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Comparing the environmental impact of stabilisers for unfired earth construction

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Abstract. Buildings account for approximately one third of the total worldwide energy emissions, of which approximately a quarter can be attributed to the embodied energy of the building. Current UK legislation for low-energy homes is only concerned with operational energy. Embodied energy, and carbon, is not currently considered but over the design life of an average building is expected to make a significant contribution to the total whole life energy used.

Earthen building materials contribute to reduce energy consumption in use through their passive regulation of temperature and humidity. In addition, there can also be significant embodied energy savings compared to other materials. Traditional methods of earthen construction, using locally sourced materials and manual labour require minimal energy for the transport and construction. A greater uptake of earth construction is likely to come from modern innovations such as industrialised manufacture. Extruded fired brick manufacturing processes has the potential to produce a high quality, low cost and low energy product suitable for the mainstream construction sector in both developed and developing nations. By not firing the extruded clay bricks, an embodied energy saving of 86% can be achieved, compared to fired clay, and 25% compared to concrete blocks.

However, there are limitations to the structural use of unstabilised earth bricks due to the loss of strength under high moisture content conditions. The use of traditional and novel stabilisation methods can be adopted to address the concerns over strength and durability. Cement and lime are widely used in some countries, but both significantly increase material embodied energy and carbon and can inhibit passive humidity regulation. The paper presents results from a study of the embodied energy of various stabilisers used for unfired clay materials. The Global Warming Potential (GWP) is a measure of the equivalent carbon dioxide that allows for the relative weightings of damaging greenhouse gasses. Both the embodied energy and the GWP figures of various stabilisers are compared and discussed.

The conclusion of the work is that there is a maximum quantity of stabiliser than should be used. Typically the quantities of stabiliser are quoted as the amount that gives the maximum strength, but this should take account of not only strength but the environmental impact of achieving the improvement.

Introduction

By 2050, the UK is lawfully committed to reducing carbon emissions by 80% of 1990 levels and currently a quarter of the global carbon emissions can be attributed to the construction and occupation of building (Metz and Davidson, 2007).The UK government has recognised this challenge and has set targets for all buildings to be carbon neutral by 2019 with domestic buildings needing to meet this requirement by 2016. Current regulations for carbon neutral buildings only account for the operational energy, but this may change in the future. Embodied energy of the materials used within the construction industry currently account for between 20% and 60% of a building's carbon footprint, and this is predicted to rise as high as 95% by 2020 (Sturgis & Roberts, 2010) as operational carbon decreases.

Concrete production accounts for approximately 7% of global CO_2 emissions (Basheer, 2009). Within the UK, 5.5 million m^2 of concrete blocks, including dense, lightweight and aerated blocks were produced during 2011 (BIS, 2012). Heath et al. (2012) showed that earth construction could be adopted and used structurally as a replacement for concrete blocks for some domestic buildings. Earth is traditionally associated with having a lower environmental impact and therefore represents a significant potential saving with respect to national and global environmental impact.

The heritage of earthen architecture within the UK largely ended during the 19th Century (Morton, 2008). Within the past decade there has been a resurgence of interest in earthen construction largely due to environmental concerns of high embodied energy and the Global Warming Potential (GWP) of fired bricks and cement based products (Lawrence et al., 2008). There has been a growing body of research investigating various earthen construction methods including rammed earth (Jaquin et al., 2009), Compressed Earth Blocks (CEBs) (Reddy & Gupta, 2006) and extruded earth masonry (Maskell et al., 2012).

Although approximately 30% of the world's population live in earth dwellings (Houben & Guillaud, 1994), its mainstream adoption has been constrained in the UK. The loss of strength with increasing Moisture Content (MC) is identified as limiting the adoption of unfired earth bricks into the mainstream construction sector (Heath et al., 2012). The common response to the durability concerns is to stabilise the earth with various chemical additives. Typically cement or lime have been added to the earth (Reddy & Gupta, 2006; Walker, 2004). In recognition of the environmental impact of using these additives there has been an increase in research focused on alternative additives as well as the utilisation of waste and by-product materials from various industrial processes (Oti et al., 2009; Santoni et al., 2005; Tingle et al., 2007).

