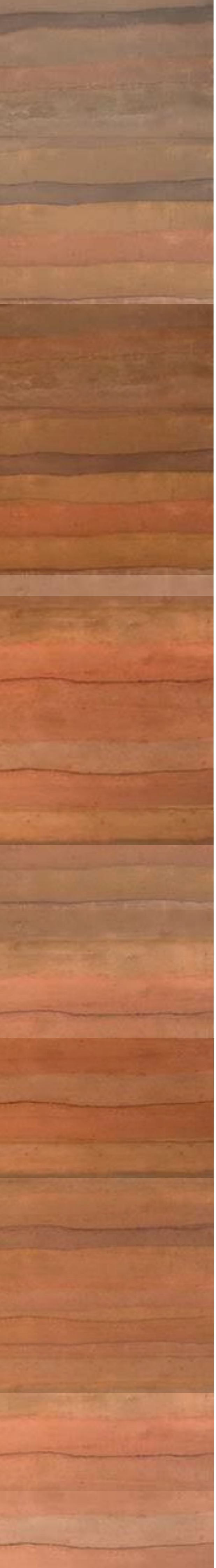

The University of Newcastle

Building a Sustainab le Future

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Supervised by

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“Education is a progressive discovery of our ignorance.”

Will Durant

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Abstract

The construction industry contributes significantly to the energy consumption of the world. Some of the most common building materials are unsustainable and their manufacturing processes account for considerable amounts of carbon emissions. Sustainable materials, such as earth, can be used a substitutes, however they must be studied to improve their reliability in order to become mainstream products. The use of these materials will maintain the environment for future generations. This project focuses on rammed earth and its combination of low embodied and operational energy. Contradictory views between energy efficiency schemes, such as NatHERS, and supporters of rammed earth have caused some speculation with regards to rammed earth's thermal performance. The thermal behaviour of rammed earth was investigated with experiments conducted with both steady state and dynamic analysis. The verdict of these tests was that rammed earth has very good thermal performance. The steady state test on the rammed earth wall produced a result for resistance capacity, similar to that which was expected, in that, it does not comply with current standards. Steady state analysis, as used by Australian energy efficiency schemes, was considered inadequate for determining the precise thermal performance of a material. Dynamic simulation takes a more realistic approach in assessing the material with conditions similar to those it will be exposed to. Therefore, it was also concluded that dynamic analysis should be incorporated into these schemes to enable materials, such as rammed earth, to be used to their full potential. With the incorporation of dynamic thermal performance, rammed earth exceeds society's expectation for energy efficiency, including both embodied and operational energy. Rammed earth is therefore is an excellent and highly sustainable substitute for energy intensive modern building materials.

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1. Introduction

Modern construction materials, such as steel and concrete, are widely used for their predictable and reliable structural properties. These materials are used for small-scale to large-scale structures, providing safe work and living spaces, however the issues associated with these materials is their high cost and their detrimental impact(s) on the environment. The intensive production of materials such as steel, concrete and masonry emit large quantities of CO_2 emissions into the atmosphere contributing to global warming. The release of greenhouse gases is not the only issue with these materials. Steel and concrete are two of the most widely used construction materials, which are sourced from iron ore and limestone, respectively, which are non-renewable resources. The material overuse and looming resource run-out are issues that are discussed in this report.

There is no one solution for an issue as large as global warming. However, there are ways of reducing the energy consumption of construction materials to preserve the environment for future generations. The use of alternative building materials for smaller scale construction can assist in achieving this reduction in energy use and also allows the stronger materials (like steel and concrete) to be saved for larger developments that require their higher strength and more predictable performance. Earth building materials employ negligible energy and therefore are appropriate resources to substitute for these high-energy consuming materials. Materials classified as earth building materials include straw bales, rammed earth, mud brick, and cob. Earth building is a construction method that has been used for hundreds of years and is currently used mainly in poorer communities. The limited research and variability of these materials is holding back their use and reliability. Further research and experimentation can lead to the development of earth building codes and thus reliable products.

