Earthen Construction:
An ancient solution to the modern problem of sustainable, safe, and affordable housing

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Outline

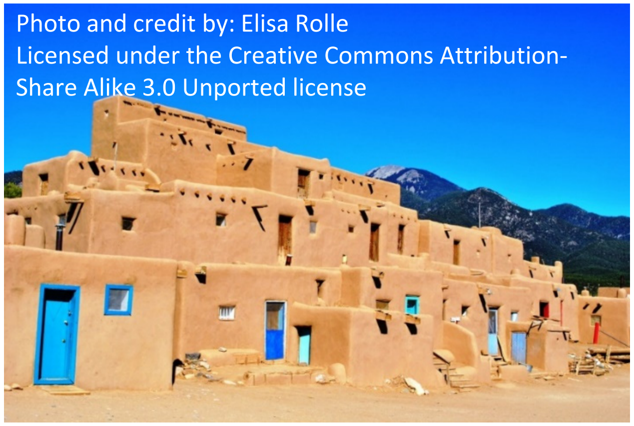
- Introduction
- Earthen Construction: Advantages and Challenges
- Compressed and Stabilized Earth Block (CSEB) Construction
- Feasibility of CSEB Houses
- Use of CSEBs for Wildfire-Resistant Building Construction
- Other Sustainability Considerations
- Conclusions

Introduction (1)

- Earthen structures are structures built using mainly soil
- Most ancient and sustainable building technique (> 10,000 years old)

China's Great Wall (300 BCE - 1650 CE)

Great Mosque of Djenné in Mali (300 BCE)



Pueblo de Taos, NM, USA (1000-1450 AC)

City of Potosí in Bolivia (1600-2100 CE)

Introduction (2)

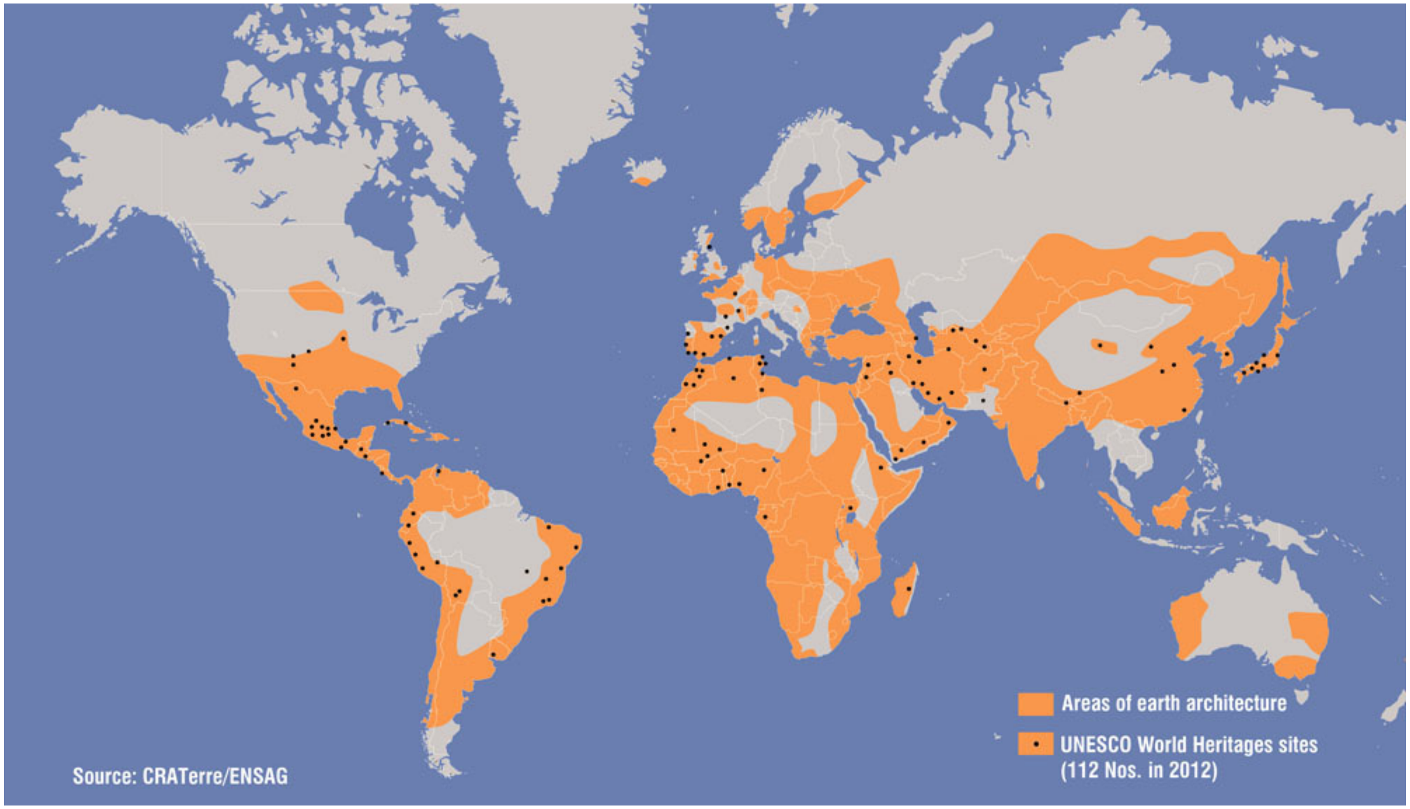
- Cob
  - Sand, clay, water, some kind of fibrous or organic material (straw)
  - Soil mix is layered to build earth structures

- Rammed earth
  - Mixture of sand, clay, water, fiber, and gravel
  - Soil mix is compacted to build earth structures

- Adobe
  - Mixture of sand clay, water, and fibers is used to fabricate blocks
  - Earth structures are built with adobe blocks

Introduction (3)

- 30%-50% of world's population currently lives in earth-based dwellings
- Earthen structures are found all over the world



Earth construction areas of the world (Source: CRATerre/ENSAG/Auroville)

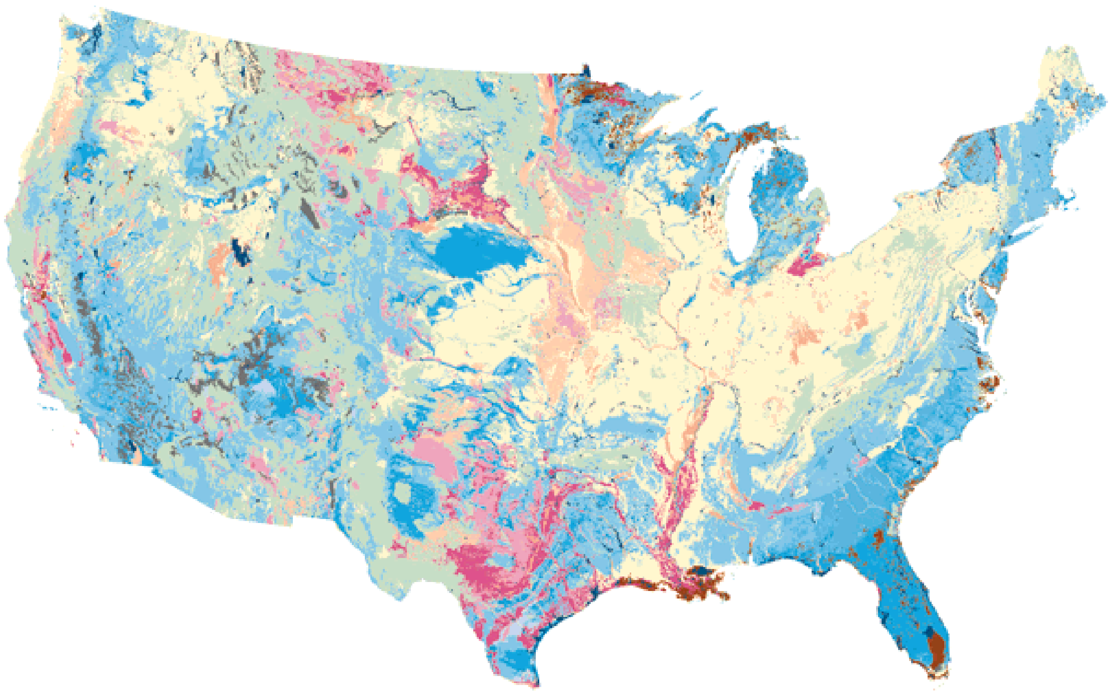
Motivation

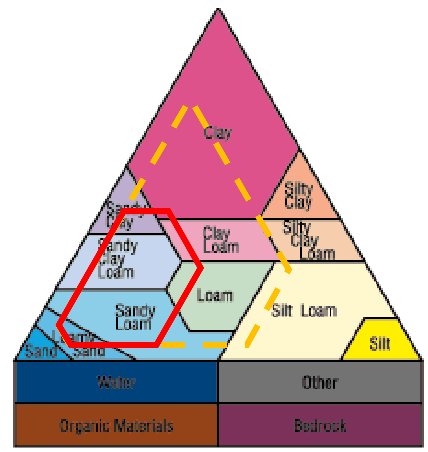
- Need for affordable and sustainable housing
  - Shortage of 0.4M houses per year in the USA
  - Accumulated shortage of ~5M houses
  - Shortage of skilled labor in construction industry
  - Dependence on construction materials from other nations
  - Significant issues with energy consumption and pollution
  - > 2B new houses needed worldwide in the next 80 years
  - Highest need for low-income/disadvantaged populations

- Need for appropriate engineering-based design approaches
  - Different mechanical behavior than ordinary masonry
  - Limitations in existing numerical models
  - Lack of standardization
  - Very limited understanding of performance and reliability

Earthen Construction: Advantages (1)

- Affordable and locally appropriate
  - Appropriate soil is widely available and inexpensive
  - Stabilization increases the range compositions that can be used