The addition of any chemical or mechanical process may have a detrimental impact on the embodied energy and GWP. The GWP considers the emission of greenhouse gasses and is a measure of the equivalent carbon dioxide that allows for the relative weightings of damaging greenhouse gasses. The GWP is calculated over a time interval, typically 20, 100, 500 years due to the way the concentration of gasses decay over different periods of times. A summary of the global warming potential for different gasses is shown in Table 1. For this study, both the embodied energy and 100 year GWP values will be used for all calculations.

Table 1: GWP of various gasses by mass (Solomon, 2007)

	GWP Time Horizon		
Gas	20 years	100 years	500 years
Carbon Dioxide	1	1	1
Methane	72	25	7.6
Nitrous oxide	310	289	153
CFC-11	6730	4750	1620
HFC-23 (hydrofluorocarbon)	12000	14800	12200
Sulfur hexafluoride	16300	22800	32600

Although the environmental impact of stabilisation has been considered by Oti et al. (2009) only Reddy (2004) has quantifiably considered how a stabilised earth construction compares against an equivalent construction with fired brick masonry wall. The suitability of a stabiliser is normally based only on the maximum compressive strength and greatest durability characteristics. Considering the intended use of the earthen material would allow for greater resource efficiency. The optimum amount of stabiliser used could then be defined as the minimum amount required to provide sufficient strength and durability.

This paper discusses the environmental impact of various methods of stabilisation. The paper will consider rammed earth, Compressed Earth Blocks (CEBs) and extruded earth bricks. Perforated blocks and bricks are common in many European countries but perforations will change mass, density and net compressive strength. Only monolithic rammed earth and solid blocks and bricks are only considered for ease of comparison and clarity. The focus will be on the embodied energy and GWP rather than a full life cycle analysis being undertaken.

Materials and Methods

Unstabilised Wall Construction. Although vernacular techniques such as adobe and cob have demonstrated the potential for earthen construction, wider impacts are likely to come from modern techniques that can be easily adopted within the mainstream building sector. Modern earth masonry including extruded earth bricks and CEBs have significant potential to be used within mainstream construction while interest for rammed earth has been predominantly due to to the aesthetics.

The embodied energy and GWP are typically expressed per unit mass or volume. These materials will be used for the construction of load bearing walls that could have varying thickness and density. To be able to compare the environmental impact, it would be of greater use to represent the impact with respect to wall area, as this would be the constant for identical constructions (Table 2). The environmental impacts of transportation have not been included as this allows for a cradle-to-gate analysis and better comparison.

Reddy and Kumar (2010) states that there are three sources of embodied energy within a rammed earth wall. These include transportation, mixing and compaction of the soil. Ignoring the energy required for transport values varied from 0.17 to 7.43MJ/m^3. Although the wall thickness increased from 200mm to 400mm respectively, the significant contribution was the addition of mechanical mixing. The energy from compaction in both cases is insignificant due to manual processes being used. Hammond and Jones (2011) considered a non-specific rammed earth construction, assuming a density of 2000kg/m^3 which gives an embodied energy of 900MJ/m^3 and GWP of 46 kg CO$_{2eq}$/m^3.

There is limited data on the environmental impacts of CEBs. Reddy and Jagadish (2003) discusses the environmental impact of stabilised CEBs and comments the significant proportions of embodied energy us attributed to the inclusion of cement. Assuming a linear relationship between the embodied energy and cement content an unstabilised CEB would have and estimated embodied energy of 154 MJ/m^3.

The manufacturing process of fired clay bricks prior to firing is also suitable, without any significant modification, for the production of unfired earth bricks. Morton (2006) demonstrated that there is an 86% saving in embodied carbon compared to conventional fired bricks.