This report focuses on furthering research of sustainable, renewable and environmentally friendly building materials. The aim is to unveil a wholly sustainable material that can counteract the harsh, energy-intensive processes of modern materials. This release of carbon dioxide, also known as carbon emissions, is the main contributor to global warming, making up for the majority of greenhouse gases. Sustainable, low embodied energy materials, such as earth building materials, can be ‘borrowed’ from the environment, rather than ‘stolen’ for intense processing like many modern materials. ‘Borrowed’ materials refer to natural resources that can be effectively reused or given back to the environment. ‘Stolen’ materials are those resources that are taken in their natural state and heavily processed. These ‘stolen’ materials generally are non-renewable and cannot return to their original state. Unfortunately, the scarcity of specialist earth building labourers has caused the materials to become exclusive. Rammed earth is currently considered to be high-class with it mainly being used for higher budget projects and is generally used for architectural feature walls. The exclusivity of rammed earth has driven up the economical cost of its construction and thus excluding it from mainstream construction.

The strength of earth building materials is largely dependent on the type of soil used. For these materials to achieve optimum energy efficiency they need to be built with the soil on site, however optimum strength is only achieved with the use of particular soils types. Due to the variability of soils in different areas, the strength properties of rammed earth walls; mud bricks and materials alike differ significantly.

The manufacturing processes of common building materials are energy intensive and contribute significantly to greenhouse gases. This energy is accounted for in the embodied energy of the material. The operational energy of the structure is largely made up from heating and cooling loads throughout the lifespan of the structure. These heating and cooling loads can be minimised through efficient thermal performance of building materials that store and release heat energy appropriately. Sustainable materials contain low embodied energy, however their operational energy is not entirely understood.

This report investigates the thermal performance of rammed earth and how energy efficiency is not only achieved through the production of the materials, but also throughout the lifetime of the structure. Thermal performance relates to the material’s ability to store and release heat energy. The thermal performance of building materials is described through its steady-state thermal resistance values

(R-values) and its dynamic thermal response (T-values), which relates to thermal mass. Australian regulations require particular energy ratings, which for earth building materials are either unknown or do not comply with regulations. Obtaining values for the thermal properties will allow people to understand rammed earth's thermal behaviour and thus build with it in such a way that it will comply with these energy efficiency regulations. This report includes a review of existing research on thermal performance of rammed earth and discusses the investigations that need to be carried out to understand the thermal behaviour of rammed earth walls. This understanding of thermal performance can be developed through testing with both steady state and dynamic simulations. Experiments of rammed earth's thermal efficiency were conducted in this project and the thermal results are discussed and compared to existing data of both rammed earth and other modern materials. Further research and testing is required for consistent and reliable results.

The accumulation of reliable thermal performance results will assist in producing energy efficient buildings. Ideally, structures should be designed so that thermal energy is absorbed during the day and released at night with appropriate ventilation for summer conditions. Broadened knowledge of this thermal behaviour of rammed earth will enable structures to achieve comfortable and stable indoor temperatures for living without the use of air heating or cooling.

The sustainability objective of society is to create a healthier living environment through reductions in carbon emissions. Substantial amounts of carbon emissions are created during manufacturing processes of modern building materials and therefore construction materials contribute significantly to global warming. The global community's growing emphasis on sustainability is a focus that the construction industry needs to take on board.

In Section 2 of this report, the energy crisis in the construction industry and the need for sustainable construction materials is discussed. Section 3 assesses the thermal performance of rammed earth based on existing literature. An experimental analysis of rammed earth's thermal performance was undertaken and is described in Section 4 of this report.

