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Contemporary use of earthen techniques in Colombia: Thermal performance of domestic and non-domestic building typologies.

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Abstract
In the last decades, particular consideration has been given to buildings' operational energy such as heating, cooling and lighting energy demand. However, with the increased environmental awareness and further advances in the regulatory frameworks globally, the energy consumption embedded in the material extraction and in the construction process is becoming increasingly relevant. The hypothesis of this paper is that naturally sourced and low embodied energy materials can be used as an alternative to conventional ones in Colombia. An analysis of earthen techniques such as Stabilized Rammed Earth (SRE) and Compressed Stabilized Earth Blocks (CSEB) is made in comparison to conventional massive and aerated fired bricks in terms of their thermal performance. Furthermore, the thermal inertia of earthen materials is analysed for both domestic and non-domestic building typologies, through dynamic thermal simulation. The applicability of earthen mass in different envelope components is assessed defining design guidelines for its successful use in the specific climate of Bogotá.
Keywords: stabilized rammed earth (SRE), compressed stabilized earth blocks (CSEB), thermal mass.

1 Introduction
The practice of sustainable design is highly related with the choice of materials since it deals with both embodied and operational energy. Traditional techniques have proven to be an alternative for reducing the embodied energy of buildings still showing potential for improving the operational one. In Colombia, these techniques are being reconsidered after several decades of urban development based on industrialized materials. The main question that is addressed in this paper is whether earthen materials can perform as an alternative to conventional ones. The focus of the article is on the thermal performance of earthen techniques such as Stabilized Rammed (SRE) and Compressed Stabilized Earth Blocks (CSEB) in comparison to conventional fired bricks. For this purpose, a first approach to earthen materials is presented through the study of earthen composites. In addition, Bogotá's climate was defined and basic questions regarding thermal performance, passive strategies and envelope specification of domestic and non-domestic building typologies were answered through simulations in EDSL TAS establishing applicability guidelines.

2 Earthen composites
Earthen constructions present structural limitations. In fact, while the thickness of conventional wall construction made out of brick or concrete is about 30 cm, a wall made out of rammed earth is normally around 50 cm thick. Earthen composites were assessed in terms of their conductivity, volumetric heat capacity and compressive strength as shown in Figure 1. It can be seen that the potential of fibres is from their insulation properties, which is due to their low conductivity values about 0.05 W/mK. Thus, they could be used as insulations boards for floors, walls and roofs. For thermal purposes, the combination of loam and fibres shows high potential due to low conductivity values about 0.2 W/mK, appropriate for

insulating purposes, and relatively high volumetric heat capacity between 1100 and 1790 kJ/m^3.K convenient for thermal mass strategies can be achieved. In the case of stabilized earthen composites, it was shown that the structural limitations of the material could be addressed. In fact, the SRE can achieve half of the structural performance of a conventional brick and the CSEB can achieve about the same compressive strength. In addition, both proved to have the highest Volumetric Heat capacity reaching values of 1900 kJ/m^3.K. From the above, further analysis considered CSEB and SRE materials for thermal mass strategies, and fibres for insulating purposes.