Table 2 shows how conventional methods of wall construction, including fired clay bricks, Autoclaved Aerated Concrete (AAC) blocks and dense concrete blocks compares with earthen wall constructions. Values of conventional methods are provided through the use of two databases that are referred to as ICE (Hammond and Jones, 2011) and Ecoinvent (Hischier et al. 2010). Although there will be a range of values that will depend on the assumptions made, these average results are meant to be considered indicatively rather than precise quantities. Allocation has not been considered for this study, although depending on the type of allocation, for example mass or economic, there can be significant variability with respect to the embodied energy and GWP (Habert et al., 2011). Descriptions of the various method of allocation used for the ICE and Ecoinvent databases can be found in Hammond and Jones (2011) and Frischknecht et al. (2005). Where standard values are assumed a range of wall thicknesses are used to calculate the effect on the environmental impact.

Table 2: Environmental impact for different wall constructions

Wall Construction	Wall Thickness [mm]	Embodied Energy [MJ/m^2]	GWP [CO_{2eq}/m^2]	Source
Fired clay	100	535.5	42.9	Ecoinvent
	100	600	44	ICE
AAC block	100	217.5	26.1	Ecoinvent
	100	220.5	15.1-23.0*	ICE
Dense concrete block	100	152.2	22.3	Ecoinvent
	100	161.9	20.9	ICE
Rammed Earth	200	0.03	-	Reddy and Kumar (2010)
	400	2.97	-	
	200	180	9.2	ICE
	300	270	13.8	
	400	360	18.4	
CEB	190	29.3	-	Reddy and Jagadish (2003)
Extruded Earth Masonry	100	77.5	6.0	Ecoinvent and Morton (2006)
	200	155.0	12.0	
	300	232.5	18.0	
	100	84	6.16	ICE and Morton (2006)
	200	168	12.32	
	300	252	18.5	

**only CO_2 value used*

As shown in Table 2, there is broad agreement with the ICE and Ecoinvent databases, with thicker (300mm) earth walls approaching the values for 100mm concrete blocks. The values for rammed earth from Reddy and Kumar (2010) vary considerably from the ICE database, most likely because of the manual compaction and mixing assumed by Reddy and Kumar (2010). The ICE database values are based on more general compacted soil and are not specific to the rammed earth process and all results and conclusions for rammed earth should be considered with the variability in input data. In this work, there was no allocation of energy for labour based construction, but this aspect is highly contentious and beyond the scope of this paper.

Stabilisation Methods. Stabilisation offers a method of improving the inherent properties of soil. Typically stabilisation is used to increase the compressive strength. Heath et al. (2012) demonstrated the structural potential for the earthen construction of 100mm thick bricks to remain unstabilised when considering typical conditions. Although the units only had a compressive strength of 3 N/mm^2, similar to AAC blocks with a compressive strength of 2.9 N/mm^2, European design codes were used to demonstrate the suitability for a two story domestic house.

Under extreme moisture conditions where these bricks undergo full saturation by submersion in water, the bricks lose all strength and disintegrate (Maskell et al., 2012). Full submersion may be considered as too harsh and not representative of in-service conditions. Testing under this conditions will give confidence, as saturated performance of earth masonry remains one of the greatest barriers to commercial adoption (Maskell et al., 2012). Providing that the wall can resist an applied total load of 0.3kN/m, the justification of stabilisation is therefore not to increase the dry compressive strength, but to increase the durability so that sufficient strength is achieved under these ‘wet’ conditions.

