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Minimizing the Carbon Footprint by Using Rammed Earth Technique

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Abstract
The construction sector holds a large of share in carbon dioxide emissions. in pursuit of minimizing the carbon footprint, it started applying new building techniques and employing environmentally friendly materials One of those applications is rammed earth wall which was originally a traditional construction method that uses soil as the main material. The purpose of this study is to propose the rammed earth technique as an alternative approach for minimizing carbon footprint. It is also discussed its thermal behaviour and required energy to construct. The advantages and disadvantages are stated accordingly. This paper help architects to rethink the traditional techniques which use soil as the main material and how they can reuse it in their design of more sustainable buildings. As a result, minimizing the carbon footprint in the built environment.
Keywords: Rammed Earth; carbon Footprint; Thermal Behaviour; Sustainability; Embodied Energy.

1. Introduction

Especially in this recent century, climate change has a global effect on nature resulting in disasters more than before, such as floods, fires, and earthquakes. For this reason, scientists initiated numerous researches to sustain life in our planet and minimize the carbon dioxide emissions in various fields. On the other hand, many cities require reconstructions because of urban decay, post-disaster, and post-conflict/war. Reconstruction processes requires also high amount of energy resulting mass carbon dioxide emissions. This process is slightly different from a regular construction since removing the rubble and finding suitable building materials that are compatible and affordable with the existing conditions due to lack of resources and high prices. Another challenge is to protect the built environment from pollution during the reconstruction

The construction sector is directly in charge of carbon dioxide emissions and holds a large share. of 19% of global greenhouse gas (GHG) emissions (Intergovernmental Panel on Climate Change (IPCC) (Venkatarama Reddy, 2009, July 19) (Stone, 2015, November 2) In pursuit of minimizing the carbon footprint, various construction techniques and environmental friendly materials are employed. One of these techniques is rammed earth which was a traditional construction method using soil as the main material. Rammed earth technique has been employed for thousands of years and currently it is still applied. Recently, it is started to gain popularity in many places around the world as a result of its sustainable features.

The main purpose of this paper is discussing the rammed earth technique as sustainable application and its potential to reduce carbon dioxide emissions. the construction sector consumes energy and emits carbon dioxide in four stages. The first stage is material production process, where a large amount of energy is consumed. This is called the embodied energy. The next stage is transferring the building materials from the suppliers to the construction site. The third stage is the construction process itself. The last stage is the energy consumption that extends to the entire life cycle of the building through adaptive building systems. Rammed earth is a good alternative in at least two stages because it is locally available, considerably less amount of cement is required compared with reinforce concrete constructions. Additionally, it performs as a natural insulation material.

In this study it is researched an addition of waste materials to the rammed earth mixture such as building rubbles and plastic materials. The further step would be creating alternatives of these mixtures and test them in terms of thermal behaviour and structural integrity. Several studies were conducted in line with similar concerns. They are mainly about the thermal behaviour of traditional rammed earth buildings underlining its thermal performance and arguing advantages and disadvantages of rammed earth, which used traditional methods and materials (clay soil, silt and sand). One study in Rabat, Morocco searched the thermal behaviour of traditional rammed earth technique by comparing it with contemporary reinforced concrete structures (Cheikhi, W., Baba, K., Lamrani, S. M., Nounah, A., & Bahi, L., 2018, January 1). The other is conducted in Australia comparing rammed earth building energy performance with the case of insulation material adding's (Soebarto, 2009, January 1) However, there are no studies combining waste materials to the rammed earth mixture in order to enhance its sustainability and reduce the carbon footprint.