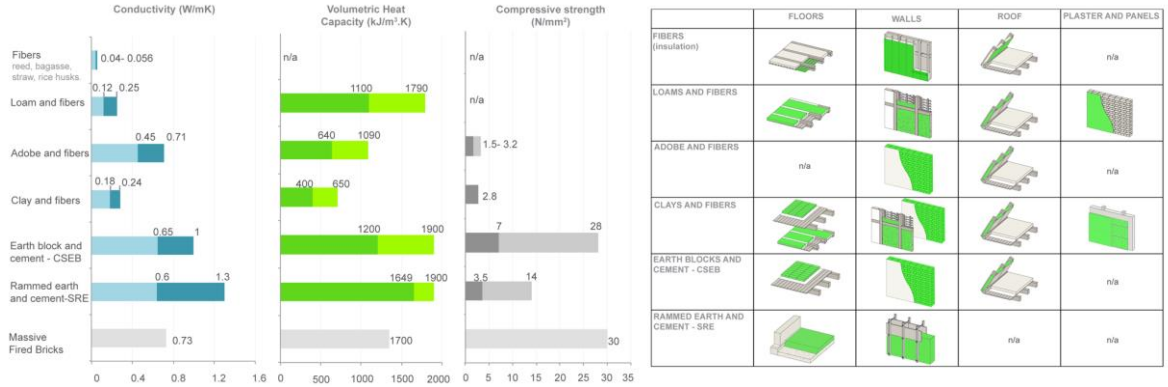

Figure 1. Earthen composites' properties and possible applications. Adapted from: Ashour et al. (2010); Lertwattanaruk and Choksiriwanna (2011); Goodhew and Griffiths (2004); Morton, (2008); Walker et al. (2005) Hall and Allinson (2008) and Schreckenback, (2004).

3 Climate

A weather file for Bogotá from Meteonorm 6.1 was analysed.

- Temperature: the mean temperature in Bogotá is constant throughout the year with a value around 13 ºC achieving a mean minimum and maximum values 7 ºC and 19 ºC respectively. In a typical day in June, diurnal fluctuations can be as high as 15 K with temperatures between 6 ºC and 21 ºC.
- Humidity: although relative humidity can achieve values up to 80 %, the humidity is not an issue since the moisture content remains within a range of 4g/kg and 12 g/kg which is within the comfortable range (Szokolay, 2004).
- Solar radiation: in regards to the mean hourly solar radiation values for different orientations, it can be seen that east and west vertical planes are likely to receive constant solar radiation throughout the year around 2.5 kWh/m^2. In contrast, north façade's radiation varies, being constant between April and September about 1.2 kWh/m^2 achieving up to 2.4 kWh/m^2 for the rest of the year.

4 Thermal comfort

Thermal perception was understood through the notion of thermal neutrality (Tn), which considers physiological factors of acclimatization. The adaptive model by Aluciems (1981) can be defined as follows: Tn = 17.6 + 0.31 Toavg; where Tn= neutral temperature and Toavg= mean outdoor temperature. In addition, adding or subtracting 2.5 K defines a comfort range with 90 % of acceptability. Conversely, adding or subtracting 3.5 K, a comfort range with 80 % of acceptability is defined (Figure 2).

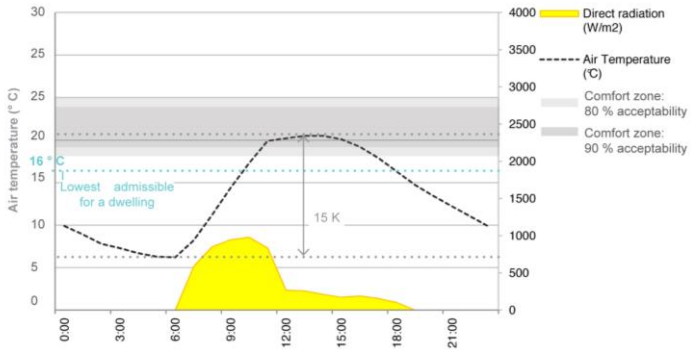

Figure 2: Diurnal fluctuations and thermal comfort parameters, June the 14th.

5 Hypothesis

In regards to the domestic building typology, the following hypothesis can be established:

- Passive heating requires no more than a well-oriented and sized window (Szokolay, 2004). West seems to be the most desirable orientation.
- Due to diurnal fluctuations, thermal storage mass maybe required. This depends on a careful distribution of the thermal mass.

As far as non-domestic and high internal gains building typologies are concerned, the following could be extracted:

- For cooling purposes in high occupancy buildings, thermal mass can be appropriate since it would perform as a heat sink.
- The climate analysis suggests north orientation as the most suitable.

As diurnal temperature fluctuations are as high as 15K, the thermal mass could work together with natural and/or night ventilation strategies (Baker, 2009).

6 Thermal analysis

An analysis regarding the thermal performance of domestic and non-domestic building typologies was carried out aiming to answer the following questions:

- How do earthen materials perform compared to conventional ones?
- How much earthen mass is required to achieve a significant heat storage effect?
- In what position is earthen mass most beneficial?
- For building programmes with potential overheating issues, can ventilation strategies improve the thermal mass effect of earthen materials?

6.1 Domestic building typology

A stand alone and west oriented dwelling with an area of 30 m^2 was defined and the input parameters for simulation can be seen in Table 1. The dwelling was assumed to be occupied by two adults between 18:00 and 6:00 in weekdays and from 16:00 to 9:00 h in weekends.