2. Construction Materials and the Energy Crisis: A Background

2.1. The Drive For Sustainability in Construction

Sustainability is about finding an ecological balance and reducing the impact of human activities that are harsh and detrimental to the environment. Particularly in construction, sustainability must be acquired through renewable and low energy consuming materials and operations. Greenhouse gases and global warming are the key factors driving the need for sustainability. Simple human activities, such as driving vehicles and the consumption of electricity, create greenhouse gases (Keefe, 2005). These gases absorb and retain heat, which has a substantial impact on the world's environment. It creates dramatic weather conditions such as hotter climates, less rain in some areas, and thus a reduction of available water, and also increased rain in other areas causing flooding (EPA, 2014). Greenhouse gases consist of carbon dioxide, methane, nitrous oxide, fluorinated gases and other gases. Carbon dioxide is the largest and most prominent contributor making up for approximately 55% of the world's greenhouse gases (EPA, 2014), as illustrated in Figure 1 below.

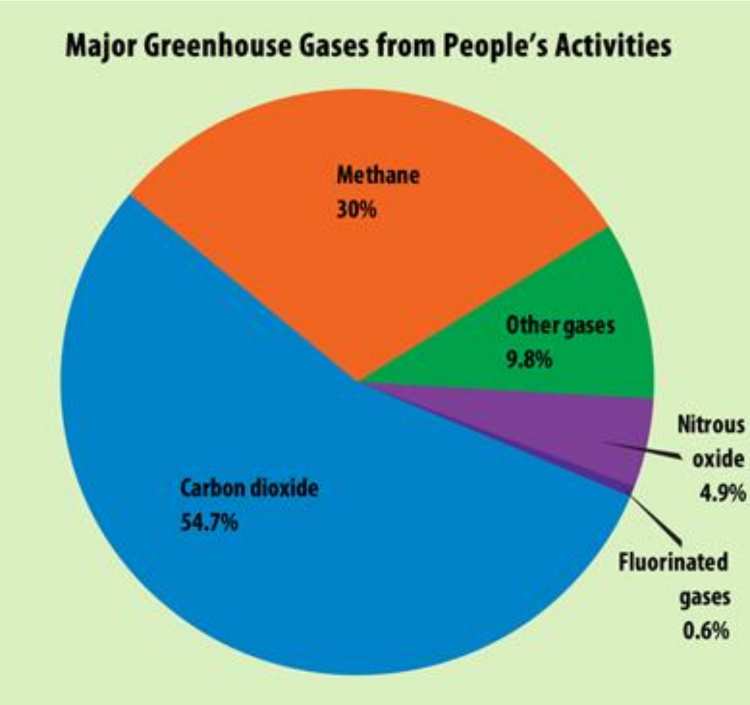


Figure 1. Greenhouse Gas Pie Graph (EPA, 2014).

The production of contemporary materials, such as steel and concrete, results in a significant percentage of the earth's carbon emissions. Since carbon dioxide makes up for the majority of greenhouse gases, a reduction in carbon emissions in the construction industry is very important and can significantly help maintain the environment substantially. With a growing population and a continual increase in development, the consumption of these reliable yet energy intensive construction materials are predicted to rise exponentially. A continually increasing amount of carbon dioxide being released into the atmosphere will eventually create an unbearable living environment with severe climatic conditions. This global warming affect has the potential to cause disastrous weather events that could be detrimental to human lives. Figure 2 shows how the concentration of carbon dioxide in the atmosphere in previous and future years, demonstrating that the growth of carbon dioxide emissions is (projected as) exponential.