2. The History of Rammed Earth Technique

Rammed earth technique has been employed for thousands of years until today. Now, it is experiencing a rebound in many places around the world as a result of its sustainable features. The rammed earth is possibly generated in Asia specially in China and around the Mediterranean, with an extension to many other destinations by the human circulation happened for various reasons making this technique to be developed in various regions independent from each other. This resulted in variety of applications in different places around the world, also scattered with the motion of humans. (Jaquin, 2012) (Gramlich, 2013)

"The ancient houses mainly the caves, and the first earth constructing may have been occurred in enhancing the living conditions of caves like adding piles of earth at cave gateways or pits drill into the land. Rammed earth needs a blend of clay soil, silt and sand. Not each material can be found in the vicinity of the ancient houses. So, the earth mixtures are a changed according to the locations. On the other hand, mountainous areas, where are no sand, clay and silt to be establish together. For this reason, rammed earth is construct at the borders of major river valleys, in mountainous areas where icy till is found, and sometimes on plains." (Jaquin, 2012)

3. Defining Rammed Earth

The idiom of rammed earth has used to characterization a large number of various processes involving the dynamic pressure of soil to shape a solid body. This has driven disruption and misdescription between its users. For this reason, there are three main featured processes are summarized. (Gramlich, 2013)

1) The floor construction with rammed earth, where pressure large area to reach the same level,
2) Lifting piles or creating platforms on the landscape with RE again with applying pressure to soil mixture. earth would be taken from the vicinity, put, mixed, and pressured to rise the height of an area. This process is also seen in the guard fences.
3) Constructing walls by formwork boards installed in the limits of the intended wall space, filled with the RE mixture and applying pressure to the mixture. This method differs from the second method by staying open above land.

4. The Rammed Earth Process

In the wall construction two types of formworks are mainly employed: wooden and metal bearing high pressure. after installing the formwork in the appropriate place, the first layer of the wet soil mixture is placed and the moist soil is compacted by a manual method or by using a machine, in normal about 50% of the original mass shrink. Then to be sure that the pressure is sufficient enough, second plate is added, which is 15 cm of the same mixture, this process is repeated until the required length of the wall is reached, and then leave the wall until it dries completely. Usually, different formworks are constructed for the floors, the foundation, the roof, and sometimes even for garden decoration, and it is constructed on the construction site. (Gramlich, 2013)

A wall is created from this process consisting of layers of earth. This shape was not desirable in the past as it was covered with layers of plaster or paint, but now it has become acceptable and sometimes some colours are added to each layer offering a variety of textures and gradient colours. (Gramlich, 2013)

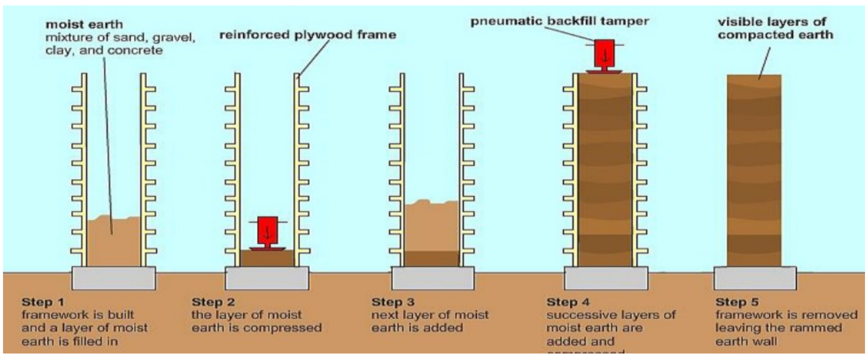

Figure 1. Section views of the compaction process for rammed earth construction. Drawing from "How rammed earth works" by Earth & Sun Construction (Gramlich, 2013)

5. The Main Material in Rammed Earth Building (Soil Analysis)

The basic component of rammed earth buildings is the soil present at the construction site. For this reason, the type of soil has a decisive role in determining whether or not the building is feasible, or sometimes the soil needs to be added with supporting materials such as cement that help to stabilize it. And these are all dependent on the proportions that make up the soil ingredient and the size of the soil grains. As the soil is divided into two parts, the first is physical, which depends on the size of the substance, and the second is chemical, which depends on the constituent materials, a typical earth substance divides into various components: boulders, cobbles, gravel, sand, silt, and clay. In rammed earth application, we are only interested in gravel, sand, silt, and clay. There are two techniques to make Rammed Earth cohesive (Krahn, 2019).