Table 1: Initial input parameters for the simplified model.

Geometry		**Internal gains**		
Area	30 m2	Equipment	7.4 W/m2	
Volume	90 m3	Set back value:	1.0 W/m2	
Window area	4.5 m2	Lighting:	1.4 W/m2	
External wall area	64 m2	Occupancy(x2)	6.4 W/m2	
Window to floor ratio	15%	**Infiltration rate**	0.5 ACH	
U Values	W/m2.K	**Schedules**	Weekday	Weekend
Aerated fired Brick Walls:	1.8	Equipment	5:00 - 7:00	8:00 to 9:00
Fibre cement roof:	5.7		18:00 to 22:00	16:00 to 23:00
Ground floor:	0.25	Lighting:	same as above	18:00 to 22:00 h
Windows (SG)	5.6	Occupancy(x2)	18:00 to 6:00	16:00 to 9:00 h

Table 2: Material properties. Adapted from Goodhew and Griffiths (2004); Hall and Allinson (2009); Ashour et Al (2010).

	Density kg/m3	Specific Heat KJ/kg.K	Conductivity W/m.K	Volumetric Heat Capacity kJ/m3.K
Lightweight	500	0.176	0.14	88
Aerated Fired Bricks (AFB)	1000	0.84	0.3	840
Fired Brick	1700	0.8	0.73	1360
SRE (7% cement)	1900	0.868	0.643	1649
CSEB (5% Cement)	1900	1	1	1900
Loam/ Earth plaster	1790	1	0.25	1790
Reed mat (20 or 50 mm thick)	190	-	0.056	-

Roof: Since earthen roofs are commonly supported by slatted timber and reeds, the effect of these was first assessed. Then, the progressive addition of external earthen mass was tested. Figure 3 shows that reed insulation (run 2) improved thermal conditions and the percentage of hours that the yearly resultant temperature was between 90 % and 80 % of acceptability increased from 21% and 30 % to 27% and 40% respectively. Moreover, the external addition of earthen mass did not show any significant improvement and above 10 cm thickness, the benefit is negligible. Up to such thickness, the improvements are mainly due to an U-Value reduction to 0.7 W/m^{2}K.

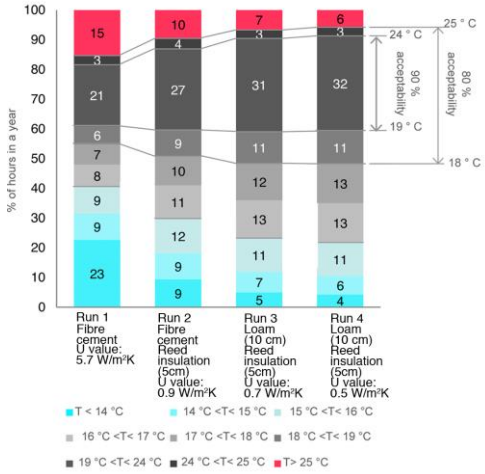

Figure 3: Resultant temperature frequency distribution in a year for different roofs.

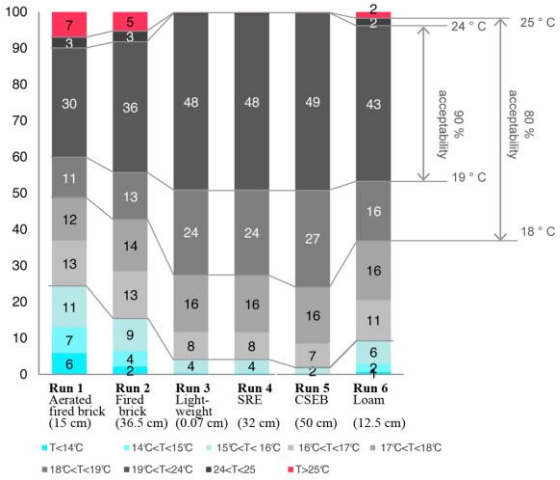

Figure 4: Resultant temperature frequency distribution in a year for different materials tested with same U value.