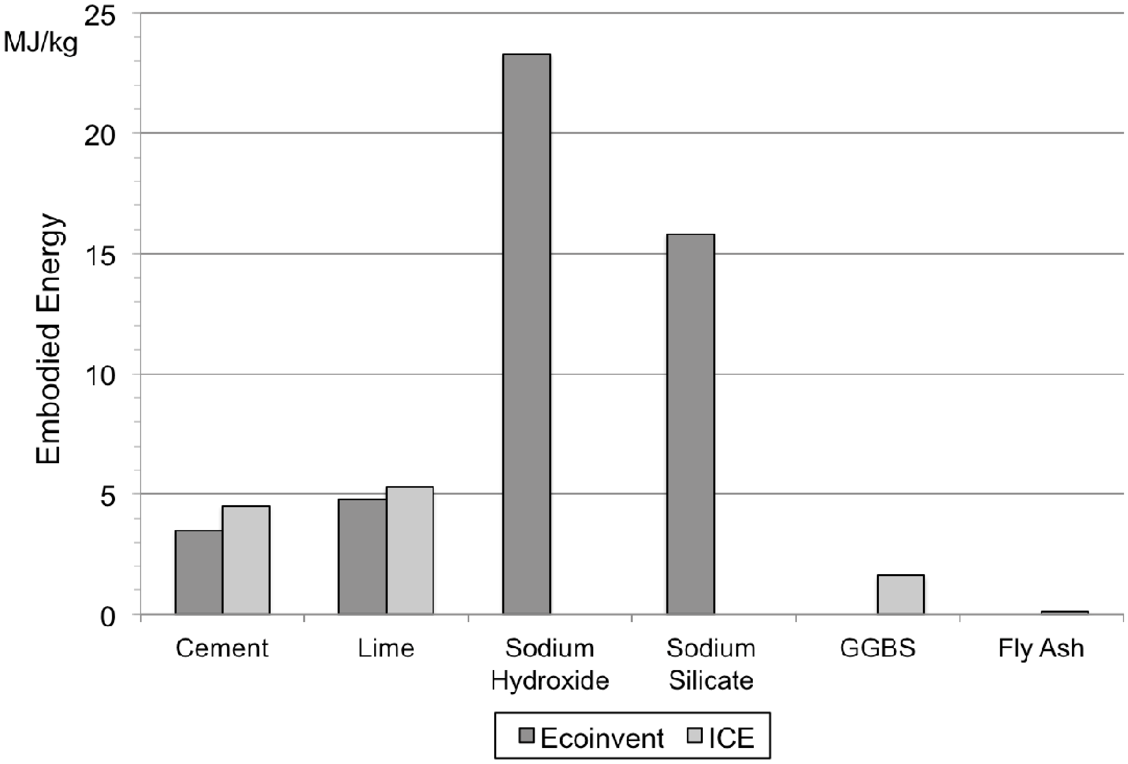
There is interdependency between the soil and stabiliser with regarding to the quantity that can achieve a maximum compressive strength. Burroughs (2008) conducted a comprehensive study of the soil property criteria suitable for stabilisation in rammed earth application. The findings show that there is an optimum particle size distribution and plasticity index for soil to be stabilised. The stabiliser will affect the physical properties of the soil including the maximum dry density and Atterberg limits. As such this will affect the energy for ramming (Reddy, 2010) and extrusion. There are additional concerns with regards to the handling of certain caustic chemicals as well as the setting time, especially when extruded. Consideration of these factors will inform the amount of additive required, while an appreciation of the environmental impact will inform if alternatives are more appropriate.

The stabilisation mechanism of cement and lime is very similar, involving cation exchange and pozzolanic reactions with cement having an additional cementitious hydration phase. The focus of recent research has been the utilisation of industrial by-products such as Ground Granulated Blast-furnace Slag (GGBS) and fly ash (Oti et al. 2009).