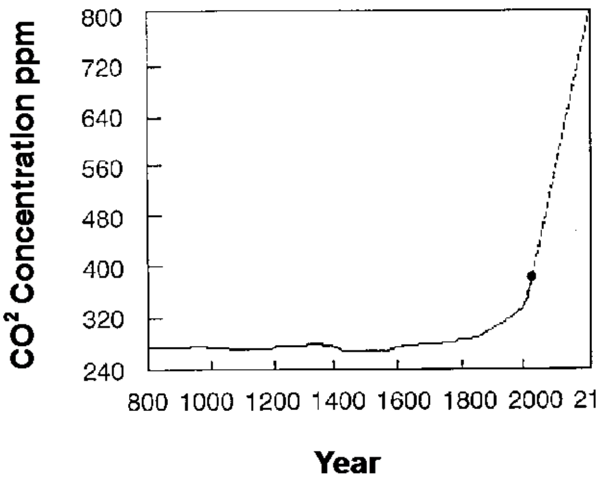


Figure 2. Past and proposed carbon dioxide concentration (Mehta, 2001).

It is important to understand this has detrimental impacts on future generations and thus solutions must be found that reduce these affects of increasing carbon emissions. Mehta (2001) provides an accurate explanation of the issue at hand:

> *"...in a finite world the model of unlimited growth, unrestricted use of natural resources, and uncontrolled pollution of the environment is ultimately a recipe for planetary self-destruction... The environment is not a minor factor of production but rather an envelope containing, provisioning, and sustaining the entire economy"*

Mehta's (2001) explanation of the problem(s) related with growing amounts of greenhouse gases helps with understanding the need and drive for sustainability. As the construction industry is a major contributor to carbon emissions, it is important to establish low energy consuming building materials and building methods.

The construction and maintenance of buildings is considered to have the greatest impact out of any other industry. The maintenance of buildings refers to the heating and cooling loads of the internal spaces of the structure, heating of water and electricity used for lighting and appliances during its operational lifespan (de Wilde et al., 2011). Research has shown that 38% of the United Kingdom's emissions has been created by construction and maintenance of domestic buildings (Keefe, 2005).

The switch to or substitution of natural materials reduces the amount of toxic chemicals and gases that are released in the environment. Smart design of houses should also be correlated with these low energy-consuming and non-toxic materials to provide appropriate ventilation and comfortable living spaces. This concept reduces the energy used throughout the life of the structure, such as the heating and cooling loads, therefore reduces the production of carbon emissions (GED, 2012).

It is also important to consider the impact of the non-renewable characteristics of contemporary building materials and how, eventually, a resource run-out will occur. It is a sustainable practice to use renewable alternative building materials today that will allow future generations to reuse these materials for newer constructions and developments, without any loss in strength. Finite resources and fuels such as iron ore for steel production, limestone for cement production, coal, oil and natural gases are all materials that cannot be wholly reused and the supply of these materials will eventually be exhausted. Since contemporary construction materials have such negative impacts on the earth, it is evident that alternatives must be found, used and researched to help sustain the environment into the future.

2.2. Modern Construction Materials

Modern construction materials are used in accordance with Australian Standards to produce reliable and sound structures. Materials that have Building Codes such as timber, steel, concrete and masonry are seen to be trustworthy and thus are popular materials. There are good reasons for the use of these materials, a significant reason being that they have excellent and predictable structural properties. The issue with some of these materials is how they are sourced, particularly with steel and concrete. Their intense manufacturing processes have a substantial impact on the environment and it will be detrimental for future generations.

2.2.1. Steel

Steel is a strong and reliable material that is one of the most common building resources with uses in both small and large scale constructions. It is used in all areas of construction, from road signposts and steel members through domestic buildings to the structural skeletons of multistorey high-rises. Steel is used so frequently, however, that the production of steel is an energy intensive process that releases vast quantities of carbon dioxide into the atmosphere.

The steel production process consists of various stages, many of which require enormous amounts of energy to achieve the extremely high temperatures. The World Steel Association (WSA) describes this process, beginning with the raw materials, such as iron ore, lime and coke, which are melted in a furnace producing a molten hot metal that contains 4 - 4.5% of carbon. This molten material is then put through a converter, again at an extremely high temperature, which blows oxygen through the molten metal and decreases the carbon content of the metal to approximately 0 – 1.5%. To produce various types of steels, the next step is to add or remove particular elements through the processes of stirring, ladle furnace, ladle injection, degassing or Composition Adjustment by Sealed argon bubbling with Oxygen Blowing (CAS-OB). Depending on the product's end use, the molten metal is then cast and formed into various shapes and sizes (WSA, 2015). This manufacturing process of steel produces approximately 6.9% of the world's carbon emissions (WSA, 2014).