5.1. First technique: The Volume Border Between Substances

Whereas, the researchers have determined acceptable sizes among the materials, depending on the study of the properties of the material, and the book RAMMED EARTH CONSTRUCTION (Krahn, 2019) provides the author with a comprehensive explanation on this topic as he has specified the acceptable sizes for the materials, for example : gravel 2-20 mm diameter (for durability in the macro-ground skeleton); coarse to fine sands 0.06-2 mm (to fill larger voids between the gravel particles); silts 0.002 -0.06 mm (to further fill in voids); and clays from 0.002 mm and down (to act as our non-cementitious binder). (Kra)

5.2. The Second Technique: The Attachment Quality of Clay

The book explains the bonding property found in clay, as the clay is composed of particles of silica and alumina, and these particles are electrically charged and grouped together by hydrogen bonds or ionic bonds. And when water is added, the bonds with the mud become strong as the water has polar properties.

It can be seen that is the presence of water in the clay matrix - under natural warmth and atmospheric compression conditions, it is almost impossible to completely remove all the water from the clay pattern because the underlying electrical charge ingrained in those particles. (Krahn, 2019)

There are some simple site experiments that help determine whether the soil contains adequate amounts of clay or a good quality of clay to aid in the construction process or that other materials must be added such as cement reinforce bonding of the mixture. Some of these tests are: smell test, taste test, ball drop test, slap test, roll test. Each test has a specific goal and purpose, and then we move on to more controlled tests, one of which is the tape test, the jar test, and the pressure test.

There are two types of rammed earth buildings. The first one contains completely raw materials without adding binders such as cement, where there is an appropriate quantity and quality of clay that makes the building durable.

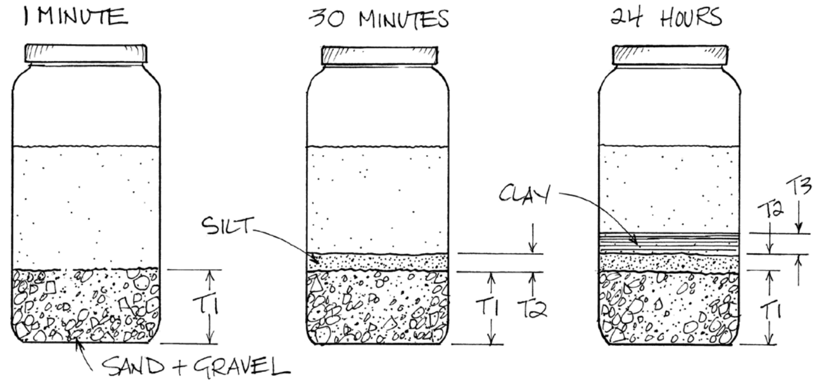

Figure 2. The Jar Test (Krahn, 2019)

The second type of building contains a low percentage or bad quality of clay, so it is forced to add binders that help to stabilize the building. As a result, there are two types of stabilized and un-stabilized rammed earth. (Krahn, 2019)

6. Analysing the Durability of The Mixtures Used in Samples of Rammed Earth

The durability and strength of the construction is an essential part of the conditions that must be met by the mixture used in the construction process. From this point, the researchers launched many studies that compared the different mixtures, depending on the quality of the soil and the type of bonding materials added to the mixture.

Among these studies, a research conducted at California Polytechnic State University, where researcher Nicholas J. D'Ambra (D'Ambra, 2016) talked about the usability of the soil found in the city of San Luis Obispo, where he studied three different soil samples containing different proportions of materials as one sandy, two clayey sands, and two clayey sands (dark yellow brown). Then Portland cement was added, about, about 7% of the mixes. The samples were left for about a week to dry and be ready for the compression analysis. the samples were tested in the laboratory and the results are given in the table .1. It shows us that the first two samples displayed lower resistance to compression, while the third one was able to achieve better durability than the rest, and this confirms that not all types of soil are usable.