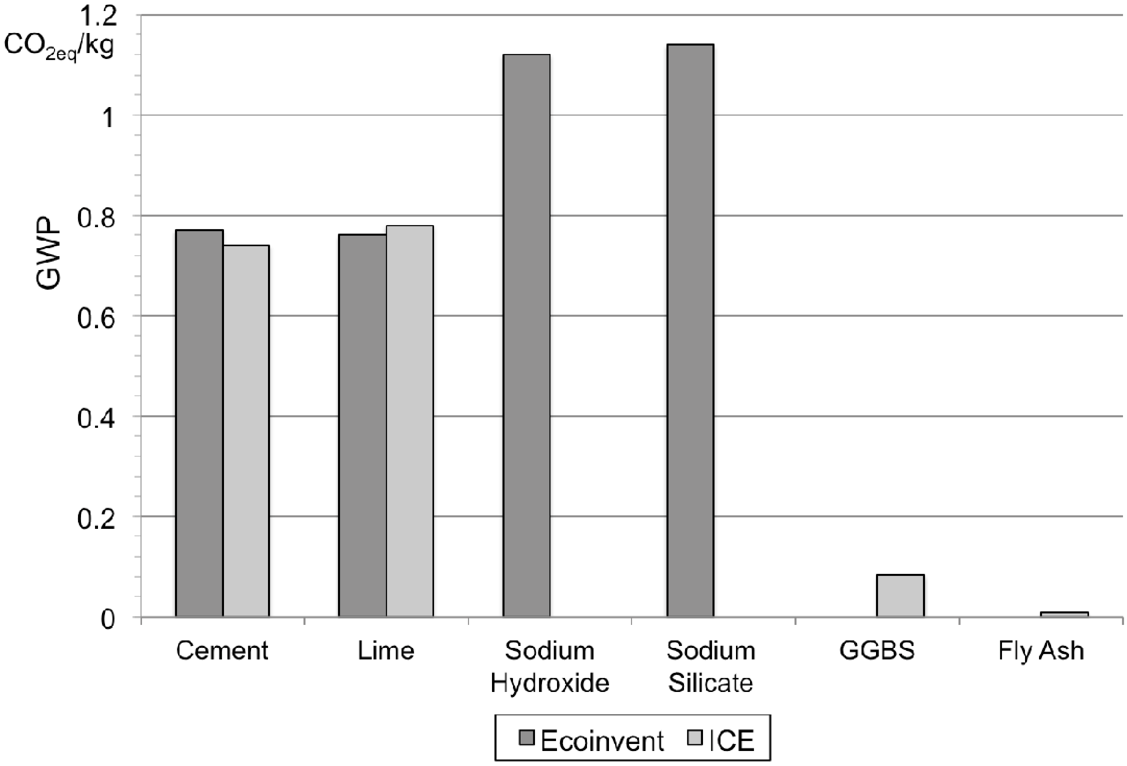
Geopolymers are a novel class of binders and can be used as an alternative to cement. Three-dimensional inorganic polymers are formed through the reaction of aluminosilicate with an alkaline solution. Natural clay minerals, that are abundant in an earthen construction, are made up of sheets of silicates and aluminium, and provide a potential source for the geopolymers. These clay minerals are activated through using sodium or potassium hydroxide and/or sodium silicates.

Heath et al. (2012) summarised the beneficial environmental impact that geopolymers based concrete has compared to concrete based on Portland cement. All of the studies show that the alkaline activator is the key contributor to the environmental impact of the concrete. Heath et al. (2012) comments that the main contributor to the environmental impact of the activators is due to the electricity demand, and therefore could be reduced depending on energy generation.

Figure 1 shows data the environmental impact of the various additives discussed above. Values are expressed with respect to the mass of the additive.



a) Embodied Energy (EE) for different additives



b) Global Warmisng Potential (GWP) for different additives

Figure 1: Environmental impact for different additives

Environmental Impact Analysis

The environmental impacts of stabilised earthen wall construction can be considered with respect to Table 2 and Figure 1. The focus of this study is on techniques that can be adopted into large scale production and mainstream construction. For the UK climate this means that there is minimum reliance on labour, and therefore mechanised forms of construction will be the focus of the environmental impact analysis.

From Table 2 it is clear that dense concrete blockwork has the least environmental impact of the conventional and typically perceived high impact materials. Therefore for any alternative earthen based to be environmentally beneficial, neither the embodied energy nor the GWP can be greater than the respective values for the 100mm thick dense concrete blockwork.

The values of the environmental impacts of the different stabilisers as given in Figure 1 have been used. Where there are multiple values for any given stabiliser, the values provided by the Ecoinvent database (Hischier et al. 2010) have been used. The values were considered to be more general and less specific to the UK. From inspection of Tables 2 and 3 it is clear that there is not significant variation with respect to the values given.

The analysis only considers the environmental impact of the building materials as given in Table 2. For the masonry elements there would be an environmental impact for the mortar of the units. This is ignored with respect to the calculations.

Results and Discussion

The maximum embodied energy and GWP cannot exceed the values of dense concrete blockwork from either the ICE or Ecoinvent database; 152.2 MJ/m^2 and 20.9 CO_{2eq}/m^2 respectively. This determines both the maximum allowable wall thickness and amount of stabiliser for any given wall thickness. It is important to consider that the calculations presented below are based on data sets which have an inherent variability. As such the data presented should be considered indicative and approximate rather than absolute. Sensitivity analysis has been undertaken that discusses the potential variability.