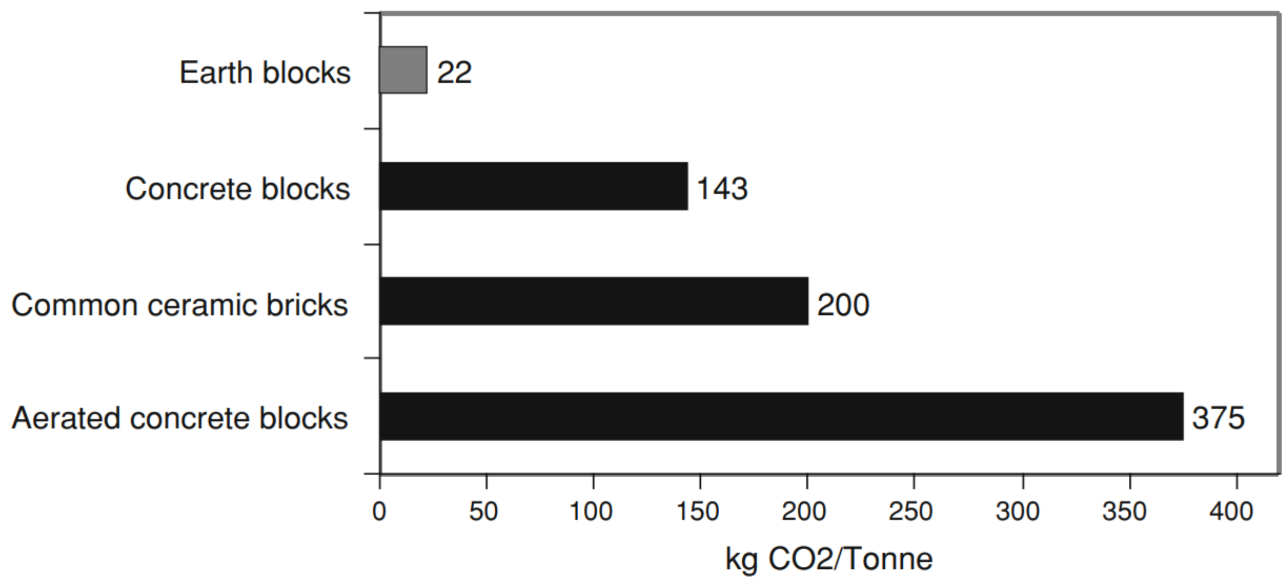
US Department of Agriculture soil textural classification and USA
(Soil Information for Environmental Modeling and Ecosystem Management)

- Earthen construction is naturally resistant to fire, mold, fungi, rot, insects, and pests

Earthen Construction: Advantages (2)

- Indoor air quality and humidity efficient
  - Earth construction can keep the relative humidity of indoor air between 40% and 60%, which is most suitable for human health.

- Eco-efficient and sustainable
  - The embodied energy of earth buildings is significantly smaller than that of other conventional construction techniques



Embodied carbon in different masonry materials (Morton et al. 2005)

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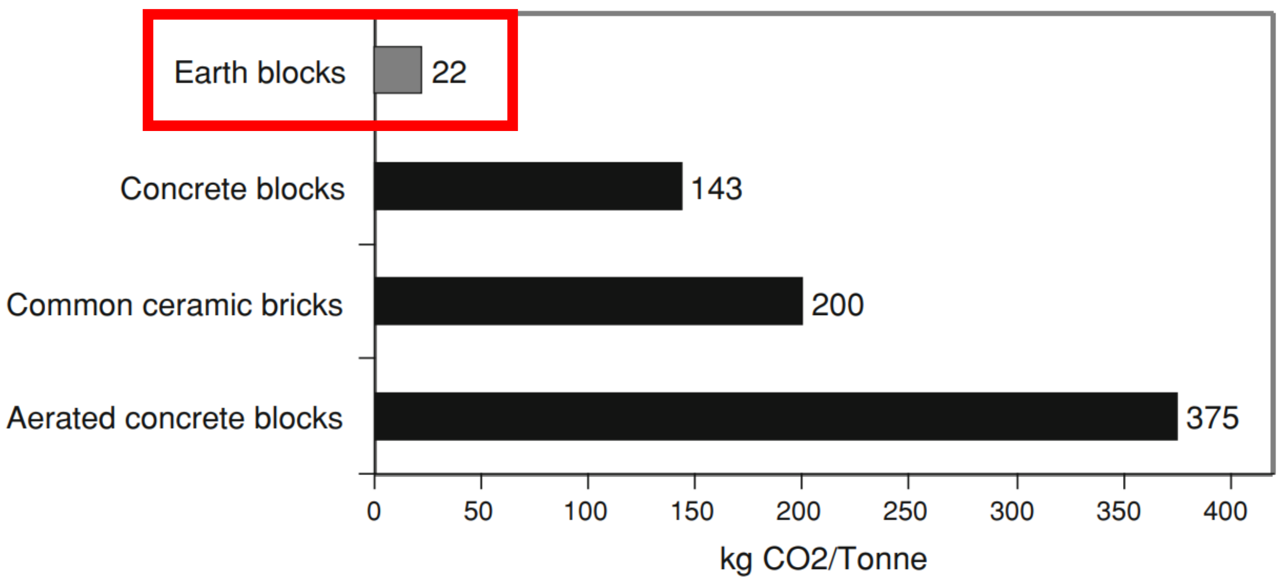
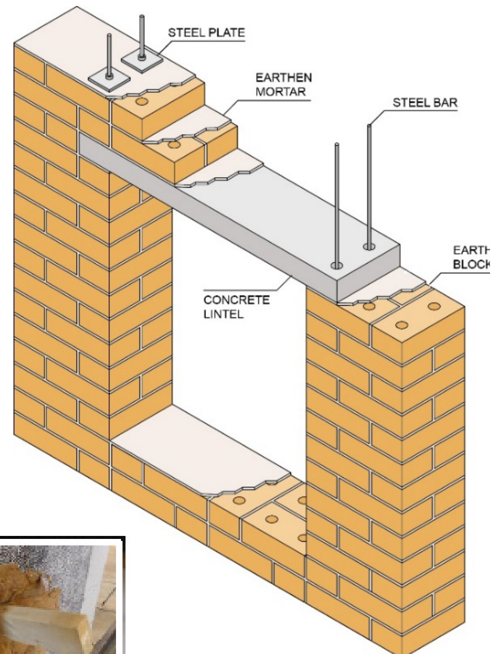


Embodied carbon in different masonry materials (Morton et al. 2005)

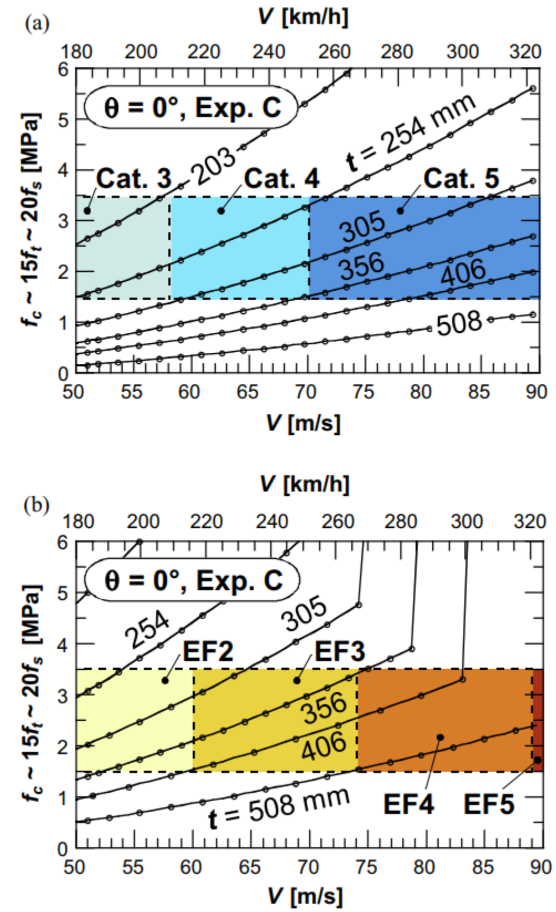
Earthen Construction: Advantages (3)

- Good hazard resistance
  - Hurricane resistance
  - Tornado resistance
  - Seismic resistance



Structural detail for seismic-resistant reinforced earth block construction

Windborne debris impact resistance of earth block walls (Cuéllar-Azcárate MC 2016)



Masonry strength demand curves: (a) hurricane effects; and (b) tornado effects (Matta et al. 2015)

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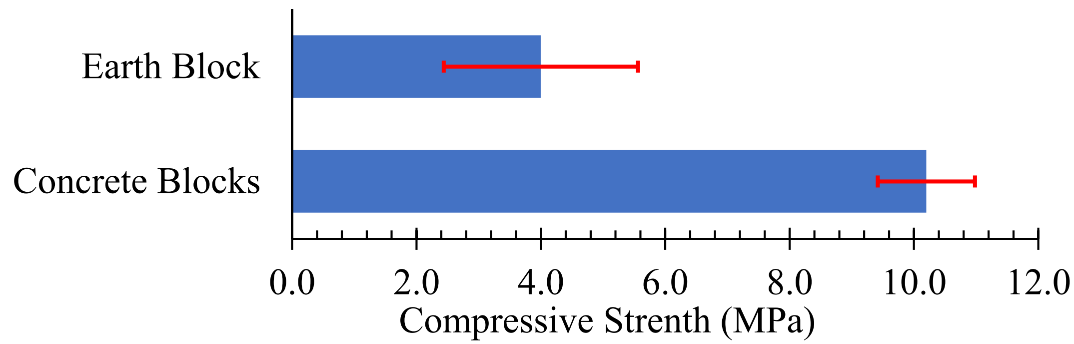
Earthen Construction: Challenges (1)

- High Variability of Earth Block Properties



Variability in compressive strength of different masonry materials

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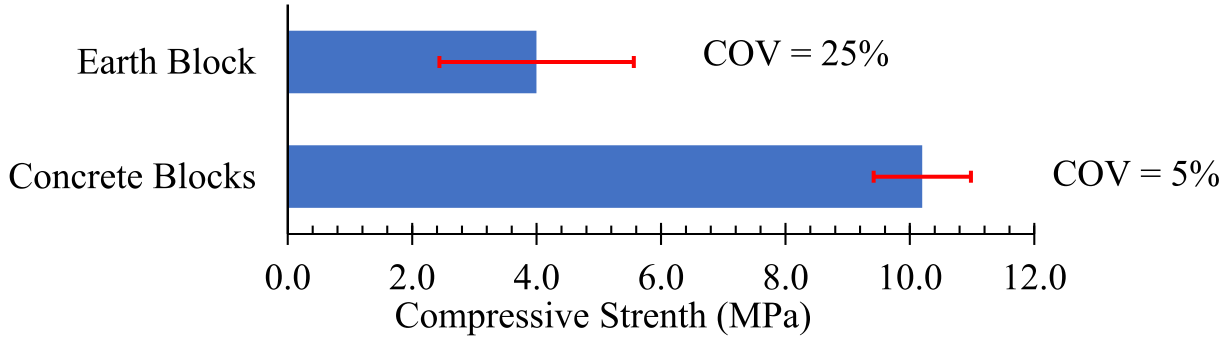

