete masonry in designing cement-stabilized earthen structures.

7.1.3 Unstabilized earth can lose much of its structural strength when moist or wet. Thus, earthen construction should not be used for below-grade applications such as foundation or basement walls, or retaining walls. Also, in designing earth walls or other structures exposed to weather, provisions of 6.3.2 (Durability) should be rigorously followed, or else reduced effective section properties used based on possible depth of wetting or erosion.

7.1.3.1 *Discussion*—A common problem with earthen walls is basal erosion: a horizontal cavity that develops at the exterior base of walls, where sheeting rain coming down the face of the wall combines with rain splash to accelerate erosion. This effect can be countered with larger roof overhangs, a stone plinth along the base of the wall, and renewed plaster coatings as needed, or some combination of these.

7.1.4 Lintels over wall openings should be designed for the weight of the wall above plus any tributary roof load, and should in all cases have at least 300 mm (12 in.) of bearing on the earthen wall at both sides of the opening.

7.1.5 Mortars should be as nearly as possible the same material as the masonry in terms of strength, stiffness, and vapor permeability. Unstabilized earthen mortars should not be used on the exterior of cement-stabilized or stone masonry, and cement-based mortars should not be used with unstabilized earthen masonry. In all cases, mortar joints should be kept as thin as practicable; the thinner the mortar joints, the stronger the wall.

7.1.6 Design of cement-stabilized rammed earth walls with steel reinforcing bars can make use of established structural design methods for reinforced concrete, except that minimum reinforcing steel requirements can, and usually must, be relaxed as needed to allow access for thorough and dense ramming of the material within the formwork. Material strengths and other key properties should be reliably established.

7.1.7 Where engineering design is not feasible or available, earthen structures can be constructed according to empirical guidelines as illustrated and defined in Appendix X1 to this guide. Detailing provisions of Appendix X1 apply to all earthen structures.

7.1.7.1 *Discussion*—The purpose of Appendix X1 is to provide guidance for safe construction in those areas without

easy access to engineering services, nor economical access to industrial building materials such as cement and steel reinforcing.

7.2 *Design Criteria:*

7.2.1 Earthen buildings, structures, and parts thereof should be designed and constructed as much as practicable in accordance with internationally recognized design standards. Design live, wind, and seismic loads can be based on local knowledge or make use of known references such as the International Building Code or American National Standards Institute/American Society of Civil Engineers document ANSI/ASCE 7. Engineered design can make use of strength (load and resistance factor) design, allowable stress design, or empirical design.

7.2.2 *Seismic Design*—Seismic design requirements for life safety vary greatly with the local degree of seismic risk, but should in all cases provide structural continuity, out of plane stability, and containment. Detailing provisions of Appendix X1 should be applied to all earthen structures. Relevant provisions of ANSI/ASCE 7 should be used to estimate seismic demand loads on elements, connections and reinforcing shown in Appendix X1, using static or dynamic procedures for unreinforced masonry structures.

7.2.2.1 *Discussion*—Seismic design of earthen buildings (or reinforcement of existing earthen buildings) has evolved enormously with the testing and research of the past few decades. Some tentative modeling for static or dynamic force procedures has emerged, but prevailing engineering thought is to emphasize global and local stability rather than traditional (and much less reliable) stress analysis. Seismic forces that any particular structure must withstand can only be approximated, but extensive field observations and shake table tests have shown where a structure should be reinforced and interconnected so as to remain intact and stable under seismic shaking.

7.2.3 *Flood Design*—Unstabilized earthen walls are not considered suitable for flood prone areas unless raised by foundation or durable plinth above the level of potential flooding.

8. Keywords

8.1 adobe; alternative agricultural products; alternative building materials; cob; compressed earth brick; earthen architecture; earthen construction; energy efficiency; indoor environmental quality (IEQ); natural building materials; rammed earth construction; sustainability; sustainable development; thermal mass