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MOVEMENT COEFFICIENTS OF COMPRESSED EARTH MASONRY UNITS

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ABSTRACT

Coefficients exist for the physical movements that clay brick and concrete masonry units undergo in service. Less well-known, however, are the movements of masonry units made of compressed earth. The standard laboratory tests for certification of quality and strength standards for fired clay brick and concrete masonry units, for example, include test procedures that must be modified for earth masonry. The hot and cold water baths used for absorption determination would cause unmodified earth bricks to dissolve. While masonry units modified with Portland cement, lime, or fly ash will have increased durability to dissolving in the water baths, very few ASTM or other standard procedures have been developed to determine the movement coefficients for compressed earth block units. A review of the literature and preliminary testing of compressed earth bricks has found that standard tests in the laboratory must be adapted to determine the physical characteristics of earth masonry. Among the coefficients needed are those for thermal expansion (k_t); moisture expansion (k_e); shrinkage (k_m); elastic shortening (ES); creep (k_c); and, deflection (Δ). A presentation of what are known and not known about the movement characteristics of earth masonry units should generate discussions that will help direct future efforts to accurately define the performance of these units. This information should be helpful to architects and engineers whose goals are to design and construct sustainable buildings.

KEYWORDS: compressed earth block, movement, coefficients, expansion, shrinkage

INTRODUCTION

Masonry walls on building exteriors are subjected to both reversible and non-reversible movements. Movements include expansion and contraction that are the result of changes in temperature and moisture content. Movements caused by changes in temperature are generally considered to be reversible, while those caused by moisture absorption in clay masonry units and shrinkage of concrete masonry units are typically not reversible.

Depending upon the design of the building and the loading conditions they are subjected to, exterior masonry walls may be subjected to other non-reversible movements, such as elastic shortening, creep and shrinkage of the supporting structure, and deflection of supporting beams and lintels from imposed dead and live loads. Whenever these movements are accommodated by proper design, they seldom cause structural problems. If they are not accommodated appropriately, however, and are therefore restrained, forces accumulate in the walls that can cause cracks and spalling, affecting the structural and service performance adversely and irreversibly.

As do most building materials, masonry walls of earth, whether of sun dried adobe bricks, rammed earth, or compressed earth blocks, respond to changes in moisture and temperature, but little is known about their behaviour. The standard tests for measuring their changes in dimension, and the coefficients needed to design the wall system for such changes are not as well developed for these materials as they are for clay bricks and concrete masonry units. This paper describes the origin and magnitude of these movements in compressed earth blocks made of stabilized and un\stabilized soils. Recommendations to accommodate the movements and to minimize the development of cracks and spalling in exterior masonry walls are given, and future research directions are suggested.

BACKGROUND – MOVEMENTS IN FIRED CLAY BRICK AND CONCRETE MASONRY UNIT WALLS

Much research has been conducted of the potential movements walls constructed of fired clay brick and concrete masonry units. Predicted magnitudes of movements for these materials, taking into account the variety of clays and firing methods used for clay bricks, and for walls constructed of the various types of concrete masonry units, have been well-developed from years of research and development. The behaviour of other types of structural components such as beams, lintels and columns are included in a number of places, including a publication by Ian R. Chin [1]. In the following sections these will be reviewed, then, coefficients of movement for compressed earth blocks (CEBs) will be provided.

THERMAL EXPANSION – REVERSIBLE

Temperature changes cause exterior wall materials to expand and contract. Following are the thermal expansion coefficients (k_t), commonly used for masonry walls of clay brick and concrete masonry units:

- For fired clay masonry, $k_t = 4.5 \times 10^{-6} / {}^{o}C$ (2.5×10^{-6} inch/inch/^{o}F) [1]
- For clay or shale brick, $k_t = 6.48 \times 10^{-6} / {}^{o}C$ (3.6×10^{-6} inch/inch/^{o}F) [1]
- For concrete masonry units made with lightweight aggregates, $k_t = 7.74 \times 10^{-6} / {}^{o}C$ (4.3×10^{-6} inch/inch/^{o}F) [2]
- For concrete masonry units made with dense aggregates, $k_t = 9.36 \times 10^{-6} / {}^{o}C$ (5.2×10^{-6} inch/inch/^{o}F) [2]

Thermal expansion from increasing temperatures and contraction from decreasing temperatures are reversible and occur along the length, height, and thickness dimensions of the wall (x, y and z axes respectively). A wall may behave differently from these coefficients, however, if it is restrained and depending upon where in the wall the temperature changes are assumed, the middle of the wall or the wythe is the recommended location to measure the mean temperature.