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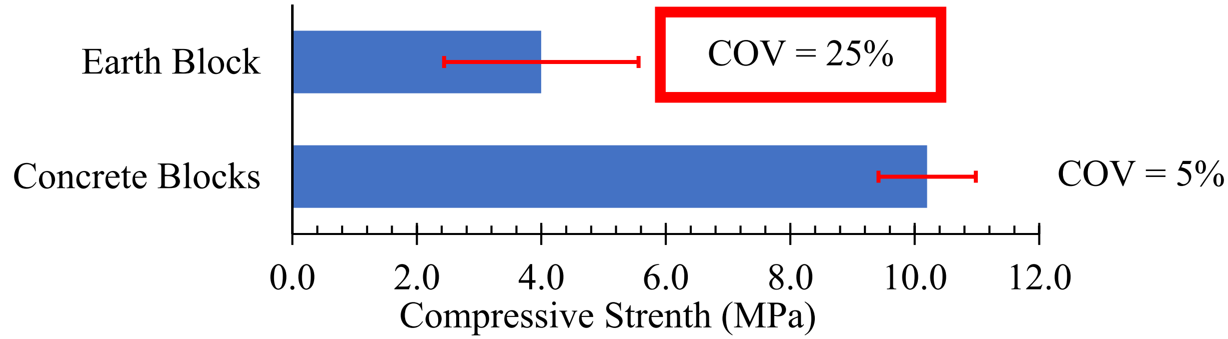

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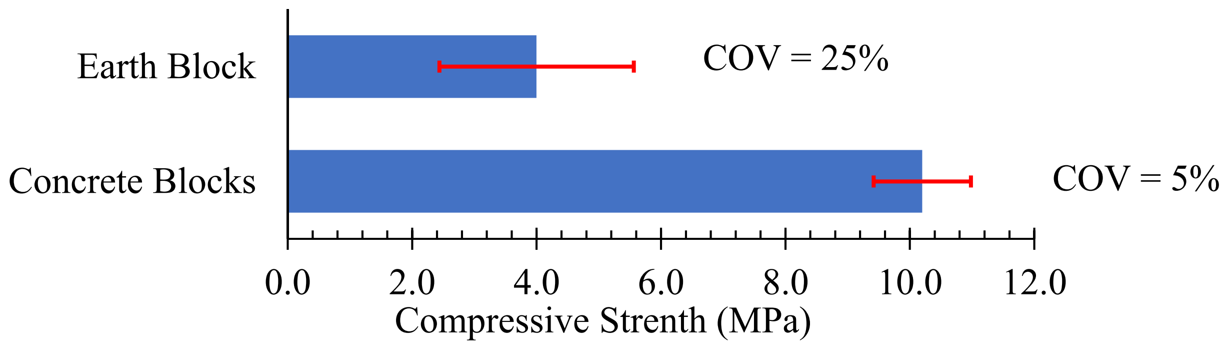

Variability in compressive strength of different masonry materials

- Poor durability against wet climates

Rammed earth masonry exposed during 20 years to natural climatic conditions (Pacheco-Torgala and Jalali 2012)

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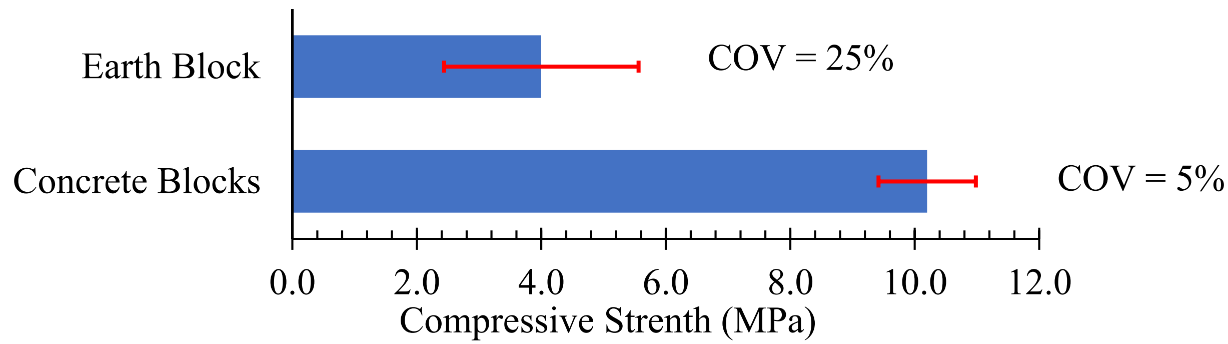

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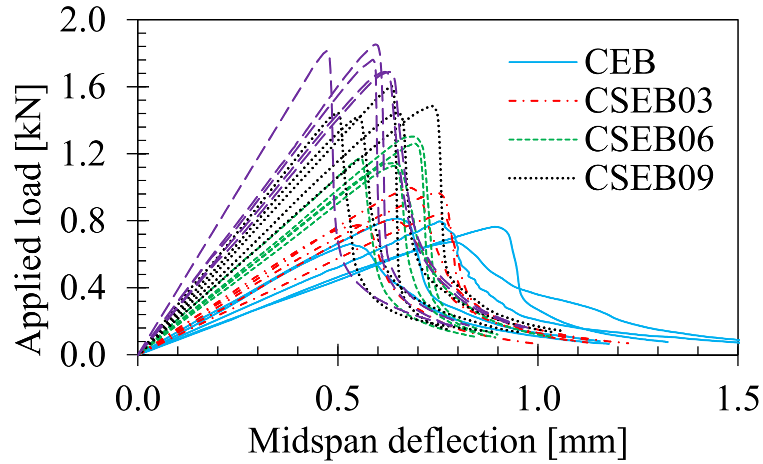
Earthen Construction: Challenges (2)

- Brittleness

Flexure test of unreinforced earth block



Flexure test results (Kumar et al. 2018)

- Labor intensive

Process of construction of earth block wall

Earthen Construction: Challenges (3)

- Lack of engineering-based design codes and standards
  - 2015 New Mexico Administrative Code – Title 14/Chapter 7, Part 4: Earthen building materials code
  - 2019 International Building Code/2021 California Building Code – Section 2109: Empirical design of adobe masonry
  - 2021 International Residential Code (IRC) - Appendix AU: Cob construction (monolithic adobe)

- Need for more education among engineers, architects, builders, insurances, lenders, and local building officials

- Widespread perception as a substandard choice due to poor performance of non-engineered earthen structures

Modern/Engineered Earthen Structures

The Ricola Herb Centre in Laufen (Basel), Switzerland

Centre for Earth Architecture / Kere Architecture

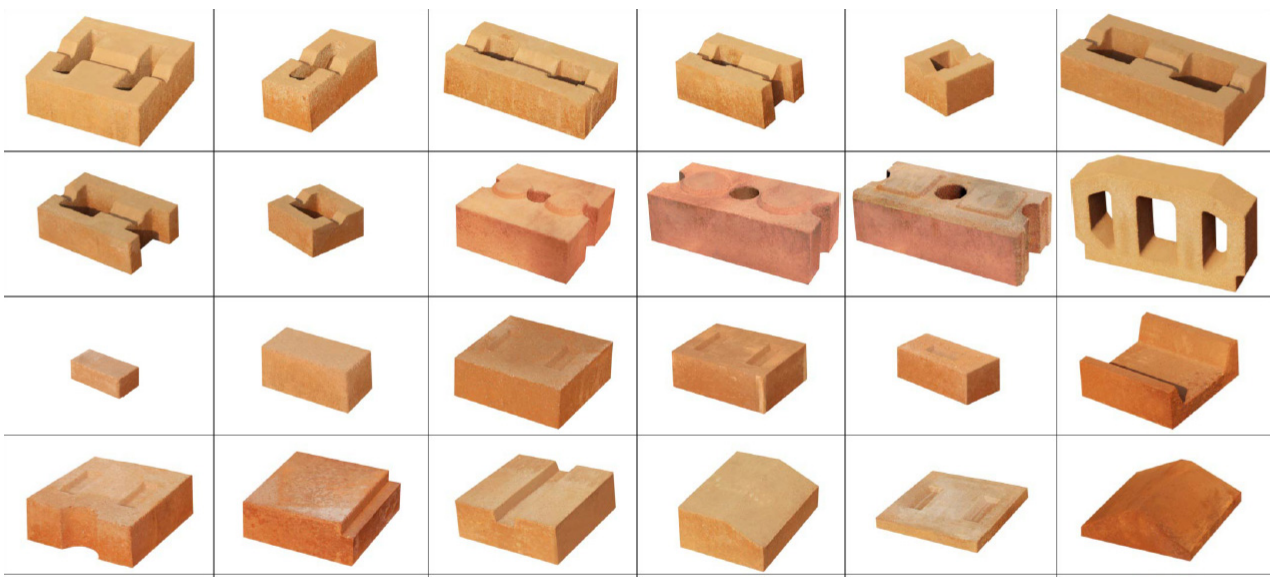
El Haj Yousif experimental school in Sudan (Adam, 2001)

Earthen house in Davis, CA, USA (1955)

Earth Block Construction

- CEB: Compressed Earth Block
  - Earth mix is compressed to increase strength (volume is reduced by about half)
  - Mechanical presses are used to compress the blocks
- SEB: Stabilized Earth Block
  - Stabilizer is used with earth mix (used to increase strength and durability)
  - Blocks are not highly compressed like CEB
  - SEB have better durability (e.g., resistance against abrasion)
- CSEB: Compressed and Stabilized Earth Block
  - Manufacturing process is combination of CEB and SEB
  - Stabilized mixture is used, and blocks are highly compressed
  - CSEB have better strength (can meet or exceed cement brick) and durability

Compressed and Stabilized Earth Blocks (CSEB)



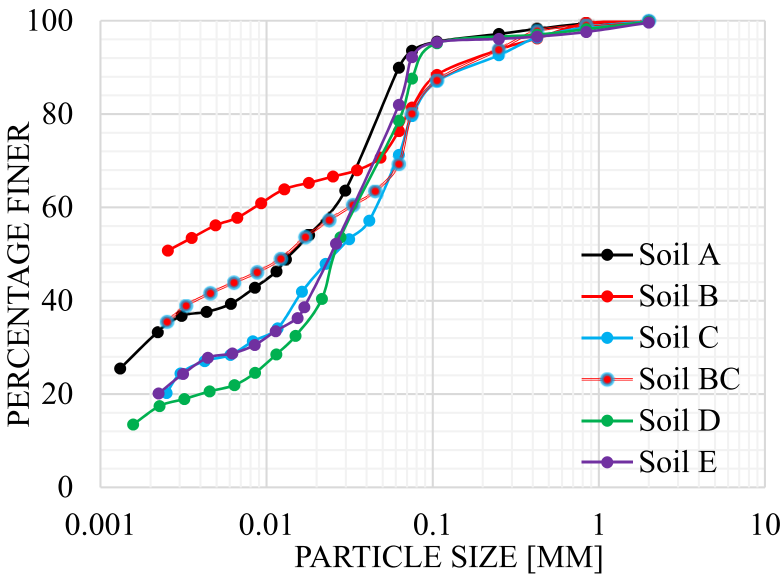
Fabrication process of CSEBs

Feasibility of CSEB Houses

- Focus on US Gulf Coast region (wet and humid climate)
- Motivation: need for affordable hurricane-resistant housing
  - 386,000 low-income households in Louisiana need affordable housing (U.S. Department of Housing and Urban Development in 2010)
- Challenges: poor soil quality, hot and wet climate, high wind loads, and cost
- Need for culturally-appropriate solutions
- Investigation performed for:
  - Structural feasibility
  - Architectural feasibility
  - Economic feasibility

(Kumar et al. 2018)

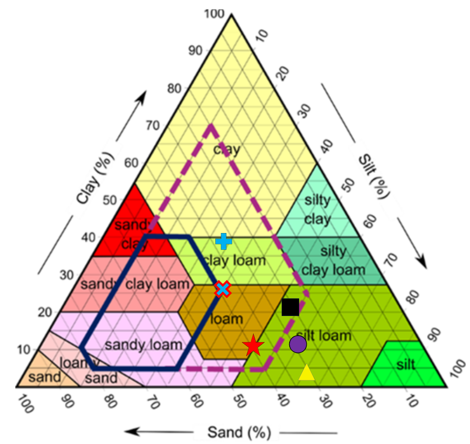
Soil Identification



Particle analysis of the soil collected from different sites in Baton Rouge, LA.

