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An American National Standard

Standard Guide for Design of Earthen Wall Building Systems[1]

1. Scope

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

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, that is, sustainability. One such decision is the selection of products for use in the building. This standard 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 This standard does not provide guidance for structural support of roofs made of earthen material.

1.3 This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and to determine the applicability of regulatory limitations prior to use.

2. Referenced Documents

2.1 *ASTM Standards:* [2]

C 666/C 666M Test Method for Resistance of Concrete to Rapid Freezing and Thawing

D 559 Test Methods for Wetting and Drying Compacted Soil-Cement Mixtures

D 560 Test Methods for Freezing and Thawing Compacted Soil-Cement Mixtures

D 5860 Test Method for Evaluation of the Effect of Water Repellent Treatments on Freeze-Thaw Resistance of Hydraulic Cement Mortar Specimens

D 698 Test Method for Laboratory Compaction Characteristics of Soil Using Standard Effort (12 400 ft-lbf/ft^3 (60 kN·m/m^3))

E 631 Terminology of Building Construction

E 2114 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

3. Terminology

3.1 *Definitions:*

3.1.1 For terms related to building construction, refer to Terminology E 631.

3.1.2 For terms related to sustainability relative to the performance of buildings, refer to Terminology E 2114. 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 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*—community of plants, animals (including humans), and their physical environment, functioning together as an interdependent unit within a defined area.

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.

[1] This Guide is under the jurisdiction of ASTM Committee E06 on Performance of Buildings and is the direct responsibility of Subcommittee E06.71 on Sustainability .

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[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 The American Society of Civil Engineers (ASCE), 1801 Alexander Bell Dr., Reston, VA 20191.

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 *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.

3.1.8.1 *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.

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

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

3.1.11 *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)* unfired masonry units made of soil, water, and straw with or without various admixtures; *(2)* the soil/straw or soil/straw/admixtures mix that is used to make them; *(3)* the mud plaster used for covering walls or ceilings, or both; *(4)* the building that is built of adobe and; *(5)* the architectural style.

3.2.1.1 *Discussion*—The word itself is believed to come from an Arabic word *atob*, which means muck or sticky glob or *atubah* "the brick." The adobe style of architecture migrated from North Africa to Spain, so the name adobe is likely to have come with it. In many other countries, the word adobe is meaningless, and it is more accurate to say "earthen-brick." Other forms of the same material with different details and names, such as rammed earth, Pisé, Jacal, Barjareque, cob, or puddled mud are sometimes referred to as adobe.

3.2.2 *adobe construction*, *n*—construction in which the exterior load-bearing and the non-load-bearing walls and partitions are of unfired clay masonry units while the floors, roofs and interior framing may be wholly or partly of wood or other approved materials.

3.2.3 *adobe, stabilized*, *n*—unfired clay masonry units to which admixtures, such as emulsified asphalt or cement, are added during the manufacturing process to help limit water absorption and increase durability.

3.2.4 *adobe, unstabilized*, *n*—unfired clay masonry units that do not meet the definition of stabilized adobe.

3.2.5 *carbon sink*, *n*—a reservoir that absorbs or takes up released carbon from another part of the carbon cycle.

3.2.5.1 *Discussion*—For example, if the net exchange between the biosphere and the atmosphere is toward the atmosphere, the biosphere is the source, and the atmosphere is the sink

3.2.6 *cast earth*, *n*—a construction system utilizing a slurry containing soil, calcined gypsum and water, which is poured into forms similar to those used for cast-in-place concrete.

3.2.7 *clay*, *n*—inorganic soil with particle sizes less than 0.005 mm (0.0002 in.) having the characteristics of high to very high dry strength, medium to high plasticity and slow to no dilatancy.

3.2.8 *cob*, *n*—a construction system utilizing moist earthen material balls stacked on top of one another and lightly tapped into place to form monolithic walls. Reinforcing is often provided with organic fibrous materials such as straw and twigs.

3.2.9 *earthen building systems*, *n*—building systems that utilize soil as the principal structural material.

