THE INFLUENCE OF SUPPLEMENTARY CEMENTITIOUS MATERIAL (SCM) STABILIZERS ON COMPRESSED EARTH BLOCK (CEB) PERFORMANCE

André Fuqua

PhD candidate in Civil Engineering, University of Texas at Austin, TX USA
andre.fuqua@utexas.edu

Dr. Raissa Ferron

Associate Professor, University of Texas at Austin, TX, USA
rferron@mail.utexas.edu

1 Introduction

1.1 Compressed earth blocks

Compressed earth blocks (CEB)(s) are unfired earthen masonry units that combine elements of adobe brick construction with modern technology. At their essence, CEBs are molded adobe bricks produced using mechanical compaction. A mass of earth (i.e. soil) is compacted under a high amount of pressure to create a block of a specific geometry. The shape and size of a CEB is contingent on the geometry of the mold in the block press used to produce it and may be solid or hollow. Similar to fired brick and concrete masonry units, CEBs may have a patterned surface for decoration, grooves for reinforcing, or interlocking geometries for free stacking.

CEBs can be engineered and tailored specifically to their environment of use. Neat (i.e. unstabilized) CEBs are those that are composed solely of raw earth: a combination of clay, sand, silt, and gravel unaltered before use to produce CEBs. Neat CEBs are used for structures in dry regions that do not experience frequent precipitation and weathering. However, in regions that experience rain and snowfall, CEBs are stabilized to resist weathering and increase strength. In the US, majority of CEBs produced for building projects are stabilized [1]. As such, stabilization is an essential step in the manufacture of CEBs, and it is aimed at improving the engineering properties and engineering performance of the blocks. The engineering of CEBs starts with a deeper understanding of how to design earth mixes through soil characterization, stabilization techniques, mixing protocol, curing protocol, and strength and durability testing. When designed and constructed using geotechnical characterization, structural design principles, and masonry craftsmanship, CEB buildings are suitable options for single and multiple story structures. However, if CEBs are under-engineered and their inherent weaknesses are ignored, poor performance can occur.

Equation 1:
Portland Cement Reaction

$$\underset{\text{tricalcium silicate}}{C_3S} + \underset{\text{water}}{H_2O} \rightarrow \underset{\text{calcium silicate hydrate}}{C\text{-}S\text{-}H} + \underset{\text{calcium hydroxide}}{CH}$$

Equation 2:
Pozzolanic Reaction

$$\underset{\text{silicon dioxide from pozzolanic material}}{S} + \underset{\text{calcium hydroxide}}{CH} \rightarrow \underset{\text{calcium silicate hydrate}}{C\text{-}S\text{-}H}$$

1.2 Stabilization of earth mixes for CEBs

Very rarely is a natural soil in its native state suitable for CEB production. Thus, the properties of the natural soil are typically stabilized to create a CEB that is apt for masonry wall construction and other superstructure and/or architectural applications. Stabilization of CEB earth mixes occurs mechanically and/or through use of additives. Mechanical stabilization involves the mixing of different soils and sands together to change the gradation of the earth mix for a desired mix composition. This is done to influence compressibility, adjust clay content, shrinkage, or drainage. Stabilization by additives is the use of organic or inorganic materials in either solid or liquid form to alter the properties of a CEB earth mix. [2 – 5] Supplementary cementitious materials (SCM)(s) that are applied in concrete mixes are commonly used as inorganic stabilizers in CEB earth mixes. This paper provides an overview of the use of SCMs as stabilizers in CEBs for strength and durability, with focus on cement, hydrated lime, and fly ash.

2 SCM stabilizers in CEBs

Stabilization is an essential step in the manufacture of CEBs and is aimed at improving the performance of earth as a construction material. A large percentage of modern day CEB building projects make use of SCMs in earth mixes to produce CEBs that are stronger, resistant to moisture, and more dimensionally stable. Cement, hydrated lime, and fly ash are the most common SCMs used as mineral stabilizers in CEB building projects. These inorganic materials interact with the minerology of a CEB earth mix to enhance engineering properties of CEBs. These SCMs can be further classified as cementitious or pozzolanic. Cementitious SCMs are powdered materials that react with water to produce hydrates that contribute to strength gain and moisture resistance in CEBs. Pozzolanic SCMs are siliceous and/or alumina materials that in finely divided form and in the presence of moisture chemically react with calcium hydroxide (CH) at ordinary temperatures to form compounds possessing cementing properties [Equation 2]. Portland cement is cementitious. Tricalcium silicate (C_3S) is the primary constituent within portland cement that reacts with water to produce calcium silicate hydrate (C-S-H) [Equation 1]. It is this C-S-H that is responsible for the strength gain that develops over time. Hydrated lime and fly ash contain cementitious and/or pozzolanic characteristics. The pozzolanic nature of these materials enables them to react with the CH produced from the primary cementitious reaction (see Equation 1) to form secondary C-S-H. SCMs are used singularly, in binary, and in ternary blends to stabilize CEBs. Figure 1 shows typical stabilization dosages used for cement, lime, and fly ash.