MOISTURE EXPANSION OF CLAY BRICK (NOT REVERSIBLE)

Firing of clay masonry, such as to produce brick, terra cotta and clay tile, heats the clay to temperatures that vary, depending upon the type of heating process used, up to about 1093.3 ^{o}C (2,000 ^{o}F) [3]. The firing process drives the moisture from the brick units and causes them to shrink. When the brick units are laid into walls, they expand slowly as they absorb moisture from the atmosphere. Rain, snow and ambient humidity are absorbed into the clay these units are made of, and the units expand. If the units are unrestrained structurally, they will increase dimensions in all three axes and so the designer must account for this expansion to control cracking. According to Chin [3], moisture-induced expansion of clay masonry units can continue for more than 50 years. He says "The rate of moisture expansion varies linearly with the logarithm of time. Typically, approximately 60 percent of the potential moisture expansion occurs about one year after the units are fired ([3] p. 21)."

SHRINKAGE OF CONCRETE MASONRY UNITS (NOT REVERSIBLE)

Concrete masonry units, which are manufactured from a wet mix of concrete, slowly shrink dimensionally from hydration and carbonation, and from changes in their moisture content as they reach equilibrium with their environment. For the design of concrete masonry unit walls, the following shrinkage coefficients (k_m) are typically used ([3], p. 21):

- For masonry made from moisture controlled concrete masonry units, $k_m = 9.8 \times 10^{-5}$ cm/cm (0.98×10^{-4} inch/inch) (maximum); and,
- For masonry made from non-moisture controlled concrete masonry units, $k_m = 3.25 \times 10^{-4}$ cm/cm (3.25×10^{-4} inch/inch).

The actual amount of shrinkage of concrete masonry units is dependent upon the method of curing, aggregate type, change in moisture content, cement content, and wetting and drying cycles [2]. The wall designer should pay particular attention to these details, and include analyses of the type of climate the units will be used in when in service [3]. Typically, the shrinkage of concrete masonry units is not reversible in normal service conditions. As before, the shrinkage occurs in the directions of all three axes.

ELASTIC SHORTENING OF SUPPORTING BUILDING STRUCTURES (NOT REVERSIBLE FOR PERMANENT LOADS)

Structural components of buildings such as columns and walls used to support the gravity loads of buildings will shorten after they have been constructed and loads have been placed on them. The approximate amount of shortening (*ES*) that occurs in these members can be calculated with the following formula:

$$\mathrm{ES} = PL/AE \qquad \text{Equation 1}$$

where
P = load supported by the column or wall
L = length of the column or wall
A = cross-sectional area of the column or wall; and,
E = modulus of elasticity of the material used to construct the column or wall.

As occurs with shrinkage that is not reversible, elastic shortening caused by permanent loads are not reversible. Reinforced concrete columns will shorten more than equally sized and loaded structural steel columns because the modulus of elasticity of steel is greater than that of concrete ([2], p. 21).

CREEP OF SUPPORTING CONCRETE BUILDING STRUCTURES (NOT REVERSIBLE)

When concrete members are stressed continuously, they will shorten in the direction of the applied stress. This kind of shortening over long periods of time, though small, is called creep. The amount of creep can be considerable in reinforced concrete members, and, it is not reversible. The Brick Industry Association [1] says that there are a number of factors that affect how much creep concrete building components may experience. High-strength concretes show less creep than low-strength concretes. Creep may be slightly higher in concretes made with lightweight aggregates than normal weight aggregates. In multi-story buildings, creep in the concrete frame may be as much as 2.54 cm (1 inch) for every 24.4 m (80 feet) of height. This equates to a creep coefficient, $k_c = 1.45 \times 10^{-10}$ unit length/Pa (1.0×10^{-6} unit length/psi) ([3], p. 21).