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

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 2 mm (0.079 in.).

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

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 *indoor environmental quality (IEQ)*, *n*—refers to the condition or state of the indoor built environment in which the building product is installed. Aspects of IEQ include: light quality, acoustic quality, and air quality.

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

3.2.14.1 *Discussion*—Loams are usually good agricultural soils due to their nutritional organic content and their ability to hold water.

3.2.15 *manufacturing process*, *n*—refers to the process of creating a building product and includes manufacturing, fabrication and distribution procedures.

3.2.16 *materials (product feedstock)*, *n*—refers to the material resources that are required for the manufacture and/or fabrication of a building product.

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

3.2.17 *moisture wicking*—the capillary uptake of water from foundation soil, ambient humidity or precipitation. Moisture wicking can result in saturation of adobe with an accompanying decrease in strength and durability.

3.2.18 *operational performance (product installed)*, *n*—refers to the functioning of a product during its service life. Specific measures of operational performance will vary depending upon the product. Aspects of operational performance include: durability, maintainability, energy efficiency, and water efficiency.

3.2.19 *pressed-block*, *n*—a construction system that consists of walls made from earthen materials formed in a block mold by the compacting of lightly moistened earth into a hardened mass.

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

3.2.20.1 *Discussion*—Walls of unstabilized soil are usually a minimum of 300 mm (12 in.) thick for load bearing purposes. Soils for rammed earth construction usually contain about 30 % clay and 70 % sand.

3.2.21 *sand*, *n*—inorganic soil with particle sizes ranging from 0.05 to 2.0 mm (0.002 to 0.079 in.).

3.2.22 *silt*, *n*—inorganic soil with particle sizes ranging from 0.005 to 0.05 mm (0.0002 to 0.002 in.) having the characteristics of low dry strength, low plasticity, and rapid dilatancy.

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

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

3.2.24.1 *Discussion*—This system is well suited for manufacturing bricks, floor blocks, and insulating 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 framing decisions for 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 (now located in Israel) which was built around 8300 B.C. Many other earthen structures have been functioning for hundreds of years. However, with the development of newer building materials, earthen building systems have been largely abandoned in part of the world where they were once commonly used.

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. The first written standards for adobe were developed in the United States in the 1930s and were based on common construction practices. Only during the last 20 years have architects and engineers attempted to engineer adobe and rammed earth for use and compliance with contemporary building codes. Standards for the use of adobe were initially limited to local and state codes, predominantly in the southwestern United States. However, over time regional and national model building codes adopted provisions for adobe construction. For example, the International Building Code (IBC)[4] provides empirical requirements allowing the use of adobe when the applicant follows specific procedures. New Mexico building code provides empirical requirements for the use of both adobe and rammed earth building systems. Where the building code does not specifically address earthen building systems, governing agencies frequently classify the construction as an alternative material, design, or method of construction. An alternative material, design, or method of construction will be approved when the code official finds that the proposed design is satisfactory and complies with the intent of the provisions of the code and that the material, method or work offered is, for the purpose intended, at least the equivalent of that prescribed in the code in quality, strength, effectiveness, fire resistance, durability and safety. However, development of standards such as this can aid in the appropriate recognition and adoption of earthen building systems materials and methods by building codes and code enforcement agencies.

5.4 *Audience:* There are existing markets in the United States and internationally using adobe, rammed earth, and other earthen building systems. It is estimated that 40 % of the world's population lives in earthen dwellings[5]. Safety, functionality, and sustainability of earthen building systems can greatly be improved through establishment of an international design standard. Intended users of this standard guide include: planners, developers, architects, engineers, interior designers, general contractors, subcontractors, owners, financial organizations related to building industry, building materials and product manufacturers, government agencies including building officials, and other building professionals.

6. Considerations for Sustainable Development

6.1 *Materials (Product Feedstock):* Materials of earthen building systems include a binder soil, typically clay, clay-silt mixture or loam; and inorganic or organic tempering materials, or both. 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. Adobe bricks may be held together by a variety of mortars. Systems may be finished with plaster or pigments, or both, or left unfinished.