The dosages of the stabilizers depend on the chemical and physical requirements of the CEB earth mix.

2.1 Cement

Cement is a multichemical system that exists in many variations. Cement is the most common and widely used stabilizer in CEB projects in the US. Cement assists in the binding properties of clay in an earth mix and is comprised of tricalcium silicate (C_3S), dicalcium silicate (C_2S) and calcium aluminates that upon reaction with water produce the hydration products calcium silicate hydrate (C-S-H) and calcium hydroxide (CH). C-S-H is responsible for strength gain in CEBs. Typical cement dosages range from 3 – 10% by mass for the CEB. [Figure 1] Curing duration for cement stabilized earth blocks differs amongst earth builders and range anywhere from 7 – 60 days, however 28 days is common. Dry and wet compressive strength of CEBs increases as cement content increases. Though the benefits of cement stabilization are celebrated and well known, the production of cement emits harmful greenhouse gases, so the environmental benefits of CEBs decrease as cement content in the blocks increases. Minimizing the amount of cement in the soil mix also increases the natural ability of the material to “breathe”, regulating indoor air environments [6]. Table 1 presents a summary of CEBs stabilized with cement.

Reference	Cement % and Type	Size of CEB sample (mm)	Curing protocol	28 Day Dry Compressive Strength	28 Day Wet Compressive Strength
[6]	5.7% Type I/II cement	63.5 x 88.9 x 25.4 mm (2.5 x 3.5 x 1 in)	28 controlled cure at ~22°C and ~92.5% RH	1887 psi (13.01 MPa)	n.a.
[7]	5%, type unknown	295 x 140 x 125 mm	28 days*	532.3 psi (3.67 MPa)	n.a.
	10%, type unknown			1031.2 (7.11 MPa)	
[8]	10 % OPC CEM I 32.5	100 mm diameter x 165 mm height	28 day air cure in a laboratory	623.7 psi (4.3 MPa)	319.1 (2.2 MPa)
[9]	5%, CEM II 52.5 N	72 x 34 x 22 mm	28 day controlled cure; 20°C and 61% RH for 2 days then air cure for remainder	1073.3 psi (7.4 MPa)	107.3 psi (0.74 MPa)
[10]	8% CEM II 32.5	295 x 140 x 95 mm	14 day moist cure then air cured until testing	478.6 psi (3.3 MPa)	n.a.
[11]	7%, CEM I 52.5 N	240 x 115 x 90 mm	28 day controlled cure; 20°C and 45% RH for 2 days then spray cure with burlap for remainder	818 psi (5.64 MPa)	335 psi (2.31 MPa)

* = curing method not mentioned. Note: All strength values are shown in SI units and US customary unit conversions

Table 1: Cement stabilized compressed earth block strength from literature

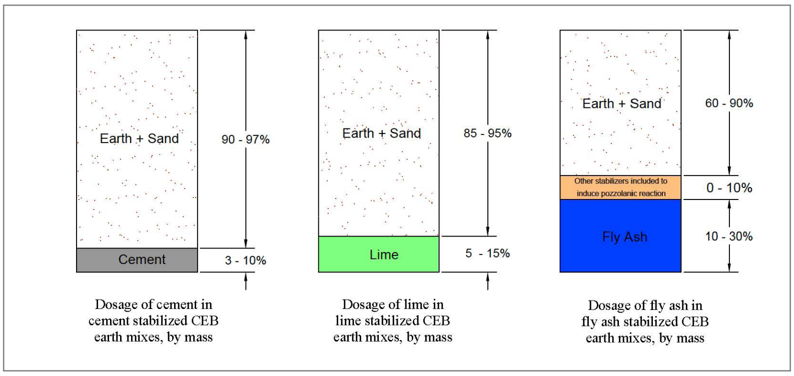

Figure 1. Dosages of SCMs as stabilizers in CEB earth mixes, by mass.