Carbon emissions from steel are formed both directly, through mining and processing, and indirectly, through electricity and consumption of raw materials (Norgate et al, 2007). The energy source used for the manufacture of steel can contribute significantly to the energy consumption of the process. It was found that the coal-based electricity used to manufacture steel uses 0.96 tonnes of carbon emissions per MWh (Norgate et al., 2007). In 2010, 2500 million tonnes of carbon dioxide were released into the atmosphere from the production of steel and it is has been predicted that this will increase to 2800 million tonnes by 2050 (ULCOS, 2013). This significant increase in carbon dioxide contributes greatly to global warming and is progressively creating a inhabitable environment.

There have been technologies developed to reduce the impacts of steel's harsh manufacturing process, however these technological solutions are not entirely energy efficient and still emit carbon dioxide. Norgate et al (2007) talks of these alternate manufacturing methods, including:

- Stainless steel production by bath melting
- Titanium production by the FFC Cambridge electrowinning process
- Vertical electrode cells for aluminium production
- Switching to natural gas based electricity.

The emission of carbon dioxide is not the only concern associated with the production of steel. Iron ore, from which steel is made, is a non-renewable resource and thus will eventually run out (Norgate et al., 2007). Some areas of the world, such as Europe, are recycling scrap metals to negate this resource run out and also reduce emissions (ULCOS, 2013). It is expected that this recycling technique will reduce carbon emissions by 15% by 2050, however more dramatic approaches, involving breakthroughs in technology, are needed to achieve global goals for carbon emission reductions (ULCOS, 2013). Recycling creates less waste products however the energy reductions are not enough to enable a sustainable future. Zeumer and Bekaert (2013) discuss the issues associated with the growing steel demand and the increasing cost and volatility of steel's raw materials. They have also addressed the possibility that iron ore has reached its peak in profitability and agree that the resource will eventually run out. This is causing speculation in the construction industry and could lead to the possible shift in focus to other products and strategies to overcome the growing scarcity of raw materials, such as iron ore (Zeumer and Bekaert, 2013).

The steel industry is strong and continually growing, however the large volumes of carbon emissions and the growing scarcity of iron ore are issues that need to be addressed with either breakthroughs in technologies or material substitutes.

2.2.2. Concrete

Concrete is another common, robust and reliable material that also has environmental costs associated with it, similar to that of steel. Concrete is made up of cement, various types of aggregates and water (HubPages, 2012). Portland cement is an important component of concrete that is responsible for hardening and making the concrete impermeable (HubPages, 2012). This hardening process, known as hydration, is a chemical process that requires water for the reaction to occur (HubPages, 2012).

The production of concrete releases a large amount of carbon dioxide into the atmosphere. This then contributes to global warming, as well as the possible scarcity of cement's raw materials, particularly limestone. Rashad (2013) has recorded that 1.5 tonnes of raw material is needed in order to produce one tonne of cement. The atmosphere is not the only sufferer of this intense production process of concrete. Mining of aggregates has a significant impact on the environment with the loss of top soil and deforestation (Mehta, 2001).

It was found that concrete is the second most used substance in the world after water with approximately 3 tonnes consumed per person per year (Rubenstein, 2012). The reason for this is that concrete is such an incredibly strong resource. Reardon (2013) addresses some of the significant advantages on concrete including:

- Speed of construction (particularly with precast concrete)
- Reliable supply
- High thermal mass
- Excellent strength and structural capacity.

Despite these excellent properties, the shift in the society's focus to environmental sustainability has prompted the search for energy efficiency in construction.