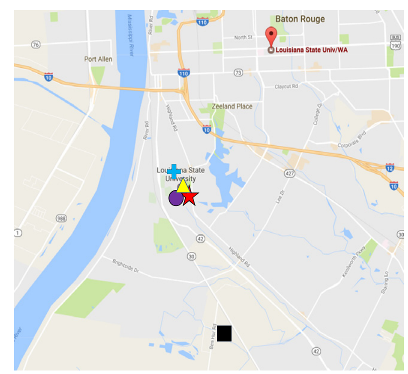
Soil type	A	B	C	BC	D	E
Sand	10%	24%	29%	31%	21%	18%
Silt	57%	19%	43%	25%	58%	51%
Clay	33%	58%	28%	44%	21%	31%

ASTM D6913-04 (2009); ASTM D7928-16 (2016); ASTM D2487-11 (2010)



USGS soil texture triangle

- Soil A
- Soil B
- Soil C
- Soil BC
- Soil D
- Soil E



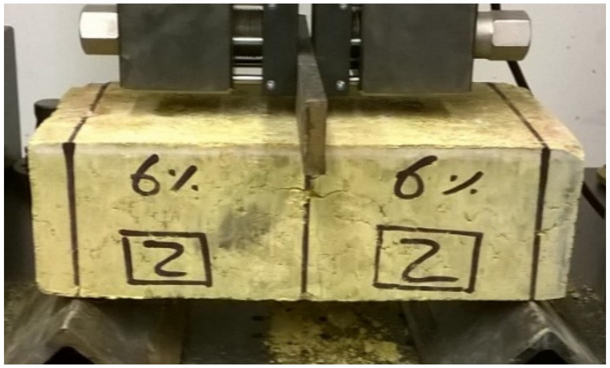
Map of Baton Rouge with site locations of different soils

Mechanical Properties of CSEBs

Mechanical properties of CSEBs for different cement content

Cement	MOR		f_{bd}		MOE		f_{bkd} (MPa)	f_{bw}		f_{bkw} (MPa)
	Average (MPa)	COV (%)	Average (MPa)	COV (%)	Average (MPa)	COV (%)		Average (MPa)	COV (%)	
0	0.33	9.50	1.22	6.38	23.28	11.40	0.74	-	-	-
3	0.39	11.40	1.66	8.74	38.53	20.49	0.96	0.75	4.91	0.47
6	0.53	6.38	2.01	6.13	44.82	11.47	1.23	0.97	9.91	0.54
9	0.66	4.87	2.97	7.19	60.45	2.34	1.78	1.58	4.32	1.01
12	0.78	4.17	3.89	5.47	74.20	13.41	2.42	2.16	5.84	1.34

MOR = Modulus of rupture; f_{bd} = Dry compressive strength; **MOE** = Modulus of elasticity; f_{bkd} = Characteristic dry compressive strength; f_{bw} = Wet compressive strength; f_{bkw} = Characteristic wet compressive strength



Specimen after flexure test


Specimen after compression test

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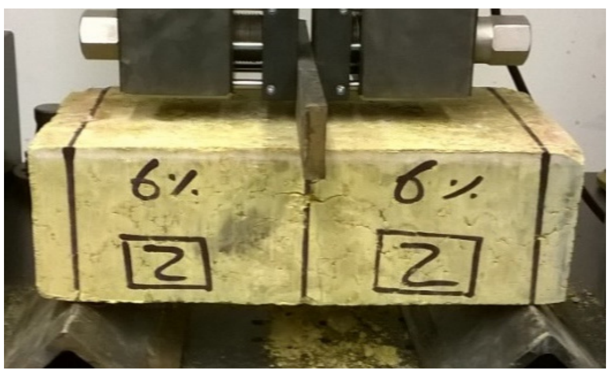

Specimen after flexure test

Specimen after compression test

- NMAC 2015 recommends average $f_{bd} > 2.0$ MPa; min(f_{bd}) > 1.7 MPa; average MOR > 0.35 MPa

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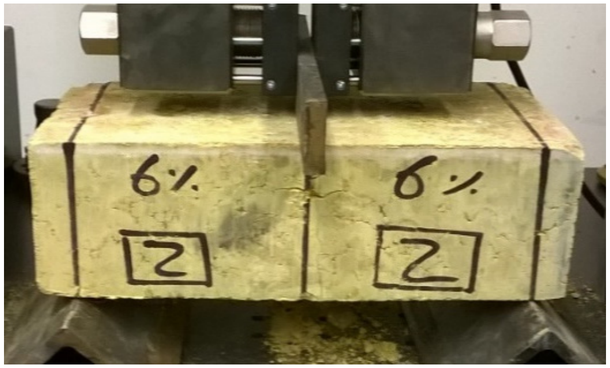

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Specimen after compression test

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- **Lunt 1980 & Houben and Guillaud 1994 recommend average f_{bw} > 1.5 MPa**

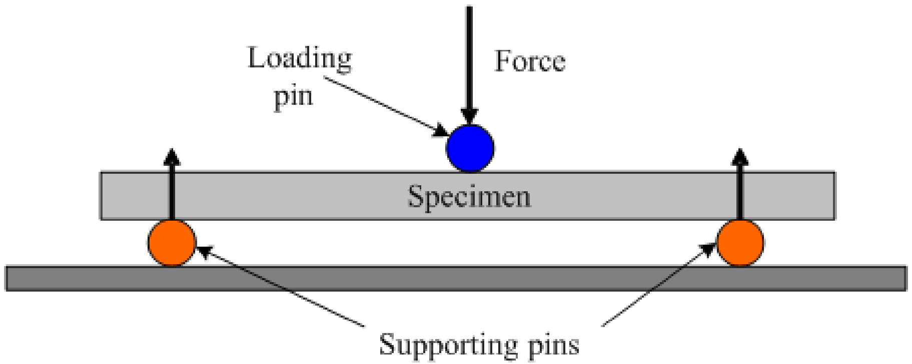
Use of Sugarcane Bagasse Fibers (SBF) in CSEBs

- Sugarcane production in 2018: 746.8 million metric tons (MMT) in Brazil, 376.9 MMT in India, and 108.7 MMT in China
  - > 400 million metric tons of SBF.
- USA sugarcane production in 2017: 28.0 MMT, mostly in Florida, Louisiana, and Texas,
  - ~ 9 million metric tons of SBFs.
- Brittle behavior of CSEBs can be improved using fibers

Sugarcane bagasse fibers

SBF stockpile in Alma Plantation, Louisiana

SBF-Reinforced CSEBs: Flexure Test

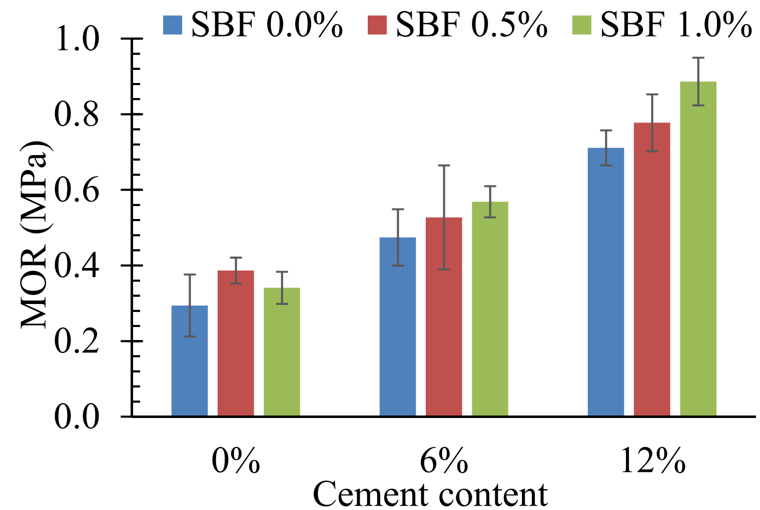


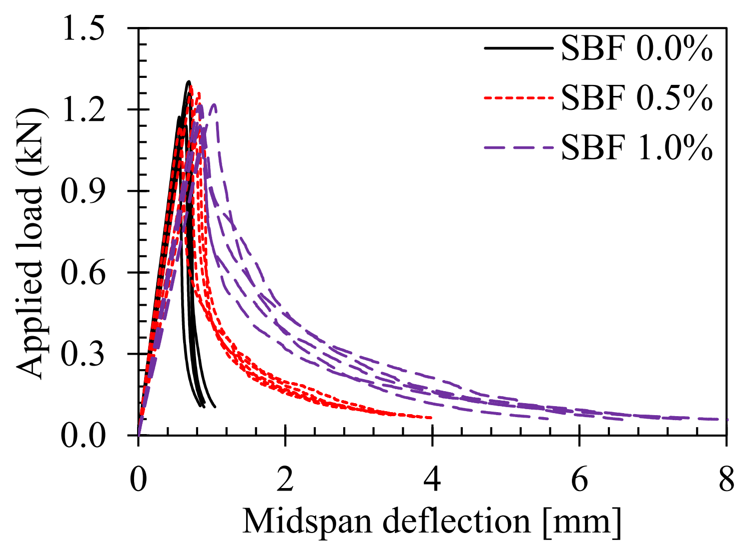
Unreinforced earth block

SBF-reinforced earth block

Crack pattern in unreinforced earth block

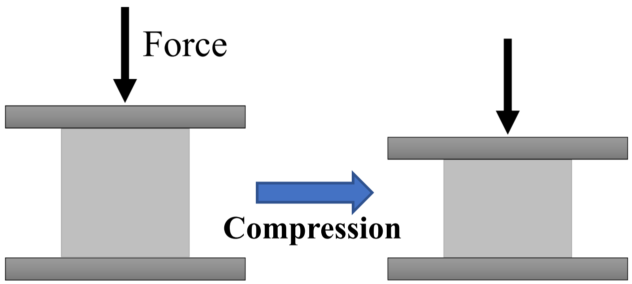
Crack pattern in SBF-reinforced earth block