6.1.1 *Soil:* Soils for earthen building systems are a mixture of a binder soil, for example, clay, silt, clay-silt combination or loam, and temper soils of 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.

Care should be taken to avoid adverse affects 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 is

[4] Available from International Code Council (ICC), 5203 Leesburg Pike, Suite 600, Falls Church, VA 22041.

[5] Information from ICBO Vol 1, published 2/2000. Available from International Code Council (ICC), 5203 Leesburg Pike, Suite 600, Falls Church, VA 22041.

a green, typically shorter, grass animal feed product containing stems and 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:* A material applied to the exposed surfaces of earthen building systems to improve durability, water resistance or modify its appearance, or both. Commonly used on adobe, pressed block, and straw clay systems to protect or conceal, or both, the joints between the units.

6.1.3.1 *Clay Plaster:* Clay plaster is a mixture of clay, sand and water. Tempering materials, such as straw, and pigments may be added.

6.1.3.2 *Cement-stabilized Clay Plaster:* Cement-stabilized clay plaster is similar to clay plaster except for the addition of Portland cement or some other hydraulic cement, which is added to improve durability and/or reduce dusting. Tempering materials, other admixtures and pigments may also be added.

6.1.3.3 *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 often less permeable than many of the structural materials used in earthen building systems, can be used to encapsulate the tops and bottoms of walls and around openings to prevent moisture wicking which can result in saturation and deterioration of unstabilized systems.

6.2 *Manufacturing Process:*

6.2.1 *Manufacturing:* Manufacturing sun-dried, unfired earthen building materials, like adobe, pressed-block and straw-clay, is more energy efficient per unit volume than the manufacturing of fired-clay masonry, like brick, terra-cotta or structural clay tile. The manufacturing of earthen building materials that use Portland cement or some other kiln produced cement is more energy efficient per unit volume than the manufacturing of cement based concrete materials, like cast-in-place concrete and precast concrete if only because of the lower cement content of stabilized soil. Stabilized materials that use Portland cement, asphalt emulsion or calcined gypsum are less energy efficient to manufacture per unit volume than similar unstabilized materials. Asphalt emulsion is made by combining asphalt, a by-product of crude oil distillation, with water and proprietary surfactants.

6.2.2 *Fabrication:* In fabrication of adobe a binder soil, typically clay, is tempered with inorganic and/or organic materials 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 the material is done by forming units, such as adobe brick, pressed-block or straw-clay, which are then stacked to form the structure; or the material is placed directly into its final position using forms, for example, the rammed earth and cast earth methods; or without using forms, for example, the cob method. Placement of adobe, pressed-block and straw-clay 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 material 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 more energy in their manufacturing processes than unstabilized earthen building mortars and, to a lesser degree, stabilized earthen building mortars.

Fabrication of rammed earth and cast earth systems 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. There are now some plastic formwork systems which, rather than being removed, are incorporated into the final structure. Where the systems differ is in the amount of labor required to place the materials in the formwork. Cast-in-place concrete and cast earth, which are continuously poured into place until the desired height or thickness is obtained, require less labor than rammed earth, which is placed into the form in short layers called lifts and compacted after each lift.

6.2.2.1 *Energy use*—Because of the additional steps required for fabrication, fired-clay, concrete masonry, wood or steel 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. While the energy required to place the rammed earthen material into the formwork is higher per unit volume, the differences are minimal in comparison to the quantity of energy used in the manufacturing and distribution procedures for cast or placed concrete or concrete/plastic systems. Important considerations for sustainable development in the fabrication of earthen building wall systems versus fired masonry, concrete, wood or steel systems are the quantities of energy consumed and carbon transferred from the biosphere to the atmosphere during manufacturing and fabrication per cross-sectional unit length of the entire system, including the foundation, bond beams, lintels, and so forth. Materials that are more energy intensive to manufacture than earthen building materials, such as concrete, are often used for foundations, bond beams and other components of earthen building systems. This results in the earthen building systems being more energy intensive than just the earthen building materials used in the systems. Quantities of energy consumption and carbon transfer associated with earthen building systems increase as wall thicknesses increase to match structural load capacities of thinner fired-clay masonry, concrete masonry, cast-in-place and precast concrete wall systems. In earthen building systems, where wall thicknesses are increased and more energy intensive materials are used for components, the quantities of energy consumed and carbon transferred can exceed quantities associated with fired-clay masonry, concrete masonry, cast-in-place and precast concrete wall systems.