Table .1 Compressive Testing Results (D'Ambra, 2016)

Sample #, Description	P.S.I.
1, Clayey Sand	179
2, Clayey Sand (Dark yellowish brown)	179
3, Sandy Clay	250

Another study by two researchers, (Shakya Binod, 2015) where different samples were prepared from two types of soil, the first one is a black cotton soil and the second one is a sandy-clayey soil, each one containing different proportions of sand and gravel, after that eight samples of the mixture were prepared with or without adding cement or dung. The table show portions for each sample.

Table 2. Ingredient content for preparation of samples (Shakya Binod, 2015)

Mix type	Clay < 1.7 mm	Black cotton soil < 1.7 mm	Sand < 4.75 mm	Gravel < 12.5 mm	Cement	Dung
A.	20 %	–	60 %	20 %	5 % added in total mix	–
B. For colour variation individual mix of clayey soil (20 %), black cotton soil (20 %) and red soil (20 %) separately with 60 % sand, 15 % gravel and 5 % cement						
C.	20 %	–	60 %	15 %	5 %	–
D.		20 %	60 %	15 %	5 %	
E.	25 %	–	60 %	15 %	–	5 % added in total mix
F.	25 %	–	60 %	15 %	–	10 % added in total mix
G.	25 %	–	60 %	15 %	–	–
H.	20 %	–	60 %	20 %	–	–

The results of this study showed varying durability of the samples depending on the ratios and types of additives such as cement and dung. Also, the possibility of using organic materials to achieve certain durability, but appropriate conditions and proportions of soil must be determined and taken into account the surrounding climatic conditions such as rainfall and others (table 3.)
the results of the compression tests showed the highest durability of A mixture where they used 20% clay, 60% sand and 20% gravel also they added 5 % cement in total mix.

Table 3. Compressive Testing Results (Shakya Binod, 2015)

Sample no.	Density (kg/m^3)	Rebound hammer test 1st, 2nd and 3rd rebound no. values	Destructive compressive test: Ultimate load (KN)	Peak displacement (mm)	Ultimate strength (MPa)	Mean strength (MPa)	Characteristic strength (MPa)	Mix type (Refer Table 1)	Category
1	2305.26	12, 12 and 14	101.5	6.2	10.15	7.78		A	Cement-stabilized samples
2	2135.00	10, 12 and 12	71.5	5.2	7.15		6.48		
3	2350.00	10, 10 and 12	60.5	4.6	6.05				
4	2211.77	12, 10 and 12	77.0	10.3	7.70	7.02		B (colour variation)	
5	2195.00	10, 12 and 12	68.5	8.9	6.85		5.86		
6	2188.89	10, 12 and 12	65.0	8.7	6.50				
7	2150.00	12, 12 and 12	70.5	8.8	7.05	6.73		C	
8	2135.00	14, 12 and 10	66.5	9.1	6.65		5.61		
9	2135.00	10, 10 and 10	65.0	9.2	6.50				
10	2152.94	No value	35.5	10.2	3.55	3.75		C (no curing)	
11	2160.00	No value	40.5	7.8	4.05		3.12		
12	2121.05	No value	36.5	8.5	3.65				
13	2172.22	14, 14 and 16	58.5	7.1	5.85	5.68		D (black cotton soil used)	
14	2206.25	10, 10 and 10	56.5	6.1	5.65		4.73		
15	2194.44	No value	55.5	5.1	5.55				
16	2183.33	12, 18 and 12	44.0	4.5	4.40	3.90		D (black cotton soil used-no regular curing)	
17	2152.94	10, 10 and 10	41.0	10.8	4.10		3.23		
18	2023.53	10, 12 and 12	32.0	11.3	3.20				
19	2190.00	No value	52.0	14.2	5.20	3.89		E	Dung used samples
20	2345.00	No value	43.0	6.3	4.30		3.24		
21	2200.00	No value	31.0	7.2	3.10				
22	2080.00	No value	29.5	15.1	2.95				
23	2030.00	No value	28.0	8.2	2.80	2.58		F	
24	1970.00	No value	26.5	7.8	2.65		2.15		
25	1945.00	No value	23.0	8.9	2.30				
26	2215.79	No value	24.0	7.2	2.40	1.88		G	Un-stabilized samples
27	2152.63	No value	17.5	7.4	1.75		1.57		
28	2015.00	No value	15.0	4.3	1.50				
29	2278.95	10, 10 and 10	31.0	4.8	3.10	2.92		H	
30	2236.84	No value	30.0	5.0	3.00		2.43		