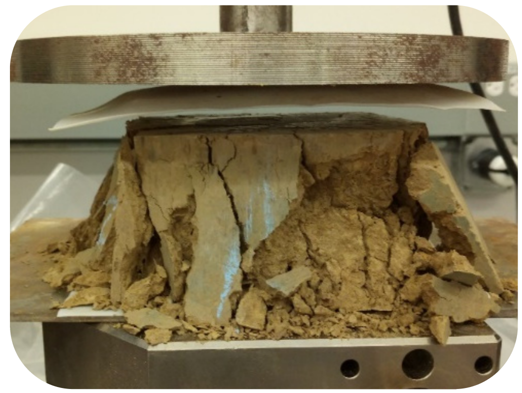




Earth block with 6% cement

SBF-Reinforced CSEBs: Compression Test





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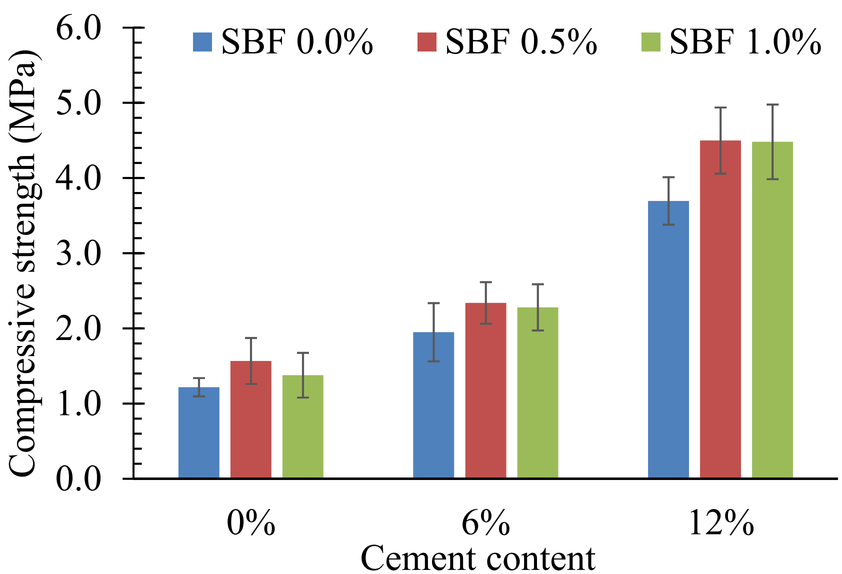
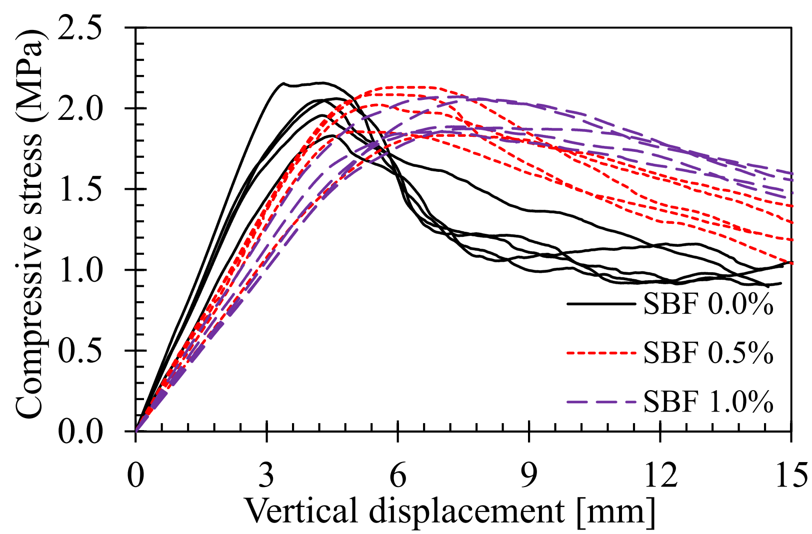
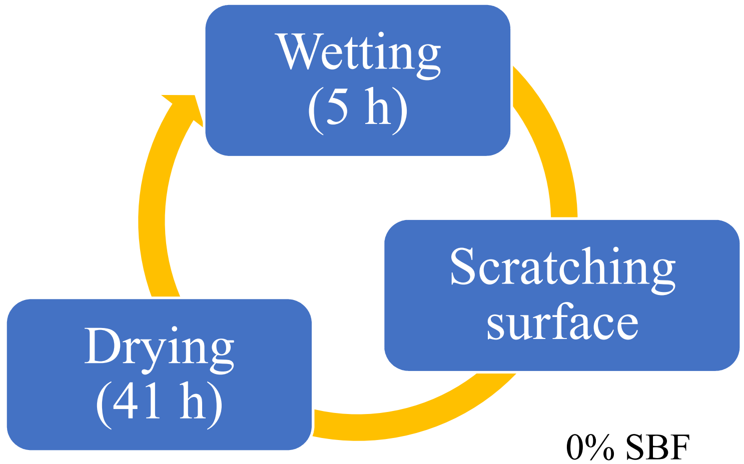




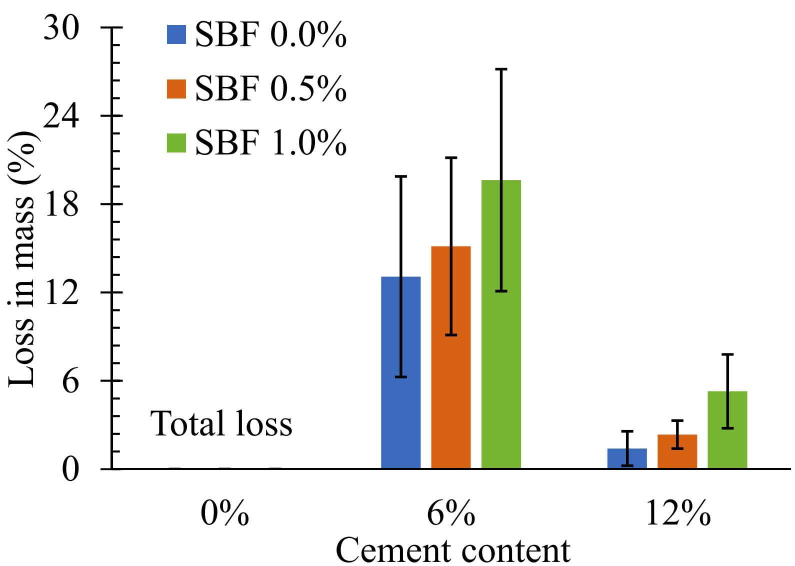
Earth block with 6% cement

SBF-Reinforced CSEBs: Durability Test

Wetting and drying durability test



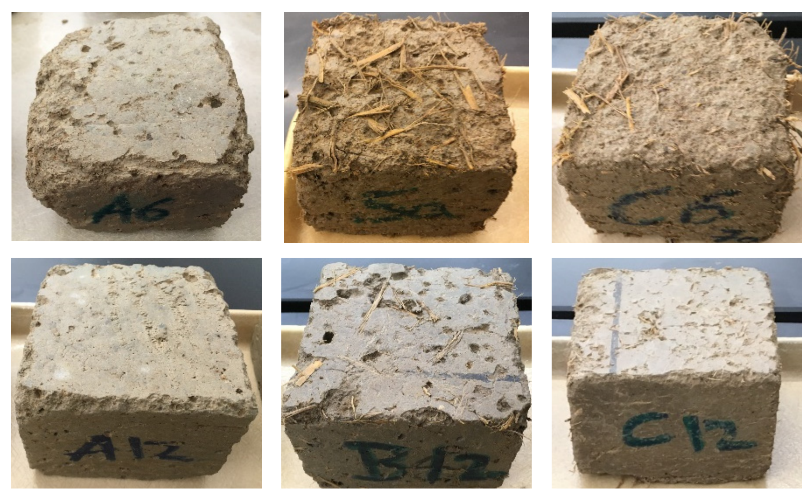
12 Cycles



0% SBF | 0.5% SBF | 1.0% SBF

6% cement →

12% cement →



Specimens after durability test

Durability Study of CSEB Wall

Masonry wall after construction

Masonry wall after application of soil-cement mortar and cement paste

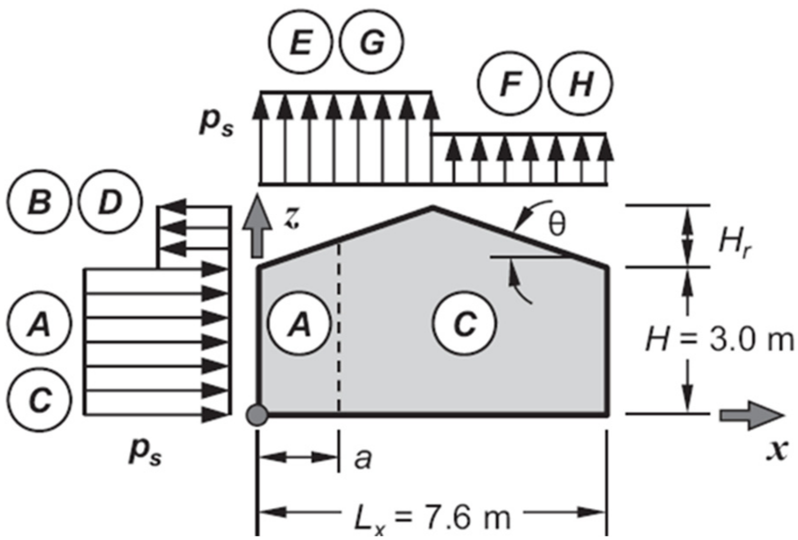
Mechanical properties of CBEBs before construction and after demolition of the wall

Tested specimens	MOR		f_{bd}		MOE	
	Average (MPa)	**COV (%)**	**Average (MPa)**	**COV (%)**	**Average (MPa)**	**COV (%)**
CSEB (initial)	0.57	11.28	1.38	6.40	31.22	16.98
CSEB (protected)	0.64	22.68	1.79	5.55	55.61	20.21
CSEB (unprotected)	0.37	21.82	1.50	13.80	44.78	26.82