Effect of wall thickness. Table 2 shows how the environmental impact changes for increasing thickness of unstabilised rammed earth and extruded earth masonry. The maximum thickness for rammed earth and extruded earth masonry is given in Table 3.

Table 3: Maximum wall thickness based on embodied energy

Wall Construction	Maximum Wall Thickness [mm]	GWP [CO_{2eq}/m^2]
Rammed Earth	169	7.77
Extruded Earth Masonry	196	11.76

The maximum wall thickness of the earthen walls is determined by equalising the embodied energy to 152 MJ/m^2, the value for dense concrete blocks. The calculated GWP based on these maximum wall thicknesses are provided. These walls remain unstabilised and concerns over strength and durability remain. The unstabilised rammed earth and extruded earth masonry would require a minimum strength of 1.78N/mm^2 and 1.53N/mm^2 respectively. While these strengths are feasible, both walls will loose all strength under high moisture contents and saturation.

These wall thicknesses are dependent on assumptions about the density of earthen construction and the values of embodied energy and GWP. Sensitivity analysis was undertaken based on changing these variables by ± 10% of the values given in Table 2. The maximum wall thickness as given in Table 3 could change up to ± 30% of the values given.

Effect of stabiliser content. The addition of any amount of stabiliser may have a detrimental environmental impact. The maximum wall thickness as given in Table 3 will have to be reduced to allow for stabilisation additives. A wall thickness of 100 mm for the earthen walls will be assumed. This is a comparable thickness to conventional masonry and would therefore be more likely to be adopted into contemporary construction.

Based on the 100mm thickness and assuming the densities do not significantly change with additive addition the maximum amount of additive can be calculate and is presented in Table 4. The maximum additive content is determined by equalising the embodied energy to 152 MJ/m^2. The additive is quantity is expressed as a percentage of the mass of dry soil. Although the environmental impacts of GGBS and Fly Ash were provided in Figure 1, there maximum amount of that could be used has not been calculated. These additives alone would not be able to stabilise earth, but are typically used as cement replacements. Calculations for various blends have not been presented here but it is clear that using these additives in blends would reduce the environmental impact, or allow for more of the primary stabiliser to be used.

These additive contents are dependent on assumptions about the density of earthen construction and the values of embodied energy and GWP. Sensitivity analysis was undertaken based on changing these variables by ± 10% of the values given in Table 2 and Figure 1. The maximum additive content as given in Table 4 could change up to ± 30% of the values given.

The maximum additive contents as given in Table 4 would need to be sufficient for the required strength and durability to be of practical use. It is likely that the dense concrete blockwork that was used for the analysis will have greater strength and durability properties. There are significant GWP reductions through the use of stabilised earthen construction. There is a range in GWP saving from 33% to 85% when using 6.9% cement stabilised rammed earth or 1.6% sodium hydroxide stabilised extruded earth masonry.

Table 4: Maximum additive content based on embodied energy

Wall Construction	Additive	Maximum additive content [%]	GWP [CO_{2eq}/m^2]
Rammed Earth	Cement	6.9	15.03
	Lime	5.9	13.95
	Sodium Hydroxide	1.3	7.79
	Sodium Silicate	2.3	9.93
Extruded Earth Masonry	Cement	8.3	17.94
	Lime	7.0	16.71
	Sodium Hydroxide	1.6	9.68
	Sodium Silicate	2.4	11.38

Consideration of the GWP. The embodied energy was the determining factor for the calculation of the maximum wall thickness and maximum stabiliser content. Sturgis and Roberts (2010) comments that, reducing carbon intensive energy use is more important than energy use alone. As such the GWP is a better proxy than embodied energy when contextualising the effect on the environment due to greenhouse gas emissions.

Considering that there is an argument to only consider the GWP, regardless that the embodied energy,, the maximum values as calculated in Table 3 and Table 4, can be re-calculated and are presented in Table 5 and Table 6.