Material comparison fixed U-Value: In order to assess only the Volumetric Heat Capacity (VHC) and the effect of mass and given the fact that the U-Value depends on the wall thickness and on the material conductivity, U-values were set to be the same (1.5 W/m^{2}K). Figure 4 shows that all-massive construction materials have a similar performance achieving 90% of acceptability for 49 % of the year. In addition, the AFB walls would generate the highest diurnal resultant temperature fluctuation in June 14 th about 10 K while the lightweight construction and CSEB would fluctuate by 8K and 2.5 K respectively. This can be partially explained by the fact that the effect of mass of thick wall constructions is required to achieve the set U-value.

Earthen mass: the effect of mass has potential for improving internal comfort and is likely to be most effective when coupled with internal spaces (Baker, 2009). In order to assess the required quantity, earthen mass was progressively added on internal surfaces. Loam was used for ceiling, CSEB for walls and SRE for floors. It was shown that the dwelling's thermal performance is sensible to the amount of applied mass on internal surfaces. By increasing envelope's elements by 20 cm, the percentage of hours within 80 % and 90 % of acceptability increased from 33% to 42 % and from 49% to 74% respectively. Nevertheless, due to construction feasibility, a maximum wall thickness of 35 cm was considered admissible. This corresponds to the addition of 15 cm of SRE and loam on floors and ceiling respectively. The addition of mass reduced the internal fluctuation from 6K to 2K in a typical day.

The window sizing and the amount and position of insulation were optimized by adjusting the window to floor ratio to 30% and 5 cm of reed insulation placed outside the wall would optimise the performance (Walls U-value = 1.1 W/m2. K). With these variations on the simplified model, further analysis was undertaken.

Earthen mass position: a concern for architectural design is the position where the thermal mass is most effective in a building. This was assessed by changing one envelope element at the time (improved roof, floors and walls) and then looking at the overall effect of the heavyweight construction from the previous analysis. For the geometry considered, the best improvements were the earthen roof and the earthen walls showing a decrease in the percentage of overheating hours, from 19 % to 10% and 9% respectively. Moreover, the use of mass for internal partitions showed a significant improvement increasing the percentage of hours within 80% of acceptability by 14 %. Overall, the extensive use of mass increased the percentage within 90% and 80% of acceptability to 67% and 86% respectively. Figure 5 shows the resultant temperatures for the base case (run 1) and the optimized scenario with extensive thermal mass (run 6). For this case the resultant temperature fluctuates by only 4K in a typical week while lightweight construction would generate fluctuations of 20 K. This is explained by the fact that the largest the surface on which it is applied, the most effective is the thermal mass (Balcomb, 1983).

6.2. Non-domestic building typology

Other building programmes such as schools may suffer from overheating issues and could benefit from the mass effect provided by earthen materials. A simplified model was simulated considering the parameters listed in Table 3. The classroom is assumed to be occupied by 32 people from 8:00 to 18:00. During lunch time (13:00 h to 14:00 h), half of the occupancy is assumed. The classroom is oriented north and south walls are shaded. The main focus of the simulations was to look at the amount of mass required in a high occupancy programme and the potential ventilation may have to improve the mass effect for cooling in Bogotá.

Table 3: Initial input parameters for classroom-simplified model.

Geometry		Internal gains	
Area	72 m2	Equipment	6 W/m2
Volume	216 m3	Set back value:	1.0 W/m2
Window area	10.8 m2	Lighting:	3 W/m2
External wall area	45.6 m2	Occupancy(x32)	45 W/m2
Internal wall area	43.2 m2	**Infiltration rate**	0.5 ACH
WFR	20%	**Fresh air req**	4.5 ACH
U Values	W/m2.K	**Schedules**	Weekday
External walls	1.9	Equipment	8:00 - 18:00
Roof:	0.7		
Ground floor:	0.25	Lighting:	6:00-18:00
Windows (SG)	5.1	Occupancy(x32)	8:00 to 18:00