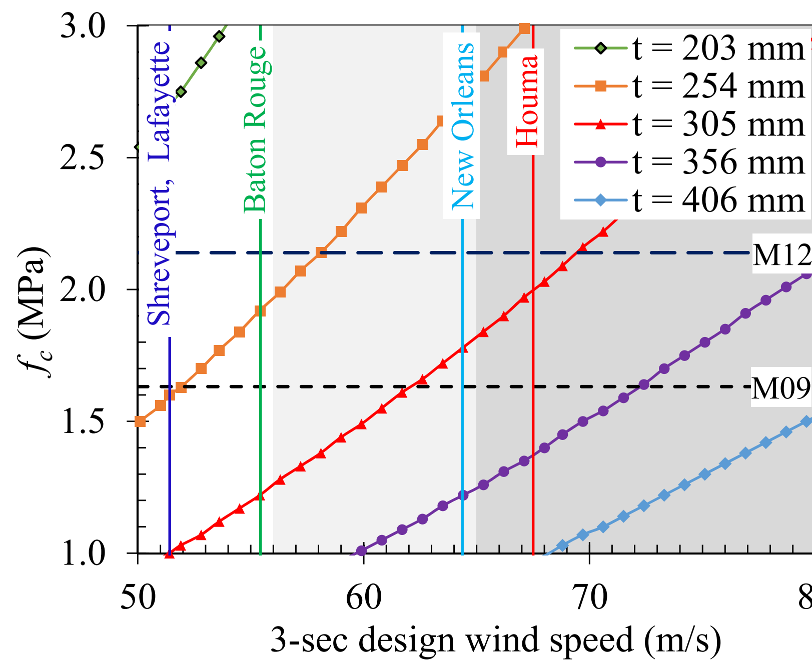
MOR = Modulus of rupture; f_{bd} = Dry compressive strength; **MOE** = Modulus of elasticity

Hurricane Wind Resistance Study

- Strength demand curves developed by **Matta et al. (2015)**
- Characteristic masonry strength as per Eurocode 6 (CEDN 2005)
  - M09 - CSEB with 09% cement and respective mortar
  - M12 - CSEB with 12% cement and respective mortar

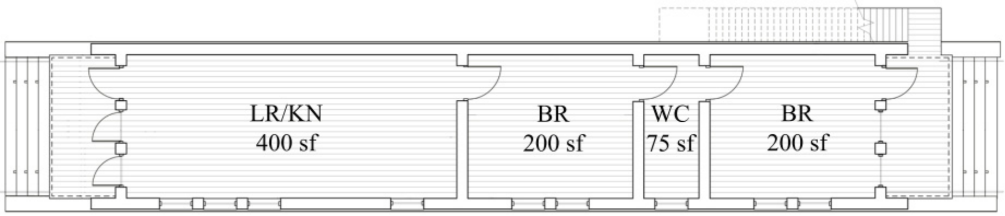


Schematic representation of wind pressures on MWFRS (Matta et al. 2015)



CSEB masonry strength demand curves for hurricane

Economic Feasibility (1)



Floor plan

Front elevation

Front elevation

Cost comparison of different wall systems for reference shotgun prototypes house (1000 Square ft.)

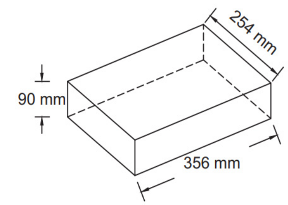
Items	ICSEB Mortarless	Mortared CSEB	Light-frame Wood	Bricks	Concrete Blocks
Material ($)	7,186	6,676	15,638	19,533	12,844
Labor ($)	20,593	34,674	13,068	27,625	20,255
Overhead ($)	11,112	16,540	12,264	19,840	13,882
Total wall cost ($)	**38,891**	**57,890**	**40,970**	**66,997**	**46,981**
Other assemblies ($)	65,110	65,110	65,110	65,110	65,110
Total cost of house ($)	104,001	123,000	106,080	132,107	112,091
Wall cost ratio (wcr)	1.00	1.49	1.05	1.72	1.21
House cost ratio (hcr)	1.00	1.18	1.02	1.27	1.08

- RS Means (2014, 2015) is used for the cost estimation

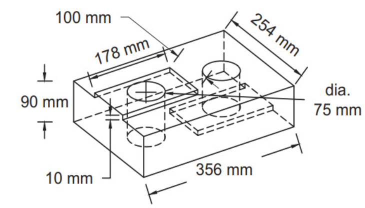
Economic Feasibility (2)

Detailed cost estimates of CSEB walls for the reference prototype house

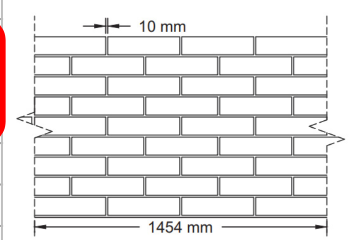
Components	Items	Mortarless ICSEB Wall			Mortared CSEB Wall		
		Quantity	Unit	Cost ($)	Quantity	Unit	Cost ($)
Blocks	Soil	133.3	Ton	-	132.6	Ton	-
	Cement	40,055	lbs.	3,676	39,851	lbs.	3,651
	Labor	584	Hours	4,234	528	Hours	3,828
	Machine	73	Hours	2,555	66	Hours	2,310
Reinforcement	Material	1,610	lbs.	483	-	lbs.	-
	Labor	29	Hour	580	-	Hour	-
Mortar & grout	Soil	10.6	Ton	-	10.6	Ton	-
	Cement	7,806	lbs.	720	7,806	lbs.	720
	Sand	10.6	Ton	531	10.6	Ton	530
Masonry Work	Stem walls	113	Hours	2,250	225	Hours	5,721
	Long walls	288	Hours	5,766	577	Hours	14,755
	Short walls	92	Hours	1,830	183	Hours	4,683
Rendering	Soil	2.7	Ton	-	2.7	Ton	-
	Cement	2,938	lbs.	271	2,938	lbs.	271
	Sand	2.7	Ton	133	2.7	Ton	133
	Ext. paint	5,964	ft2	1,372	5,964	ft2	1,372
	Plastering	87	Hours	2,185	87	Hours	2,185
	Painting	48	Hours	1,193	48	Hours	1,193
Total cost				**27,779**			**41,352**