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-corporation systems involving off-site quarries, masonry manufactures, and building contractors.

6.3 *Operational Performance (Product Installed):* It is commonly held in Europe and other parts of the world that stabilization is not necessary. In the United States, many builders have used stabilization to prevent dusting or to increase strength, or both, depending on soil characteristics. The need for stabilization will vary from project to project and professional judgment is required.

6.3.1 *Durability:* Moisture will disintegrate earthen building systems; therefore, earthen building systems should be protected with foundations, protective coating such as cement plaster and/or overhangs. Vertical surfaces in areas with rain up to 640 mm (25 in.) per year will likely erode at the rate of approximately 25 mm (1 in.) in 20 years. Horizontal surfaces such as the top of a wall, on the other hand, will likely erode much more rapidly (50-75 mm (2-3 in.) per year.) 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 alter soils and their suitability for agricultural uses.

There are currently ASTM standards for freeze-thaw testing of soil-cement (Test Methods D 560), concrete (Test Method C 666/C 666M) and hydraulic cement mortar (Test Method D 5860) and wet-dry testing of soil-cement (Test Methods D 559) but not for unstabilized adobe.

6.3.1.1 Standard construction materials tests such as dry compressive strength, wet compressive strength, modulus of rupture, percent absorption, moisture content, field density and dry density can be used to assess the probable durability of earthen building systems. In many areas of relatively high adobe usage, some criteria, based on these tests but modified to reflect the unique characteristics of adobe materials, are already in place for determining moisture susceptibility and load resistance. Examples of these criteria follow:

6.3.1.1.1 Moisture susceptibility can be assessed using criteria of either an average wet compressive strength of 2068 kPa (300 psi) after submersion of a 76 mm (3-in.) cube for 24 hours or an absorption rate of no more than 2.5 percent of the initial dry weight of a 76 mm (3-in.) cube after 7 days on a constantly saturated porous surface.

6.3.1.1.2 Load resistance for dried adobe units can be addressed using current criteria for an adobe unit dried to a constant mass of having an average dry compressive strength of 2068 kPa (300 psi) and an average modulus of rupture of 345 kPa (50 psi). According to these criteria, a cured adobe unit should have a moisture content of less than 4 %. For rammed earth construction a common criteria is that it have a field density greater than or equal to 95 % of maximum dry density, determined in accordance with Test Method D 698, for the material being used. For cement-stabilized rammed earth one criteria currently in use is a 14-day compressive strength greater than 2068 kPa (300) psi.

6.3.2 *Maintainability:* While proper testing for durability will also aid in maintaining the earthen building system, some tests such as random sampling of adobe units for shrinkage cracks will increase maintainability by decreasing the likelihood of significant breaches in the materials, which may allow moisture to the interior of the building. One criteria already in use requires that randomly sampled adobe units have no more than 3 shrinkage cracks and that no single shrinkage crack be longer than 76 mm (3 in.) or wider than 3.2 mm (1/8 in.).

6.3.3 *Energy efficiency:* Earthen building systems provide thermal storage capacity. The specific heat and U-factor of earthen building systems are high in comparison to insulated wood or steel stud frame construction making it suitable for thermal storage and unsuitable for thermal insulation.