One of the ways to reduce CO_2 emissions is to use recycled materials such as plastic materials or reuse building rubble, which may help reducing pollution caused by rubble and recycle these materials. One of the studies dealt with the use of building rubble in rammed earth technology, where the study (Alessandro Arrigoni . Christopher T.S. Beckettb, 2018) found that building rubble can be used with engineered soil where the proportions and elements of the materials used in the formation of soil are determined. The results of the compression test showed acceptable strength and durability according to the Australian code, and this is shown in the following Table 4.
The unmodified normal soil showed lower rates of strength in the comparison analysis. It appears from this study that the building rubble can be used in the construction process of rammed earth under certain conditions and circumstances.

Table 4. Overview on the different mixtures (Alessandro Arrigoni . Christopher T.S. Beckettb, 2018)

Table 1
Overview on the different mixtures analysed. wt. % indicates the weight percentage of dry substrate.

GROUP	MIXTURE	SUBSTRATE			ADDITIVES		Optimum Water Content (OWC)	Maximum Dry Density (MDD)	Coefficient of uniformity	Coefficient of curvature
		RCA (Sieved (S)/ Non-Sieved (NS)) [wt. %]	Engineered Soil (ES) [wt. %]	Crushed Limestone (CL) [wt. %]	Cement (CEM) [wt. %]	Fly Ash (FA) [wt. %]	[%]	[g/cm^3]		
1	100CL + 7CEM	–	–	100	7	–	8.2	1.97	3.4	1.1
	75CL + 7CEM	25 (S)	–	75	7	–	11.7	1.93	17	0.2
	50CL + 7CEM	50 (S)	–	50	7	–	12.4	1.93	30	0.2
	25CL + 7CEM	75 (S)	–	25	7	–	14.7	1.79	22	9.9
2	100ES + 7CEM	–	100	–	7	–	6.8	2.21	9.0	0.1
	75ES + 7CEM	25 (S)	75	–	7	–	9.6	2.06	29	0.1
	50ES + 7CEM	50 (S)	50	–	7	–	10.3	2.00	89	0.6
	25ES + 7CEM	75 (S)	25	–	7	–	11.9	1.89	62	28
3	100RCA + 7CEM	100 (S)	–	–	7	–	16.0	1.79	1.4	0.8
	100RCA + 10CEM	100 (NS)	–	–	10	–	12.7	1.98	34	0.6
	100RCA + 5CEM 5 FA	100 (NS)	–	–	5	5	12.7	1.99	34	0.6

Simenson (SIMENSON, 2011) has conducted his thesis at University of Colorado Denver. The research was about the possibility of using plastic fibres in rammed earth technology. The researcher prepared three different samples. In the first one he used soil without adding binders, the test showed that the soil was not suitable for building directly without adding binders. As the results of the tests showed a weakness in the durability of the sample. For the second sample the cement was added as a basic binder, the results of the compression test showed high durability in accordance with the required code. For the third sample, the cement and plastic fibres were added, and pressure test showed a slight increase in the durability of the sample than the former one. We conclude from this study that the use of plastic fibres did not have a significant effect in terms of sample durability (Table 5.). (SIMENSON, 2011).

Table 5 Compressive Testing Results (SIMENSON, 2011).

Table IX.1 Unconfined Compressive Strength for Soil Samples.

Soil	
Sample	Pressure [psi]
1	53
2	74
3	64
4	68
5	66
6	67
Average Strength [psi]	65
Std. Deviation [psi]	7
COV	0.11

Table IX.2 Unconfined Compressive Strength for Soil-Cement Samples.