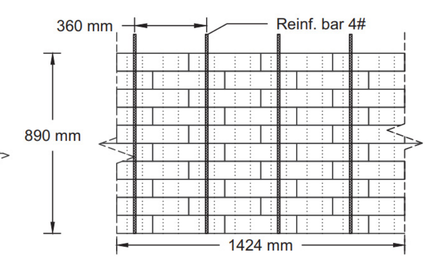
Ordinary CSEB element



ICSEB element



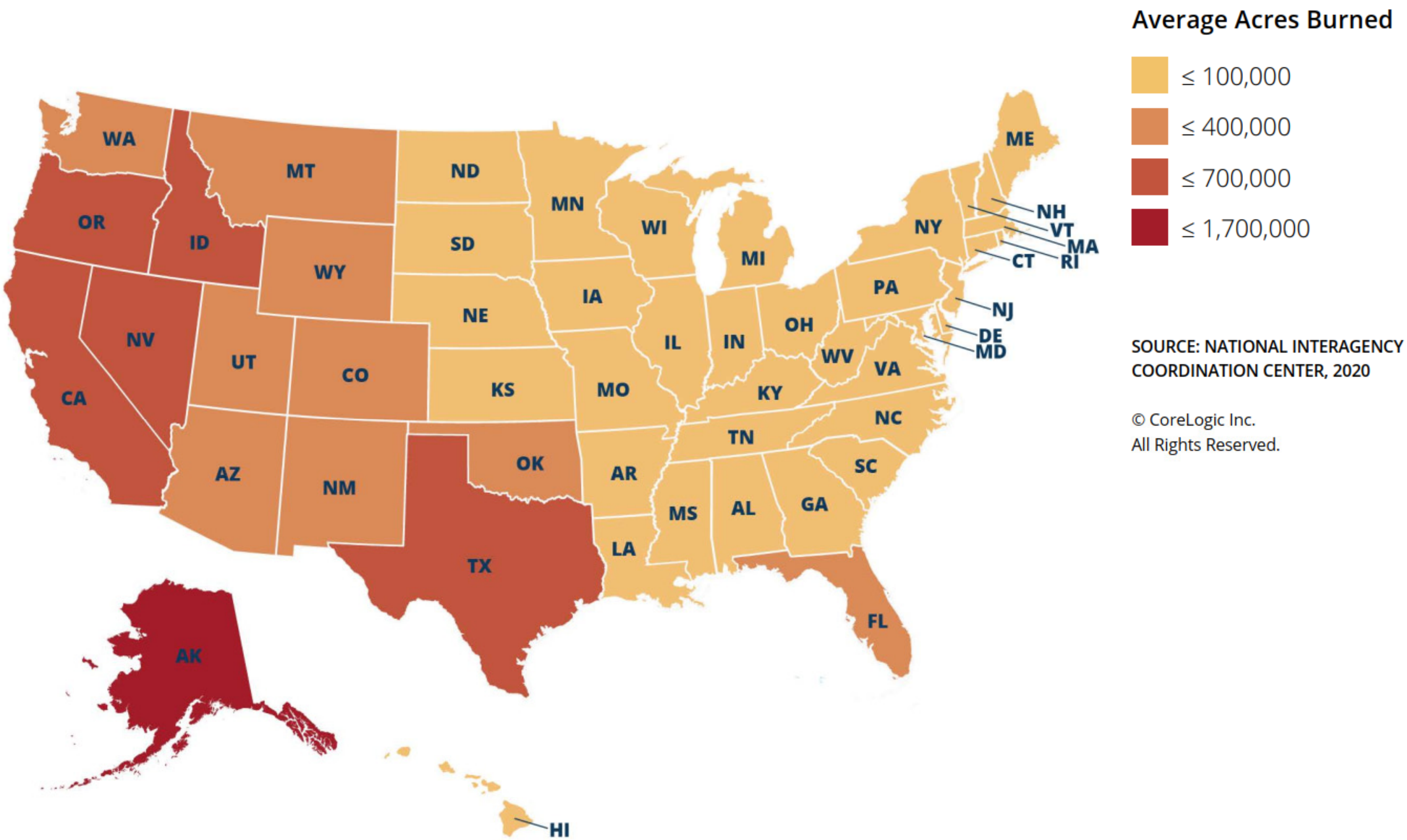
Mortared CSEB wall system



Mortarless ICSEB wall system

- RS Means (2014, 2015) is used for the cost estimation

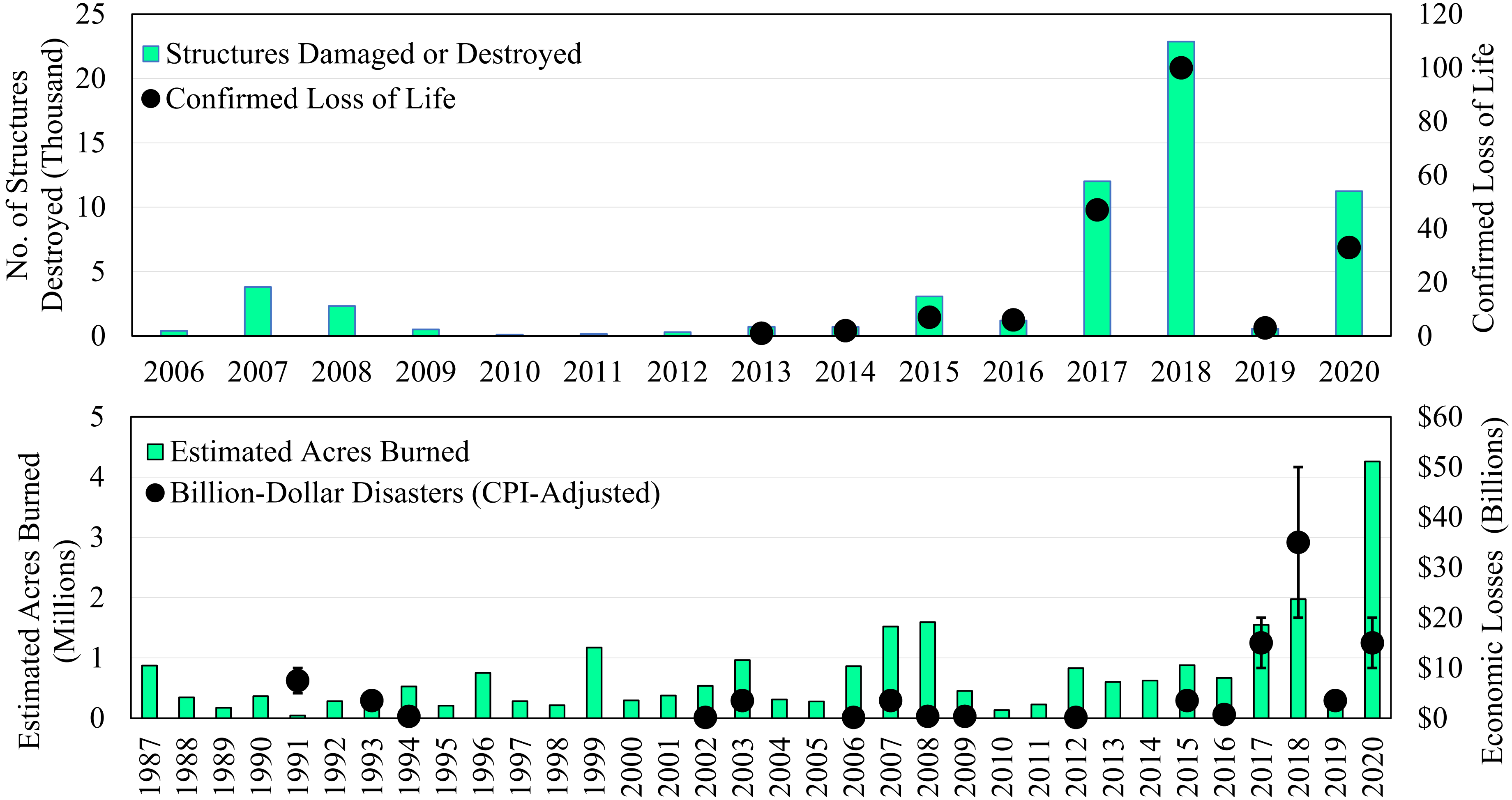
Wildfire: Nationwide Risk



Average yearly acres burned by wildfire (2002-2019)

CoreLogic 2020

California Wildfires History & Statistics



Data sources:

1. Estimated acres burned and confirmed loss of life: https://www.fire.ca.gov/incidents/
2. Damaged/destroyed structures: https://headwaterseconomics.org/natural-hazards/structures-destroyed-by-wildfire/
3. Economic losses: https://www.ncdc.noaa.gov/billions/time-series/CA

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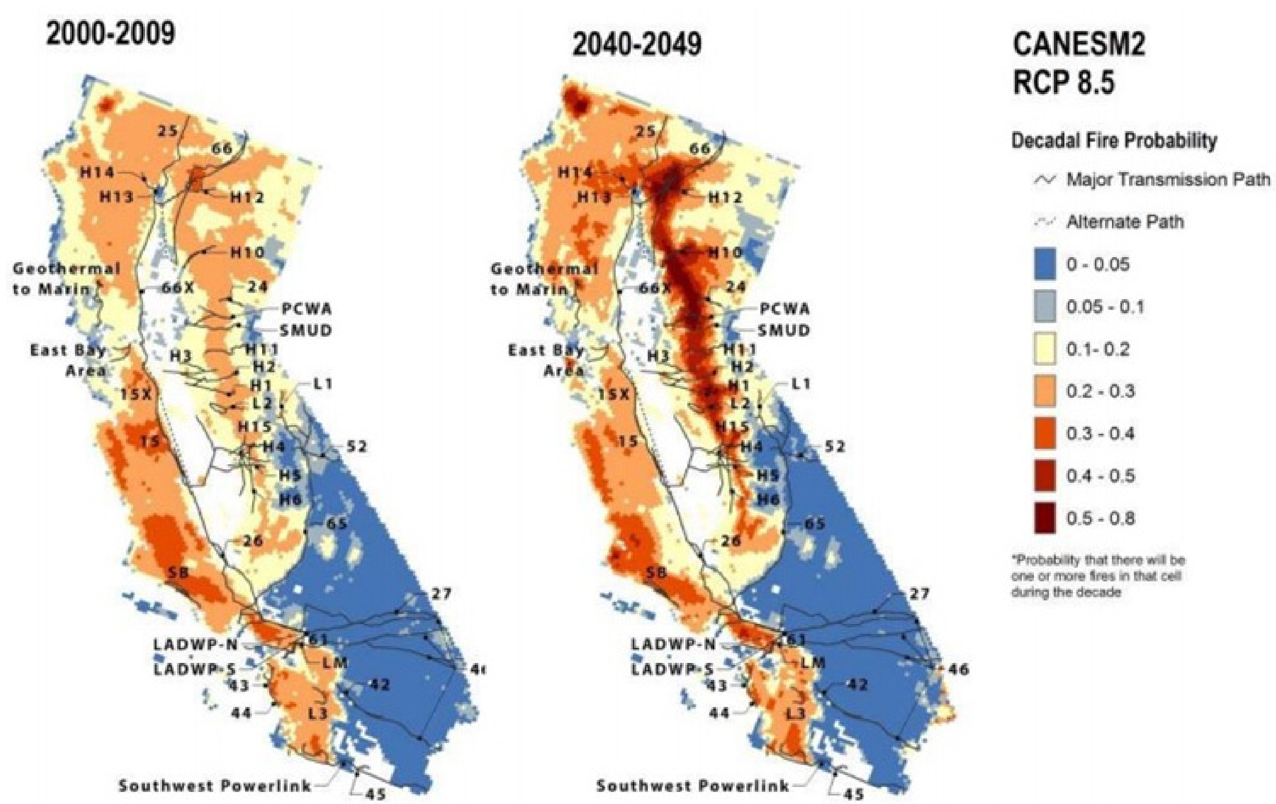
Effect of Climate Change on Wildfire Hazard

➢ Rising global temperatures are increasing the severity of wildfires across the western United States (Westerling 2018: CEC Report No. CCCA4-CEC-2018-014)

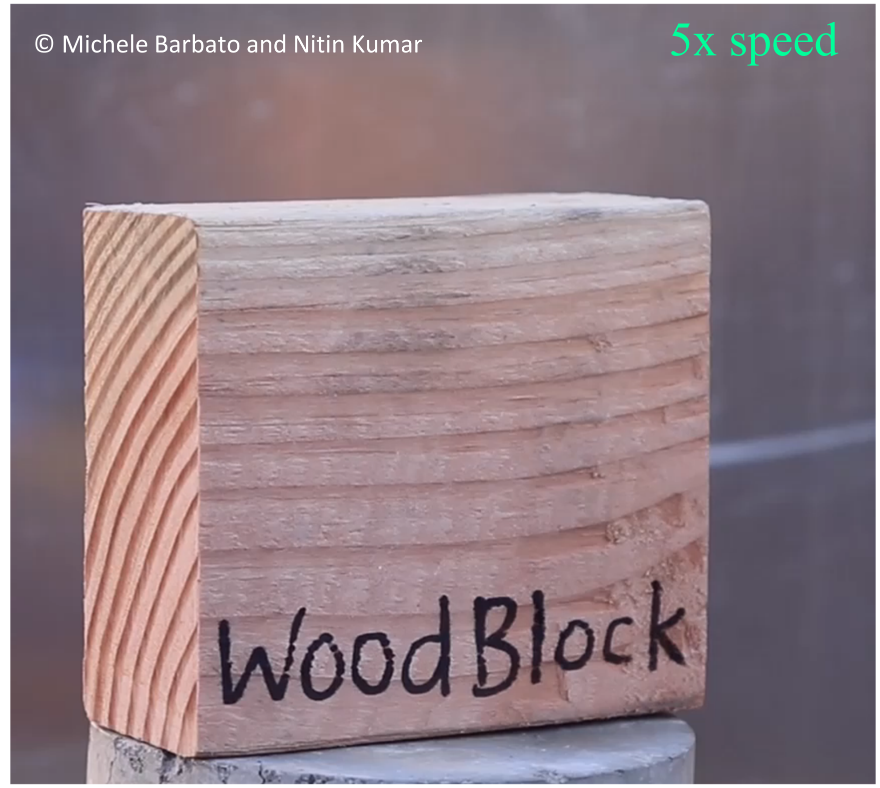


Wildfire simulations for California's fourth climate change assessment projecting changes in extreme wildfire events with a warming climate

California Building Code for WUI (Ch. 7A)