DEFLECTION OF SUPPORTING BEAMS AND LINTELS (NOT REVERSIBLE)

Deflection of supporting beams and lintels is also not reversible in the presence of permanent loads or when the elastic limit is exceeded. This movement is in addition to the movements related to the physical properties of the materials used in masonry walls. The building codes (e.g. ACI 530) generally limit the deflection of beams and lintels when they support masonry to the lesser of l/600 of the span, or 7.6 mm (0.30 inches). For reinforced concrete beams, the final deflection of the beam including creep can be up to 2 ½ times its initial deflection, which the designer must compute based on professional judgment.

OTHER CAUSES OF MOVEMENT IN MASONRY

There are other causes of movement in masonry according to service conditions. These include freezing expansion, carbonation of concrete and mortars, drift of the building frame, deflection of building elements, and the action of unstable soils upon which the structure is supported. One of the more common coefficients used in the design of masonry walls is for expansion caused by freezing. This expansion can be added to other forces that affect expansion of masonry. According to the BIA [1], the freezing expansion coefficients for water-soaked brick may range from 0 to 10.3×10^{-4} cm/cm (0 to 10.3×10^{-4} inch/inch), depending upon their moisture content. A design value for brick of 2×10^{-4} cm/cm (2×10^{-4} inch/inch) is recommended [1]. The designer should consider the potential for the other forms of movement in the masonry and accommodate them using sound professional judgment.

COMPRESSED EARTH BLOCK CONSTRUCTION

Contemporary machines have made it possible to produce high quality bricks using soil as the basic ingredient. Firing is not required to make bricks/blocks made of soil or earth materials. Sun dried, uncompressed adobe bricks can be improved greatly by compressing the soil to higher densities. In many cases, compressed earth blocks come out of the machine ready to lay in the walls in their “green” condition, without additional drying or baking because the soil is compressed to very high densities. Further, the machines used to produce compressed earth blocks are capable of making many bricks in a short period of time that are uniform in density, shape and overall dimensions. Machines in use today include both manually operated and mechanically operated methods to compress the soil into bricks. One of the major limitations of the manual machines is that they are slow and one is limited in how much force can be applied to the bricks. Figures 1 and 2 shows examples of two manually operated machines.

Adding a hydraulic ram to compress the soil and automated conveyors to deliver bricks from the machine to the work area provide a high level of production capacity and quality to the process and as many as 320-350 bricks per hour can be produced from these machines. Compressed earth blocks, even without stabilization, may have compressive strengths of 8.27- 9.65 MPa (1,200 –1,400 psi), suitable for load-bearing construction under the right conditions. Stabilizing the soil with lime, cement or fly ash can increase the strength to even higher levels.

As noted previously, bricks from these machines are consistent in strength and dimension, as long as standard procedures are followed for quality control (e.g. soil mixes have to have the correct amount of clay and sand, moisture has to be very close to being the same in all units produced, and handling and placement techniques have to follow accepted procedures). The Advanced Earthen Construction Technologies (AECT) machines, produced in San Antonio, Texas, are good examples of quality mechanically operated machines. These machines are available in three different sizes: the 2001 Series, the 3000 Series, and the 4000 Series.

Figure 1 – Cinva Ram Manual Machine

Figure 2 – Auram Press Manual Machine

Figure 3 shows the Impact 2001 Series machine. It is a small, trailer-mounted machine that comes with either a 4.85 kw (6.5 h.p) gasoline or 5.22 kw (7.0 h.p.) diesel engine, and either a manually operated mould or an automatically operated mould. This machine can produce 230 - 300 blocks per hour in a variety of dimensions: 5.0 cm – 10.16 cm (2 ½" - 4") thick, 14 cm (5.5") wide, and 30.5 cm (12") long are common. Each blocks weights between 4.1 kg to 8.1 kg (9-18 lbs) depending on the soil and block thickness. Blocks are bonded together using the wet, thin soil slurry or other conventional methods. The soil slurry is made with water and screened soil. Blocks can also be placed in the wall using the traditional thick mud mortar method which produces joints more like conventional masonry.