2.2 Hydrated lime

Lime comes from limestone, a sedimentary rock with a high percentage of calcium carbonate ($CaCO_3$). It is the oldest material used for soil stabilization applications. The term “lime” is used changeably and can refer to lime in its different forms depending on the industry. Limestone in its pure form as a stabilizer is susceptible to moisture related distress, but once processed is appropriate for use in CEBs. To process lime for use in CEBs, first limestone is thermally decomposed through endothermic reaction in a rotary kiln to yield calcium oxide (CaO), quicklime. This quicklime is either: (1) carefully hydrated with the appropriate amount of water and agitated to produce $Ca(OH)_2$, hydrated lime (i.e. calcium hydroxide, CH), or (2) contains inherent or artificially introduced amorphous silica in the burning process to produce hydraulic lime, a cementitious compound. Both hydrated lime and hydraulic lime take the form of a very fine, bright white powder. Quicklime, hydrated lime, and hydraulic lime are used for soil stabilization in infrastructure projects (i.e. roadways, runways, foundations, parking lots). However, some earth builders deter from using quicklime as a stabilizer because its lack of hydration can lead to drying and cracking in earthen building materials. Hydrated lime is the form of lime used most frequently in CEBs across the world. Typical lime dosages range from 5 – 15% by mass for the CEB. [Figure 1]

CEB earth mix stabilization using hydrated lime results in five basic reactions: cation exchange, flocculation, agglomeration, pozzolanic reaction, and carbonation [9],[13]. The first three reactions result in modifications in plasticity, shrinkage, and workability characteristics in an earth mix. The pozzolanic reaction is the main contributor to strength development in the earth-lime mixes. When hydrated lime is added to CEBs, the siliceous and aluminous components present in natural clays and silts react with the hydrated lime to create C-S-H and calcium aluminum silicate hydrate (C-A-S-H). The success of hydrated lime as a stabilizer is contingent on the clay present in a CEB earth mix. Over a period of time, the hydrated lime in CEBs is converted back to calcium carbonate as the stabilized blocks absorb CO_2 from the air and calcium carbonate precipitates via carbonation. In CEBs, it is likely that carbonation will further enhance strength gain. Curing protocol has a great effect on strength in lime stabilized CEBs. Steam cured lime stabilized CEBs appear to have strength values double or more than those that are moist cured. Table 2 presents a summary of CEBs stabilized with various forms of lime.

Reference	Lime % and Type	Size of CEB sample (mm)	Curing protocol	28 Day Dry Compressive Strength	28 Day Wet Compressive Strength
[12]	12% natural hydraulic lime, NHL 2	294 x 141 x 97 mm	28 day controlled cure at 20°C and 50% RH	661.4 psi (4.56 N/mm2)	n.a.
[13]	14% hydrated lime	76 mm cube	24 hour steam cure	n.a.	423.5 psi (2.92 N/mm2)
			28 day moist cure with burlap		137.8 psi (0.95 N/mm2)
[14]	10% quicklime	100 x 100 x 200 mm	24 hour steam cure	1450 psi (10 MPa)	1015.3 psi (7 MPa)
			28 day moist cure with burlap	696.2 psi (4.8 MPa)	493.1 psi (3.4 MPa)
[15]	10% hydrated lime	125 x 125 x 60 mm	28 day controlled cure of 7 days at a 100% RH then 21 days at 24°C and 55% RH	95.7 psi (0.66 MPa)	n.a.
[16]	6% hydrated lime	50 × 100 mm cylinders of slenderness equal to 2	28 day oven cure at 65°C and stored in lab at 20°C	812.2 psi (5.6 MPa)	n.a.
[17]	10%, type unknown	150 x 150 x 150 mm	7 days in a burlap bag on a damp floor	246. 6 psi (1.7 N/mm2)	≤ 72.5 psi (≤ 0.5 N/mm2)

Note: All strength values are shown in SI units and US customary unit conversions.

Table 2. Lime stabilized compressed earth block strength from literature.