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 will reduce thermal comfort by increasing conducted heat transfer, due to the high U-factor; and increasing radiant heat transfer, due to high mean radiant temperatures (MRT) during hot weather and low MRT's during cold weather. Since both the specific heat and U-factor of earthen building systems is high, it is difficult to alter the surface temperature of walls. In these climates, earthen building systems can improve energy efficiency by isolating the earthen building systems from outdoor temperature with insulation on the exterior surface or limiting earthen building systems to interior walls.

6.4 *Indoor Environmental Quality (IEQ):* IEQ for earthen building systems is generally considered good. Possible causes for poor IEQ are; VOC outgassing associated with asphalt emulsion, dusting from unstabilized systems, and radon gas production from certain soils.

7. Technical Requirements

7.1 *Earthen building systems:* Earthen building systems include adobe, rammed earth, cast earth, and pressed block.

7.2 *Design Criteria:*

7.2.1 Earthen buildings, structures, and parts thereof should be designed and constructed in accordance with internationally recognized design standards such as IBC or ANSI/ASCE 7 for strength design, load and resistance factor design, allowable stress design, empirical design, or conventional construction methods.

7.2.2 Earthen buildings, structures, and parts thereof, should be designed and constructed to support safely the factored loads in load combinations defined in ANSI/ASCE 7 without exceeding the appropriate strength limit states for the materials of construction. Alternatively, earthen buildings, structures, and parts thereof, shall be designed and constructed to support safely the nominal loads in load combinations defined in

ANSI/ASCE 7 without exceeding the appropriate specified allowable stresses for the materials of the earthen building systems.

7.2.3 *Earthquake Loads:* Consider lateral forces on earthen structures and structural components form seismic events. Consider in terms of the effects of earth movement, soil conditions, building occupancy, and location of the earthen component within the structure.

7.2.4 *Wind Loads:* Consider lateral forces on earthen structures and structural components from wind forces.

7.2.5 *Rain and Snow Loads:* Comply with design loads based upon rain as required for conventional construction. Care should be taken during construction to protect work from rain or snow since moisture uptake during construction can be extremely detrimental.

7.2.6 *Dead Loads:* Consider the impacts, both negative and positive, of gravity and dead loads as they affect earthen building systems.

7.2.7 *Flood Loads:* Earthen materials are not considered suitable for flood prone areas.

7.2.8 *Load Combinations:* Consider the effects of various load combinations and develop recommendations for design requirements consistent with conventional construction.

7.2.9 *Impact Loads:* Consider the stability of earthen wall systems to resist impact loads.

7.2.10 *Bending Loads:* Earthen materials do not perform well in bending conditions. Limit use of earthen materials as bending elements.

7.2.11 *Compressive Loads:* Develop safe and practical compressive loads stress formulas for earthen materials of different strengths and for the various uses in earthen building systems.

7.2.12 Tensile Loads Earthen materials are limited in tensile strength. Limit use of earthen materials as under tensile loads.

7.2.13 *Shear Loads:* Develop safe and practical methods of determining allowable shear stress and its relationship to dead load stress for earthen materials.

7.3 *Structural Systems:*

7.3.1 *Load-bearing wall braced:* This system utilizes bond beams as lateral force resisting elements. This system utilizes shear resistant earthen walls.

7.3.2 *Diaphragm braced load-bearing wall:* This system utilizes conventional diaphragms such as roofs or floors to transfer loads to shear resistant earthen walls.

7.3.3 *Post and beam:* This system utilizes wood, concrete, or steel as the vertical and lateral load resisting system. This system utilizes earth as an infill material only.

7.4 *Structural Components:* Earthen building systems should especially consider the appropriate design for the following structural components:

7.4.1 Bearing walls,

7.4.2 Non-bearing walls, and

7.4.3 Inverted cantilever walls and elements.

7.4.4 *Bond Beams:* Consider materials and attachment to walls.

7.4.5 Bolting and attachments.

7.5 *Non-Structural Systems*:

7.5.1 *Veneer:* This system uses earthen materials as non-load bearing veneer.

7.5.1.1 Adobe brick

7.5.1.2 Adobe plaster

8. Keywords

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