The Impact 2001 Series machine uses a wide variety of soils with prepared natural soil moistures in the range of 4-12 percent. Typically, the machine requires soil with a combined clay (15-20 percent) and silt (powder) content of approximately 25-40 percent (by volume) and a sharp sand content of approximately 40-70 percent (by volume). The machine does not require any aggregates (rocks) to make a strong soil block for most applications. The block compressive strengths range from 4.14 MPa (600 psi) to 8.27 MPa (1,200 p.s.i.) depending on the soil. A force of 32 658.65 kg (72,000 lbs) is used to produce blocks with 7.52 MPa (1,091 psi MPa) compressive strength on 14 cm x 31 cm x 5-12 cm (5.5 in x 12 in. x 2.0-4.5 in) block. This machine operates at less pressure placed on the block during block production and thus it can work across a wetter soil range than the larger AECT machines.

The next higher production capacity is provided by the 3000 Series machine. It has a diesel engine and a large enough hopper to hold soil for dozens of blocks to be produced at a time. This machine is capable of producing 300 blocks per hour and is suitable for the medium capacity contractor. An example of this machine is shown in Figure 4.

Figure 5 gives an example of the largest machine available from AECT, the 5000 Series. This machine has a four cylinder diesel engine and an even larger hopper for soil storage. It utilizes a turntable that has four molds in it. Each time the machine makes a compressed soil block, the turntable rotates 90º. In the first stage, the soils are dropped into the mould; in the second stage, the soil is compressed; in the third stage, the brick is raised up out of the mould; and in the fourth stage, the bricks exit onto the conveyor. Bricks come out of the machine at the rate of 800 bricks per hour minimum. Up to 104,326 kg (230,000 lbs) of force is applied to the soil to produce bricks of 11.33 MPa (1,643 psi) compressive strength on 25.4 cm x 35.6 cm x 10.2 cm (10"x 14"x 4") block. The manufacturer claims that it takes six or seven workers to keep up with the machine when removing bricks and stacking them near the work areas.

Figure 3 – AECT Impact 2001 Compressed Soil Block Machine

Figure 4 – AECT 3000 Series Compressed Soil Block Machine

Figure 5 - AECT 5000 Series Compressed Soil Block Machine
Source: Photos in Figures 3, 4, and 5 courtesy of AECT at http://www.webspace4me.net/~fwehman

PHYSICAL CHARACTERISTICS OF COMPRESSED EARTH BLOCK (CEBs)

Research is currently underway at Texas A&M University to determine the physical characteristics of compressed earth blocks. The testing procedures for defining these coefficients are based on Uniform Building Code Sections 21.906 - 21.911. A review of the literature indicates that there is considerable knowledge about the soils needed to make good CEBs, but little is known about the physical characteristics of the compressed earth blocks when used in walls, either as a veneer or as solid or multi-wythe walls. Proper placement of movement control joints in walls made with these materials will help to improve their service performance and durability.

The movement coefficients shown in Table 1 were developed based on the research at Texas A&M University. Soil mix designs, combining sand, silt and clay, to make blocks that can pass the modulus of rupture and compressive strength requirements of the earthen building codes, are pretty well understood. The following coefficients will serve as a point of departure for design professionals to use when locating movement control joints in their structures to accommodate the stresses walls may have applied to them so cracks do not occur. The coefficients shown are conservative in their values to accommodate a wide range of soils and manufacturing processes.

Table 1 – Potential Movement Values for
Walls Constructed of Compressed Earth Block Masonry Units

ORIGIN	Compressed Earth Blocks – Unstabilized	Compressed Earth Blocks – Stabilized[(a)]	Building Structure	Beams & Lintels	Reversible?
Thermal Expansion, k_t	1.8 x 10^{-6} / °C (1.0 x 10^{-6} inch/inch/°F)	2.7 x 10^{-6} / °C (1.5 x 10^{-6} inch/inch/°F)	N/A	N/A	Yes
Moisture Expansion, k_e	N/A	N/A	N/A; N/A	N/A; N/A	No; No
Shrinkage, k_m	2.5 x 10^{-4} m/m (2.5 x 10^{-4} inch/inch)	1.25 x 10^{-4} m/m (1.25 x 10^{-4} inch/inch)	N/A; N/A	N/A; N/A	No; No
Elastic Shortening, *ES*	$\frac{PL}{AE}$	$\frac{PL}{AE}$	$\frac{PL}{AE}$	N/A	No (for permanent loads)
5. Creep, k_e	2.9x10^{-4}/unit length/MPa (2.0x10^{-6}/ unit length/ psi)	2.2x10^{-4}/unit length/MPa (1.5x10^{-6}/ unit length/ psi)	1.5x10^{-4}/unit length/MPa (1.0x10^{-6}/ unit length/ psi)	N/A	No (for permanent loads)
6. Deflection, Δ	N/A	N/A	N/A	<l/240 or 0.318 cm (b) (0.125 in)	No