Since the maximum wall thickness of the unstabilised walls has substantially increased the required compressive strength of the walls has reduced to 0.66N/mm^2 and 0.86N/mm^2 for rammed earth and extruded earth masonry respectively. Assuming that the walls achieve a greater strength than these then there would be a significant amount of redundancy and sacrificial thickness for durability concerns.

The maximum stabiliser content has also increased as expected. As these values are still based on a 100mm thick wall then the stabilised wall will still have to provide a minimum strength of 3N/mm^2 as wall resistance to increased moisture content.

Table 5: Maximum wall thickness based on GWP

Wall Construction	Maximum Wall Thickness [mm]
Rammed Earth	454
Extruded Earth Masonry	348

Table 6: Maximum stabiliser content based on GWP

Wall Construction	Additive	Maximum additive content [%]
Rammed Earth	Cement	11.0
	Lime	10.4
	Sodium Hydroxide	7.3
	Sodium Silicate	7.8
Extruded Earth Masonry	Cement	10.1
	Lime	9.6
	Sodium Hydroxide	6.7
	Sodium Silicate	7.1

Summary and Conclusions

The embodied energy and GWP of building materials is a significant contributor to the whole life footprint of a building. While the current focus is to reduce operational energy this will mean the relative effect of the embodied environmental impact will increase. This has led to the increase in interest in earthen construction, which is perceived as a sustainable material due to the abundance of soil as minimal processing. If the environmental benefits of earthen construction are going to be felt on a national and global scale then the material and manufacturing techniques need to conform to current building practices.

There has been limited research on the environmental impacts of earthen construction. A full life cycle assessment was not undertaken but the embodied energy and GWP was considered. This was expressed with respect to the elevation area of the wall. The functional unit of a building element allows for direct comparison of the environmental impact for same function, irrespective of density or thickness. A dense concrete block had a relative low environmental impact and therefore and earthen wall construction would need to better this.

Data from various sources was used for the analysis. There remain concerns over the variability of this data and the allocation of embodied energy and GWP. As such, all results should be taken as assumptions with respect to the results of the sensitivity analysis. The maximum thickness of an unstabilised rammed earth and extruded earth was calculated. Based on a 100mm wall thickness for both methods of construction the maximum content of additives were considered. The determining factor for both these calculation was the embodied energy that allowed for GWP reductions. There is an argument that the focus should be on GWP reductions, since it is the greenhouse gasses that directly effect climate change. The maximum wall thickness and additive content was recalculated and presented.

If the required strength and durability of the earthen wall can only be achieved through the exceeding the values stated, then from an embodied energy or CO_2 impact, a concrete block would provide advantage. The maximum additives calculated are larger than those typically used in literature and therefore present a structurally sufficient and lower embodied environmental impact option. This indicates that stabilising a thin earth wall may present embodied energy or CO_2 advantages over using concrete blocks or using a thicker earth wall. There are, however, numerous other advantages to using earth, including potentially reduced transportation impacts, the ability to buffer temperature and humidity (especially in thick walls), architectural reasons and the development of local skills in the community. A full life cycle profile would consider the impact of the choice of material has on a number of different areas. A suitable mix design, appropriate selection of materials and considered engineering solution will ensure that earth will have the lowest possible environmental impact.

References

[1] BIS (2010). Estimating the amount of CO2 emissions that the construction industry can influence. Supporting material for the Low Carbon Construction IGT Report. Department for Business, Innovation and Skills.

[2] Burroughs, S. (2008). Soil property criteria for rammed earth stabilization. Journal Of Materials In Civil Engineering, 20(3), 264-273.

[3] Frischknecht, R., Jungbluth, N., Althaus, H., Doka, G., Dones, R., Heck, T., Hellweg, S., Hischier, R., Nemecek, T., Rebitzer, G., et al. (2005). The ecoinvent database: Overview and methodological framework (7 pp). The International Journal of Life Cycle Assessment, 10(1):3–9.

[4] Habert, G., d'Espinose de Lacaillerie, J., and Roussel, N. (2011). An environmental evaluation of geopolymer based concrete production: reviewing current research trends. Journal of Cleaner Production, 19(11):1229 – 1238.