Soil-Cement	
Sample	Pressure [psi]
1	732
2	806
3	766
4	632
5	634
6	651
Average Strength [psi]	704
Std. Deviation [psi]	75
COV	0.11

Table IX.3 Unconfined Compressive Strength for Soil-Cement-Fiber Samples.

Soil-Cement-Fiber	
Sample	Pressure [psi]
1	766
2	735
3	720
4	716
5	658
6	655
Average Strength [psi]	708
Std. Deviation [psi]	44
COV	0.06

7. Embodied Energy of Rammed Earth and Other Construction Materials and Building Systems

Consumption of the energy in buildings divide into two mains parts: first one is embodied energy (primary energy) which relays on the kind of construction materials and techniques implemented, the second part is the energy which consumes by the building (thermal behaviour) during its operational time it highly relies on the building design and climatic conditions in a different geographical place.
Unfactored materials like earth, chalk, stone and wood are the best option for minimize carbon emissions also it has a possibility for recycling and reusing. And rammed earth is one of these techniques which uses natural materials like soil.
There are two kinds of rammed earth buildings: first one is raw rammed earth where it is built by mainly earth, chalk, sand and gravel without adding any isolation or binding materials such as lime, hay, or cement. This type is nearly zero carbon emissions. The second type is a stabilized rammed earth which use additional binding materials and

isolation materials which may result in lower amounts of carbon footprint. the again, it cannot be compared with other types of materials as it is given in table 6. The study shows different types of building elements built with different materials, and focuses on embodied energy in different walling and flooring/ceiling systems. (Venkatarama Reddy, 2009, July 19)

Table 6 Embodied energy in diverse parts of building elements. (Venkatarama Reddy, 2009, July 19)

Type of building element	Energy per unit (GJ)
Burnt clay brick masonry (m3)	2.00–3.40
SMB masonry (m3)	0.50–0.60
Fly ash block masonry (m3)	1.00–1.35
Stabilized rammed earth wall (m3)	0.45–0.60
Unstabilized rammed earth wall (m3)	0.00–0.18
Reinforced concrete slab (m2)	0.80–0.85
Composite SMB masonry jack-arch (m2)	0.45–0.55
SMB filler slab (m2)	0.60–0.70
Unreinforced masonry vault roof (m2)	0.45–0.60

The table shows that burnt clay brick masonry is the highest in terms of embodied energy, with its value ranging between 2.00 - 3.40. The unstable rammed earth building is also the lowest in terms of embodied energy, as its value ranges between 0.00 - 0.18 while the embodied energy for stable rammed earth buildings is 0.45 - 0.60 and it is considered a good value compared to burnt clay brick masonry. (Venkatarama Reddy, 2009, July 19)

8. Compared Between Rammed Earth and Concrete Building as Thermal Behaviour

For the last a few year's rammed earth become more popular in sustainable applications, which has the potential to reduce the energy consumption of buildings and enhance their energy performance. For this reason, numerous studies were conducted that compare energy performance between common concrete and rammed earth buildings. One of these researches were in Rabat, Morocco where they studied two different types of buildings. The first one was a traditional rammed earth building, completely constructed with the method of rammed earth, and the second one was built of concrete and masonry. In order to analyse the thermal behaviour of these buildings, the researchers used a dynamic thermal simulation software which is in this case Design Builder. The result of using this program helped them to take out warmth diagrams, a measurement of the warming and cooling necessarily. Table 7. Show the temperatures performance in both building. (Cheikhi, W., Baba, K., Lamrani, S. M., Nounah, A., & Bahi, L., 2018, January 1).

Also, table 7. shows that the walls and roofs of the rammed earth building displays less heat loss than the other masonry building. In addition, the table shows the annual energy demand on heating and cooling between masonry and rammed earth building.