Notes:
(a)) Stabilized Earth Blocks include bricks stabilized with cement, calcium carbonate, asphalt, flyash etc.
(b) CEBs are not as brittle as clay brick or concrete masonry units

Source: Adapted from Chin, Ian R. Closing the Gap – Recommendations to Minimize Cracks in Exterior Masonry Walls. Structural Engineer. February, 2004. p. 20.

THERMAL EXPANSION – REVERSIBLE

Thermal changes will cause walls constructed of CEBs to expand and contract. The following are the block thermal expansion coefficients (bk_t) for masonry design with both un-stabilized and stabilized CEBs:

- For CEBs with un-stabilized soils, bk_t = 1.8 x 10^{-6} / ^{oC} (1.0 x 10^{-6} inch/inch/ ^{o}F)
- For CEBs with stabilized soils, bk_t = 2.7 x 10^{-6} / ^{oC} (1.5 x 10^{-6} inch/inch/ ^{o}F)

Thermal expansion from increasing temperatures and contraction from decreasing temperatures are reversible and occur in the direction of the x, y and z axes. The CEB walls may behave differently from these coefficients, however, if they are restrained structurally. As noted for clay brick and concrete masonry units, where in the wall the temperature changes are assumed also affects the amount of movement to be computed. The center of the wall (for thick walls) and the center of the wythe for veneer walls should be where the temperature changes are taken.

SHRINKAGE OF CEBs (NOT REVERSIBLE)

Compressed earth blocks are not fired during their manufacturing process, so moisture expansion as in fired clay brick is not a concern. However, experience has shown that blocks laid "green" from the machine to the wall will lose moisture until they reach equilibrium with their environment. As they give off this moisture, they shrink. The amount of shrinkage (k_m) is dependent upon the climate location, and soils used to make the CEBs, but the following coefficients may be used until further research is completed:

- For CEBs with unstabilized soils, k_m = 2.5 x 10^{-4} cm/cm (2.5 x 10^{-4} inch/inch)
- For CEBs with stabilized soils, k_m = 1.25 x 10^{-4} cm/cm (1.25 x 10^{-4} inch/inch)

The amount of shrinkage in the wall is dependent upon the length of time that has elapsed since the manufacturing of the units and the conditions under which they were stored. Soil types, aggregate types and sizes, lime/cement/fly ash content, and wetting and drying cycles may also affect moisture shrinkage. As before, this shrinkage is not reversible under normal service conditions.

ELASTIC SHORTENING OF SUPPORTING BUILDING STRUCTURES (NOT REVERSIBLE)

Structural components of buildings such as columns and walls used to support the gravity loads of buildings will shorten after they have been constructed and loads have been placed on them. The approximate amount of shortening (ES) that occurs in these members can be calculated according to Equation 1.

For CEBs, the modulus of elasticity has been calculated to be in the range of 199.95 MPa-282.68 MPa (29,000-41,000 psi), while assuming a dense clay/sand/silt unfired block formed by compression, a factor of safety of 3, and a time of aging >60 days ([4] pp. 151-161, 455-463).

As occurs with shrinkage that is not reversible, elastic shortening caused by permanent loads applied to walls constructed of CEBs is not reversible. Walls of un-stabilized CEBs will shorten more than equally sized and loaded walls of stabilized CEBs because the modulus of elasticity of un-stabilized soils is greater than that of stabilized soils. Elastic shortening of walls or columns of compressed earth blocks is not reversible.