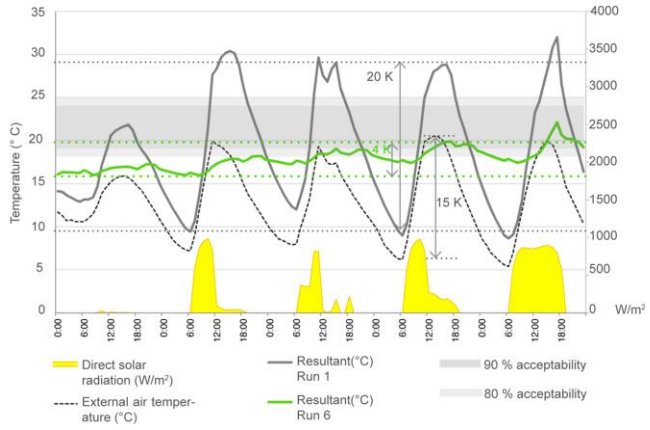

Figure 5: Resultant temperatures between June 11 th and 15 th for base case and heavyweight constructions, domestic building type.

Earthen mass: By changing the wall construction from lightweight to heavyweight, the percentage of overheating hours during occupancy decreased from 37 % to 12 %. The addition of internal mass proved to be effective up to 10 cm thickness for floors and ceilings and 30 cm thick walls. Figure 6 shows the resultant temperatures during a week from lightweight walls, to heavyweight walls and the optimal internal addition of mass. It can be seen that the second (run 2) reduced the temperature peak by 3K compared to the first for the warmest day of the week. Moreover, the addition of internal mass (run 4) reduced this peak by 2K compared to the second.

Ventilation: Natural ventilation and night ventilation could work jointly with thermal mass (Baker, 2009). Simulations aimed at assessing the impact of multiple ventilation rates as well as night ventilation potential. It was shown that the increase of ventilation rate during the day would reduce the percentage of hours within 90 % of acceptability. In contrast, ventilating at 4.5 ACH during occupancy and doubling the rate during the night allowed to increase the percentage of hours within 90 % of acceptability from 84 % to 86 %. In addition, it was shown that night ventilation has potential for reducing the resultant temperature's peak by about 2K compared to the initial case (Figure 7).

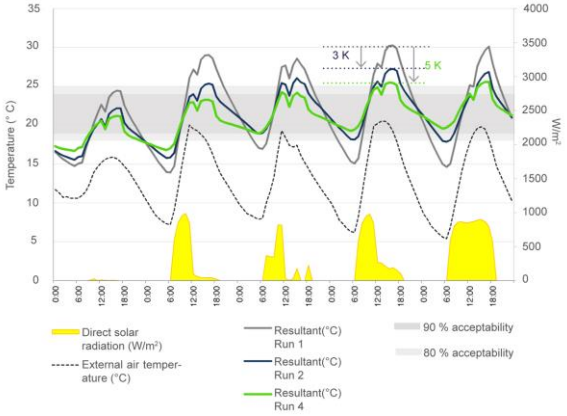

Figure 6: Resultant temperatures between June 11th and June 15 th for base case, heavyweight walls and optimal case**.**

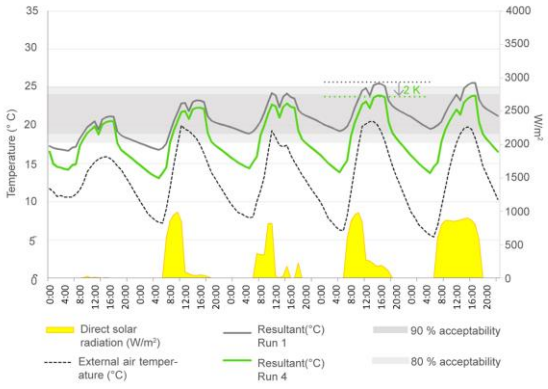

Figure 7: Resultant temperatures between June 11th and June 15 th for base case and optimal ventilation strategy.

7 Conclusion

The questions answered in this paper aim to conceive guidelines for the applicability of traditional building techniques in a contemporary context. Earthen composites made with low cement proportions were mainly considered. Material comparisons, envelope specifications, thermal mass and ventilation strategies framed the contemporary application of traditional earthen materials for domestic and non-domestic buildings. It was proven that locally sourced techniques such as compressed stabilized earth blocks could perform thermally as well as conventional bricks. Moreover, the thermal mass strategy proved to be more effective for cooling than for heating purposes in Bogotá. Further research should consider the effect of earthen techniques in terms of embodied energy and cost in order to reach a holistic assessment of the material.

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