[5] Hammond, G. & Jones, C. (2011). Inventory of carbon \& energy (ICE). Sustainable Energy Research Team (SERT). Version, 1.

[6] Heath, A., Goodhew, S., Paine, K., Lawrence, M., & Ramage, M. (2012). The potential for using geopolymer concrete in the UK. Construction Materials.

[7] Heath, A., Maskell, D., Walker, P., Lawrence, M., & Fourie, C. (2012). Modern earth masonry : Structural properties and structural design. The Structural Engineer, 90(4), 38–44.

[8] Hischier R., Weidema B., Althaus H.-J., Bauer C., Doka G., Dones R., Frischknecht R., Hellweg S., Humbert S., Jungbluth N., Köllner T., Loerincik Y., Margni M., and Nemecek T. (2010) Implementation of Life Cycle Impact Assessment Methods. Final report ecoinvent v2.2 No. 3. Swiss Centre for Life Cycle Inventories, Dübendorf, CH.

[9] Houben, H. & Guillaud, H. (1994). Earth construction: a comprehensive guide. Intermediate Technology Publications. ISBN: 9781853391934

[10] Jaquin, P., Augarde, C., Gallipoli, D., & Toll, D. (2009). The strength of unstabilised rammed earth materials.. Géotechnique., 59(5), 487–490.

[11] Lawrence, R., Heath, A. C., & Walker, P. (2008). Mortars for thin unfired clay masory walls. In Proceedings of LEHM 5th International conference on Building with Earth, Koblenz, Germany (pp. 66--73).

[12] Maskell, D., Walker, P., & Heath, A. (2012). The compressive strength of lignosulphonate stabilised extruded earth masonry units. In Terra 2012: 11th International Conference on the Study and Conservation of Earthen Architecture Heritage.

[13] Metz, B. and Davidson, O. (2007). Climate Change 2007: Mitigation: Contri- bution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Intergovernmental Panel on Climate Change.

[14] Morton, T. (2008). Earth Masonry: Design and Construction Guidelines. IHS BRE press. ISBN: 9781860819780

[15] Morton, T. (2006). Feat of clay. Materials world, 14(1), 2–3.

[16] Oti, J. E., Kinuthia, J. M., & Bai, J. (2009). Engineering properties of unfired clay masonry bricks. ENGINEERING GEOLOGY, 107(3-4), 130-139.

[17] Reddy, B. & Gupta, A. (2006). Strength and elastic properties of stabilized mud block masonry using cement-soil mortars. JOURNAL OF MATERIALS IN CIVIL ENGINEERING, 18(3), 472-476.

[18] Reddy, B. V. V. (2004). Sustainable building technologies. Current Science, 87(7), 899–907.

[19] Reddy, B. V. V. & Jagadish, K. (2003). Embodied energy of common and alternative building materials and technologies. Energy and Buildings, 35(2), 129–137.

[20] Reddy, B. V. V. & Kumar, P. P. (2010). Embodied energy in cement stabilised rammed earth walls. Energy and Buildings, 42(3), 380 - 385.

[21] Santoni, R. L., Tingle, J. S., & Nieves, M. (2005). Accelerated strength improvement of silty sand with nontraditional additives. Transportation Research Record: Journal of the Transportation Research Board, 1936(-1), 34–42.

[22] Solomon, S. (2007). Climate change 2007: contribution of working group I to the fourth assessment report of the intergovernmental panel on climate change. Cambridge University Press. ISBN:

[23] Sturgis, S. & Roberts, G. (2010). Redefining Zero: Carbon profiling as a solution to whole life carbon emission measurement in buildings. RICS Research Report, RICS, London.

[24] Tingle, J. S., Newman, J. K., Larson, S. L., Weiss, C. A., & Rushing, J. F. (2007). Stabilization mechanisms of nontraditional additives. Transportation Research Record, 2(1989), 59-67.

[25] Walker, P. (2004). Strength and erosion characteristics of earth blocks and earth block masonry. Journal Of Materials In Civil Engineering, 16(5), 497-506.