OTHER CAUSES OF MOVEMENT IN CEB MASONRY

There are other causes of movement in CEB masonry according to service conditions. These include hydration of the chemical additives in stabilized CEBs, drift of the building frame, deflection of building elements, and the action of unstable soils upon which the structure is supported. One of the more common coefficients used in the design of masonry walls is for expansion caused by freezing of blocks with high moisture content. This expansion can be added to other forces that affect expansion of masonry. A coefficient of expansion from freezing for CEBs of 0.5×10^{-4} cm/cm (0.5×10^{-4} inch/inch) is recommended for CEBs. A low freezing expansion coefficient for CEBs is used because CEBs must be protected from moisture, and therefore, they are really only subject to moisture gained by vapour diffusion. The designer should consider the potential for the other forms of movement in the CEB masonry and accommodate them by using sound professional judgment.

LOCATION OF MOVEMENT CONTROL JOINTS IN CEBs

To accommodate the movements defined above in compressed earth block walls, proper joint detailing and construction is necessary. Experience has shown that walls of CEBs are very forgiving in terms of crack tolerance, when compared to the more brittle clay bricks and concrete masonry units. The following are recommendations for location of joints in masonry walls. Note that a distinction is made here between expansion joints, and control joints. Expansion joints are usually 0.95 cm -1.27 cm (3/8 inch – ½ inch) wide joints between clay brick panels that are subject to thermal and moisture expansion, and structural movement. Control joints are 0.95 cm - 1.27 cm (3/8 inch – ½ inch) wide and are located between separate panels of concrete masonry units that are subject to shrinkage and structural movement. Control joints are often made of non-compressible filler material, but it is recommended that they be constructed like expansion joints, which generally consist of a compressible backer rod with a flexible sealant applied between the separate panels. The rule-of-thumb for these joints is that they not be subjected to more than 50% compression or expansion (tension).

Vertical control joints should be installed to accommodate horizontal movements from shrinkage of the CEBs. These joints should be installed at the following locations:

- Intermittently along the length of long, uninterrupted walls;
- At changes in wall height or thickness;
- At construction joints in the structure;
- At openings in the wall; and,
- Where a wall and column or pilaster meets.

The spacing of vertical control joints in CEB walls is dependent upon a number of factors, including the use of intermittent concrete columns and bond beams, type of supporting structure and soils conditions, freeze/thaw potential, wetting/drying potential, and types of finishes on both sides of exterior walls. A good rule-of-thumb for typical 0.95 cm (3/8 inch) wide joints is to limit anticipated shrinkage or expansion of the joint to no more than 50% of the joint width, or 0.48 cm (3/16 inch). Assuming a maximum coefficient of shrinkage, $k_m = 2.5 \times 10^{-4}$ cm/cm (2.5×10^{-4} inch/inch), the maximum distance between vertical control joints would be about 19.05 m (62.5 feet). In the majority of residential applications, straight walls of this length would be rare, so placement of control joints would be governed by other design considerations.

Settlement or elastic shortening of load bearing CEB walls, or CEB walls constructed as infill beneath concrete or timber bond beams can occur and so allowance must be made for this settlement beneath the structural member. The building codes for earth construction require the top of exterior walls to be affixed to the lintel or bond beam, but this is primarily for the lateral loads that will be applied against the wall. Application of flexible ties or connections will allow the CEB wall materials to shorten without applying unwanted stresses or loads on the lintels or bond beams.

CONCLUSION

Exterior masonry walls are subjected to horizontal and vertical movements that are caused by many factors. The physical nature of the masonry materials themselves must be known, as some have a propensity to expand (e.g. fired clay brick), while others have a propensity to shrink (e.g. concrete masonry units and compressed earth blocks). These movements will generally be in the directions of the x, y and z axes. All movements, no matter what their nature, will affect the masonry if it is not detailed correctly. Experience has shown that walls of compressed earth block are very forgiving as compared to the more brittle clay bricks and concrete masonry units. They have more flexure and ductility, and hence, can move with less of a propensity to crack. However, these walls too can develop cracks if measures are not taken to accommodate the stresses that would accumulate in them. As stated, the coefficients given for CEBs are estimated based on preliminary research findings and practical application in the field. They should be satisfactory in most design situations. Further research into these characteristics, however, is necessary to develop a more refined understanding of the coefficients and the variety of conditions under which they are used. Designers are urged to use these coefficients with professional judgment.

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