Table 7. Walls and roofs of the rammed earth building (Cheikhi, W., Baba, K., Lamrani, S. M., Nounah, A., & Bahi, L., 2018, January 1)

Heat loss (KW)	Masonry	Rammed earth
Walls	7,75	4,11
Roofs	2,73	1,94

Option	Heating demand [kWh/m2]	Cooling demand [kWh/m2]
Rammed earth	33.96	668.68
Masonry	49.94	507.32

These graphs show that rammed earth is a recyclable, energy-saving, environmental construction material. On the other hand, rammed earth is a material with high thermal capacity.it absorbs and stores the heat through sun rays during the day and emits it out during the night. This makes the building more comfortable and reduces the energy demand during winter. As a result, it decreases the energy consumption by an average of 30%. In order to decrease energy consumption even more the authors recommended to reduce the total rate of external ventilation holes (windows) in rammed earth building. Because the less holes there are, the more chance to building to absorb heat. Also, encourage people to utilize shading tool for south-facing windows (in northern hemisphere). All these help the building to benefit from passive solar energy practices (Cheikhi, W., Baba, K., Lamrani, S. M., Nounah, A., & Bahi, L., 2018, January 1)

9. Compared Between Normal and Isolated Rammed Earth Building as Thermal Behaviour.

In order to be confirm sustainable potentials of rammed earth and to increase its energy, a study was initiated to explore the thermal performance of two types of existing houses in Australia one that utilizes rammed earth as main wall substance and of the other utilizes rammed earth walls covered with insulation materials. (Soebarto, 2009, January 1).

As a result, interior temperature in the non-insulated rammed earth building in summer is the same as in the insulated rammed earth building of the similar design. But, in the winter season, it is observed that the insulated building is 5 degrees better in terms of thermal behaviour than the non-insulated building (Table 9).

Table 9. Summary of simulated temperatures in summer and winter between isolated and no isolated rammed earth building.

SUMMER													
		Living Room						South Bed					
		House 1		House 2		House 3		House 1		House 2		House 3	
	Outside	Sim	Mea	Sim	Mea	Sim	Mea	Sim	Mea	Sim	Mea	Sim	Mea
Maximum	41.8	32.8	33	31.5	31.8	33.2	32.3	33	32	33	31.5	30.5	28.7
Average	21.8	21.8	21.5	22.5	22.6	22.8	22.5	21.5	21.4	21.7	22.3	21.6	22.1
WINTER													
		Living Room						South Bed					
		House 1		House 2		House 3		House 1		House 2		House 3	
	Outside	Sim	Mea	Sim	Mea	Sim	Mea	Sim	Mea	Sim	Mea	Sim	Mea
Average	10.3	12.0	12.5	13.3	13.5	18.4	18.6	12.7	12.9	13.0	12.9	14.7	16.3
Minimum	3.7	7.8	7.3	11.5	10.2	13.1	15.2	9.6	10.6	10.3	10.2	10.9	14.5

In addition to that, the study found that rammed earth walls consume approximately 29% more energy per hour than insulated rammed earth walls. This means that non-insulated rammed earth buildings require more energy than insulated rammed earth buildings. However, energy consumption in non-insulated rammed earth buildings is approximately 50% less than the general consumption in the same area. (Soebarto, 2009, January 1) The data shows that the average energy consumption in the first and second homes are approximately 4,200 kWh per person per year, while the average energy consumption in South Australia is approximately 8,100 kWh per person per year.

10. Conclusions

This paper discusses mainly rammed earth buildings. Its sustainable features are summarized and various studies in terms of its structural integrity and thermal performance is reviewed under various conditions. This paper has proven the results of other studies that have shown that rammed earth can help reduce the emission of carbon dioxide in the building construction stages. Whereas, the results of the compression tests conducted on different samples of soil and mixtures showed that they comply with some of the required code standards. It also showed the possibility of using building rubbles, plastic fibres, and some organic materials with certain percentages and soil conditions. Some studies have also shown that insulated and non-insulated rammed earth is more efficient and qualified in terms of thermal insulation than common concrete buildings. However, there is a lack of study of the thermal behaviour of different samples of mixtures, such as samples that used rubble and recycled materials in addition to organic materials.