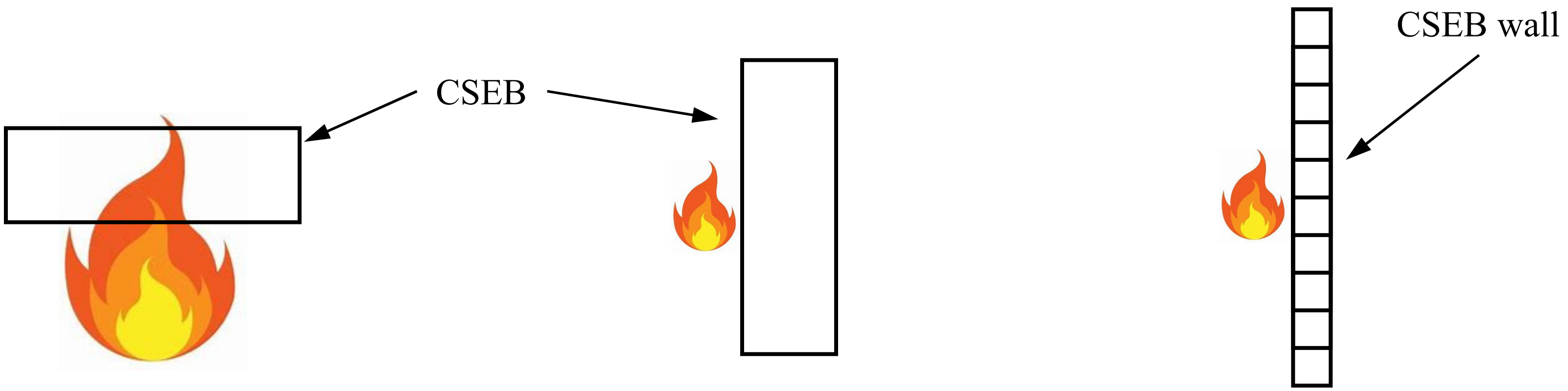
- Fire Resistance Test Standards
  - **Exterior wall siding and sheathing**: 150-kW intensity direct flame exposure for a 10-minute duration
  - **Exterior windows**: 150-kW intensity direct flame exposure for an 8-minute duration
  - **Decking**: under-deck exposure to 80 kW intensity direct flame for a 3-minute duration.
  - **Roof**: comply with varies the requirements (for Coverings, valleys, and gutters) of Chapter 7A and Chapter 15 of California Building Code
  - **Horizontal projection underside**: 300-kW intensity direct flame exposure for a 10-minute duration
  - **Other ignition-resistant materials** (e.g., fire-retardant-treated wood): 30-minute ASTM E84 or UL 723 tests
- Exterior Protection
- Defensible Space

CSEB Construction: Fire Resistance (1)



CSEB Construction: Fire Resistance (2)

- Ongoing research
  - Characterize fire-induced changes in mechanical properties of CSEBs and CSEB masonry at different temperatures and temperature gradients
  - Investigate the integration of other fire hardening systems (roof system and cover, vents, defensible space, etc.)

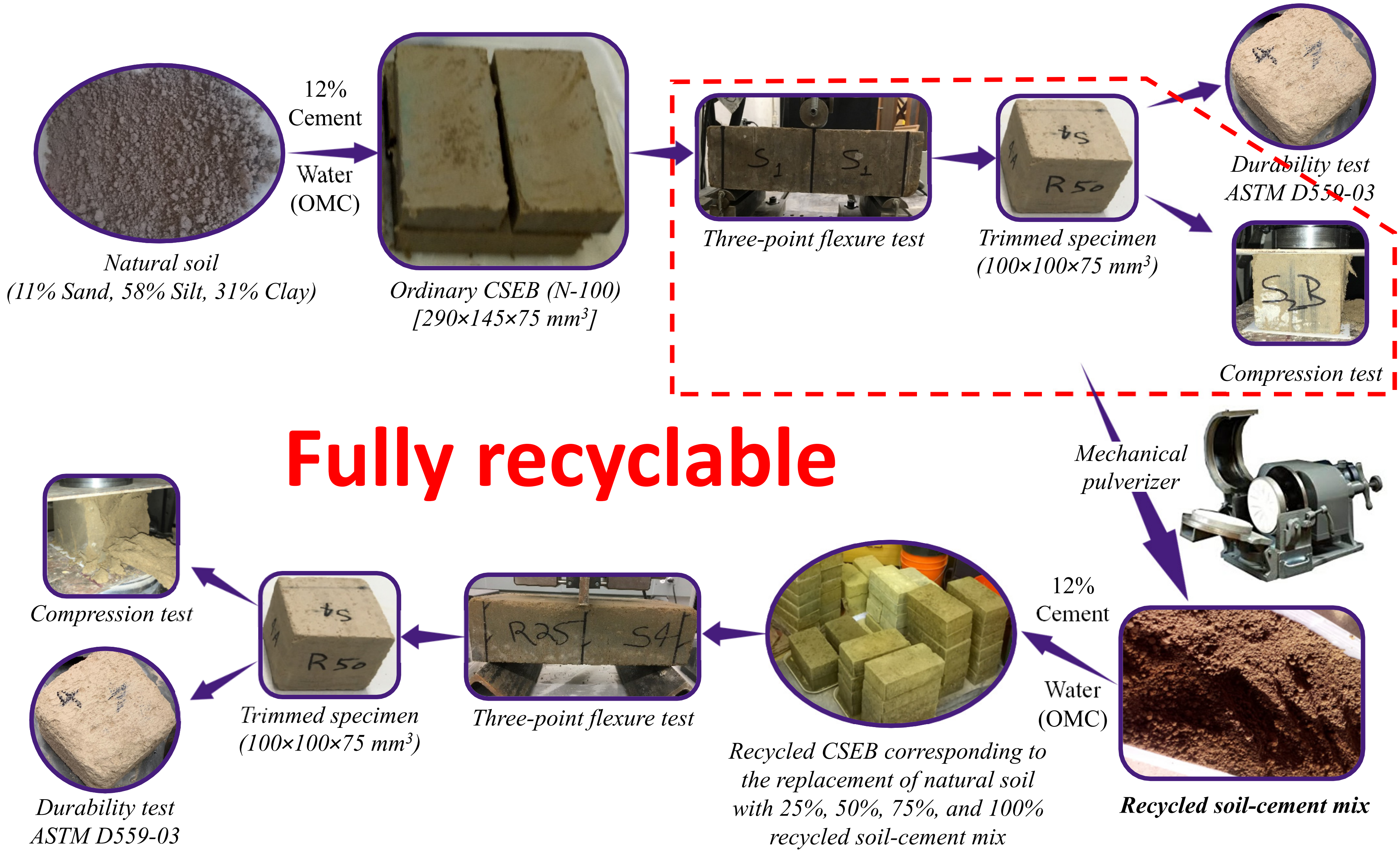


All sides of CSEBs expose to time-temperature profile

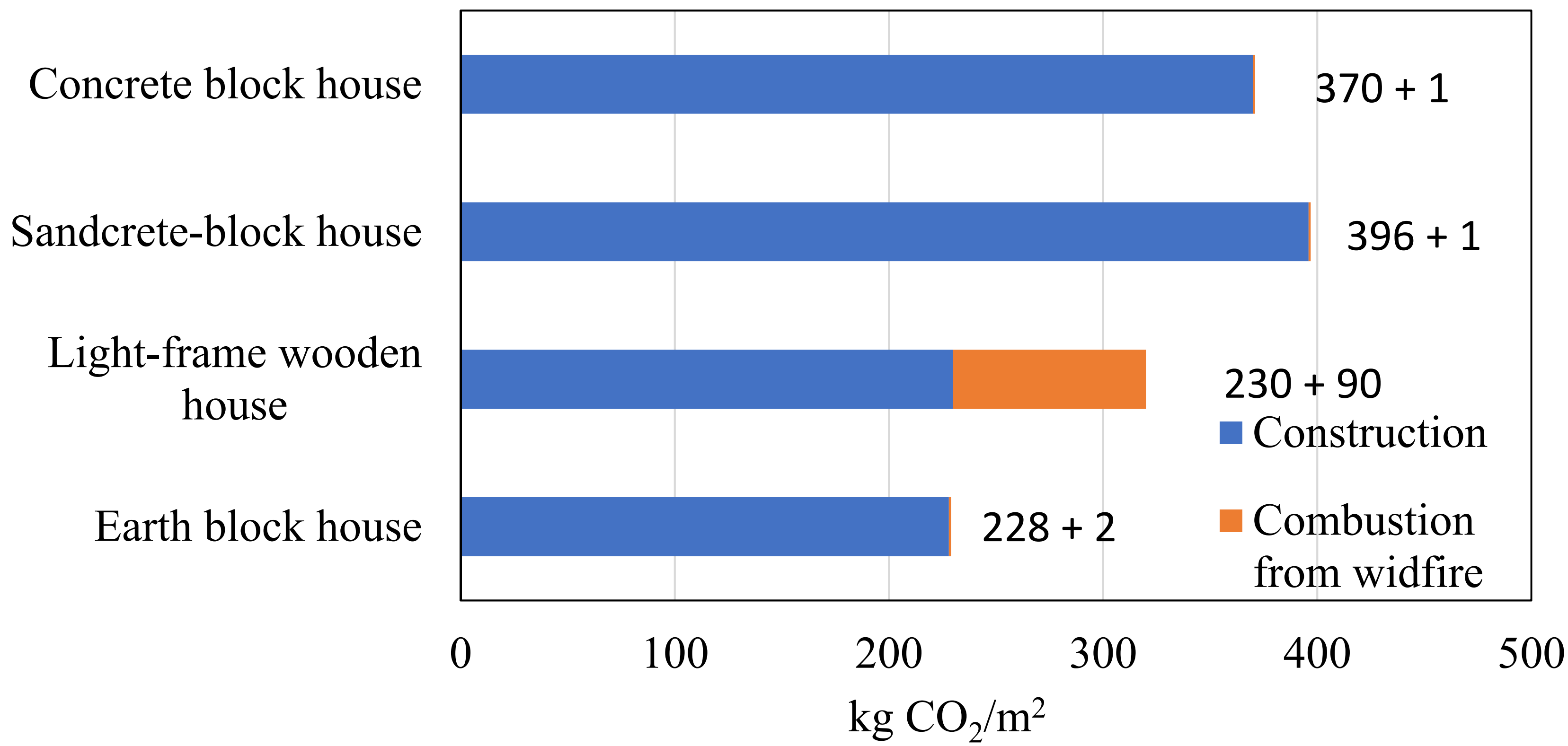
Only one sides of CSEBs expose to time-temperature profile

One sides of CSEBs wall expose to time-temperature profile

Other Sustainability Considerations (1)



Other Sustainability Considerations (2)



- Operational Energy consumption savings between 30%-70%, depending on climate.
- Design service life can be easily extended to 100 years (currently ~35 years).

Initiatives Using CSEB Construction

- Good Earth Lodge, Crow Tribe, MO

- Brick-by-Brick, Scottsdale, AZ

- Welcome Home Haiti, Northern Haiti

Conclusions

- Earthen masonry represents an affordable, safe, and sustainable technique for construction of houses and low-rise buildings
- Several issues still hamper the mainstream use of modern earthen masonry
- Appropriate and feasible solutions have been proposed for structures subject to hurricane hazard in Louisiana
- Research is ongoing to develop an affordable fire-resistant construction technique based on CSEBs
- Earthen masonry shows great potential to address climate change and equitable economic development

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Thank you
Questions?

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