2.3 Fly ash

Fly ash is a material byproduct of the coal industry that has been beneficial in concrete products due to its reactivity and similar particle size and shape as cement. There are two types of fly ashes: Class F fly ash which is pozzolanic, and Class C fly ash which displays cementitious and pozzolanic properties. The silica and alumina in fly ash reacts with calcium hydroxide in an earth mix to form C-S-H and/or calcium aluminum silicate hydrate (C-A-S-H) which contributes to strength gain. The pozzolanic reaction requires CH to activate, so in many cases fly ash is coupled with either cement or lime in an earth mix. In addition, organic materials such as cassava peels and wood aggregates have been coupled with fly ash to stabilize CEBs. The fly ash content should be optimized with respect to the cement and lime content in order to maximize the amount of fly ash reacted; otherwise the fly ash may remain unreacted which can reduce cohesion in an earth mix. Class F fly ash has been used more prominently in scientific literature, however as Class C ash is more cementitious in nature than Class F ash, it may be better to use Class C ash if strength is the primary consideration. Typical fly ash dosages range from 10 – 30% by mass for the CEB [Figure 1]. Table 3 presents a summary of CEBs stabilized using fly ash.

Reference	Fly Ash % and Type	Size of CEB sample	Curing protocol	28 Day Dry Compressive Strength	28 Day Wet Compressive Strength
[18]	7.5 % coal ash and 2.5 % cassava peels, types unknown	32 x 80 x 150 mm	28 day controlled cure at 25°C and 80% RH	366.9 psi (2.53 MPa)	n.a.
[19]	10% coal ash with 10% lime and 10% cement and 1.5% wood aggregates, types unknown	60 mm diameter and 85 mm height	28 controlled cure at 21.5°C	1189.3 psi (8.2 MPa)	216.1 psi (1.49 MPa)
[20]	20% Class F with 9% cement	190 x 90 x 90 mm	28 day controlled cure at 20°C and 45% RH for 2 days then spray cure with burlap	1064.6 psi (7.34 MPa)	542.4 psi (3.74 MPa)
[21]	10% fly ash with cement, type unknown	100 x 100 x 100 mm	28 day spray cure	197.3 psi (1.36 MPa)	n.a.
[22]	30% Class F with 10% Type I cement	190 x 90 x 90 mm	28 day controlled cure at 25 ± 2°C and ≥ 96% RH	870.2 psi (6 MPa)	391.6 psi (2.7 MPa)
[23]	20% Class F with 10% Type I cement	254 x 127 x 76 mm	28 day controlled cure at 20 ± 2°C and ≥ 95% RH	522.1 psi (3.6 MPa)	232.1 psi (1.6 MPa)

Note: All strength values are shown in SI units and US customary unit conversions.
Table 3. Fly ash stabilized compressed earth block strength from literature.

2.4 Conclusions/Future work

The effectiveness of SCMs as stabilizers in CEBs cannot be generalized. A number of factors contribute to the final performance characteristics of CEBs and not all of these are considered in existing scientific assessments of CEBs. The response of cement, lime, and fly ash stabilized CEB earth mixes is greatly dependent on the chemical and mineralogical composition of the earth in the mix. Thus, soil characterization that assesses particle size distribution, soil mineralogy, moisture content, clay type, and pH is necessary to accurately connect stabilizer use to CEB performance. Stabilized CEBs undergo a variety of curing mechanisms including, but not limited to: moist curing, steam curing, conditioned curing and/or oven curing. Curing protocol is another variable, and considering curing mechanism, curing climatic conditions (temperature and relative humidity), and curing duration is also necessary when assessing SCMs effects on CEB performance. The method for compaction and compaction pressure (i.e. degree of compaction) of the press used to make a CEB affects the density of the product which influences porosity in the block. Imaging techniques such as microcomputed tomography could be useful to understand pore volume and the development of cementitious gels (C-S-H, C-A-S-H, etc.) which is directly related to moisture transfer and carbonation in the blocks over time. Durability testing on the blocks vary amongst researchers, specifically for durations and methods of submersion for moisture resistance testing. A quality-controlled engineering testing regiment that includes all of the above variables will yield results on CEB performance with greater reliability.

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André Fuqua *is a PhD Candidate in Civil Engineering at the University of Texas at Austin. His research interests lie at the nexus of materials engineering, design, and human health. His research work is focused on engineering earthen materials and their effects on indoor air environments. His background includes work in civil design, transportation, art, and architecture.*

Dr. ***Raissa Douglas Ferron*** *is an Associate Professor at The University of Texas at Austin. She is a fellow of the American Concrete Institute and is the Secretary of ACI Committees 552 (Cementitious Grouting) and 564 (3D Printing with Cementitious Materials). She is an expert on the materials science and engineering of sustainable, durable, and smart cement-based materials.*