As a result, it is observed that each study conducted with only one parameter such as sustainability, duality, embodied energy, thermal capacity etc. All these studies proposed techniques to generate rammed earth buildings addressing only these particular parameters. Combining several parameters and conducting related research has the potential to further develop this technique and increase its employment. Therefore, this paper is prepared in order to initiate a new study where to achieve an optimum formula of a rammed earth mixture that has both a good thermal and structural performance.

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Conflict of Interests

The authors declare no conflict of interest.

References

Alessandro Arrigoni . Christopher T.S. Beckettb, D. C. (2018). Rammed Earth incorporating Recycled Concrete Aggregate: a sustainable, resistant and breathable construction solution. doi:https://doi.org/10.1016/j.resconrec.2018.05.025

Cheikhi, W., Baba, K., Lamrani, S. M., Nounah, A., & Bahi, L. (2018, January 1). Study of indoor performances of a building using Rammed earth. *ResearchGate*. doi:10.1051/matecconf/201714902089

Cheikhi, W., Baba, K., Lamrani, S. M., Nounah, A., & Bahi, L. (2018, January 1). Study of indoor performances of a building using Rammed earth. *ResearchGate*. doi:10.1051/matecconf/201714902089

D'Ambra, N. J. (2016). Rammed Earth Compressive Testing Using Soils From. Retrieved from https://www.researchgate.net/publication/311515831_Rammed_Earth_Compressive_Testing_Using_Soils_From_San_Luis_Obispo

Giesekam, J., Barrett, J. R., & Taylor, P. (2015). Construction sector views on low carbon building materials. *Building Research & Information*. doi:10.1080/09613218.2016.1086872

Gramlich, A. (2013). A Concise History of the Use of the Rammed Earth Building Technique Including Information on Methods of Preservation, Repair, and Maintenance |. *Semantic Scholar. Engineering.* Retrieved from https://core.ac.uk/download/pdf/36687567.pdf

Hegediš, I. K. (2017, October 31). ENERGY SUSTAINABILITY OF RAMMED EARTH BUILDINGS. *ResearchGate*. doi:10.7251/afts.2017.0917.039H

Jaquin, P. (2012). A HISTORY OF RAMMED EARTH IN ASIA |. *Semantic Scholar. Structural Engineer.* doi:Corpus ID: 39523366

Khadka, B. (2019, October 30). Rammed earth, as a sustainable and structurally safe green building: a housing solution in the era of global warming and climate change. *Asian Journal of Civil Engineering.* Retrieved from https://link.springer.com/article/10.1007/s42107-019-00202-5

Krahn, T. (2019). *Essential Rammed Earth Construction.* doi:ISBN: 9781550926514

Miller, B. (2020, March 12). 18 Advantages and Disadvantages of Rammed Earth. *Green Garage.* doi:https://greengarageblog.org/18-advantages-and-disadvantages-of-rammed-earth

Shakya Binod, K. M. (2015). Comparative compressive strength of stabilized and un-stabilized rammed earth. doi:https://doi.org/10.1617/s11527-015-0765-5

SIMENSON, E. W. (2011). RAMMED EARTH: FIBER-REINFORCED, CEMENT-STABILIZED. *Faculty of the Graduate School of the*. Retrieved from http://digital.auraria.edu/content/AA/00/00/01/56/00001/AA00000156_00001.pdf

Soebarto, V. (2009, January 1). .Analysis of indoor performance of houses using rammed earth walls. *ResearchGate.* Retrieved from http://www.ibpsa.org/proceedings/BS2009/BS09_1530_1537.pdf

Stone, C. B. (2015, November 2). Feasibility of Integrated Insulation in Rammed Earth. *ResearchGate.* doi:10.1088/1757-899X/96/1/012030

Venkatarama Reddy, B. (2009, July 19). Sustainable materials for low carbon buildings. . *OUP Academic.* doi:https://doi.org/10.1093/ijlct/ctp025