The production of Portland cement is the element of concrete that causes the most significant amounts of carbon emissions to be released into the atmosphere. Cement originates from a variety of materials, including limestone, shells, shale, clay, slate, blast furnace slag, and silica sand, most of which have to be mined (PCA, 2015). The cement manufacturing process consists of these materials being heated in a large cylindrical kiln to approximately 1500 degrees Celsius to produce a substance called "clinker". This "clinker" substance is then cooled and finely ground into the end result of Portland cement. This highly energy intensive process uses the burning of coal, oil, gas or alternative fuels to create the heat in the kilns, which also contributes to the release of carbon dioxide (PCA, 2015).

The manufacturing process of Portland cement is known to be the second largest creator of greenhouse gases, which is caused by its intense production process (Rashad, 2013). Rashad (2013) states that more than 1.6 billion tonnes of cement is produced each year and is expected to grow approximately 3% per year with increasing demand. Carbon emissions that are created from manufacturing of cement are expected to double by 2020, with the global demand set to triple by 2050 (Rashad, 2013). It has been found by Mehta (2001) that the energy required to manufacture one tonne of cement is about 4GJ, producing one tonne of carbon dioxide and accounting for approximately 7% of the world's carbon emissions. The energy consumption of the Portland cement sector is recorded as the third largest in the world, making up for approximately 5% of the world's energy (Rashad, 2013). In addition to this energy consumption, the mining and transportation of aggregates contributes to the overall energy costs associated with concrete.

Admixtures for concrete are used to provide concrete with enhanced properties, however the use of these admixtures does not necessarily reduce the amount of cement needed. Therefore, these admixtures do not reduce the environmental impact of cement processes and can actually increase the embodied energy of the material significantly due to admixture manufacturing processes (Mehta, 2001).

Waste materials such as fly ash, slag, silica fume and rice hull ash are reused and combined with cement in concrete to improve specific properties of the concrete. These waste materials are produced through combustion and smelting of some sort, therefore can be just as harsh to the environment as cement. Carbon emissions are still very prevalent in the production of these waste materials (HIRL, 2001).

It is clear that the production of concrete requires a significant amount of energy consumption relating to large quantities of carbon emissions. This poses a threat to the environment of future generations and therefore solutions to reduce this impact must be found.

2.3. Energy Efficiency

Energy efficiency of a structure depends on both operational and embodied energy consumption. Operational energy is energy used during the life of the structure such as the use of heating or cooling appliances (Milne, 2013). Whereas embodied energy is the energy exerted by the production of the material up to after the structure has been built. This includes the energy required for production of the raw materials, the process of combining the raw materials to create the product, the transportation to the site and the energy exerted during the construction phase of the structure (Keefe, 2005). The transportation energy of construction materials can increase with respect to distance and type of transportation. The energy required for various types of transport per kilometre are shown in Table 2.1 below.

Table 2.1 — Transportation energy (Pacheco-Torgal and Jalali, 2012)

Transport mode	MJ/ton km
Plane	33–36
Highway (diesel)	0.8–2.2
Railway (diesel)	0.6–0.9
Railway (electricity)	0.2–0.4
Boat	0.3–0.9

The transport energy compared in Table 2.1, shows that the highest amount of energy is exerted though plane transport. Although the energy from boat transportation is relatively low in comparison, the travel distances tend to be overseas travel and therefore the journeys are much longer. With recent steel fabrication being outsourced to China, it is clear that this only adds to the embodied energy of a structure due to the long distances of shipment.

Research by Milne (2013) has shown that the embodied energy of a building can take up about 10% of the building's total energy, given that the building is proposed to have a 100-year lifespan. The CSIRO has found that this amount of embodied energy for an average house amounts to approximately 1000 GJ which is equal to about 15 years of normal operational energy (Milne, 2013). Milne compares high, normal and low operational energy and embodied energy over a 100-year lifespan of a building in Figure 3 below.

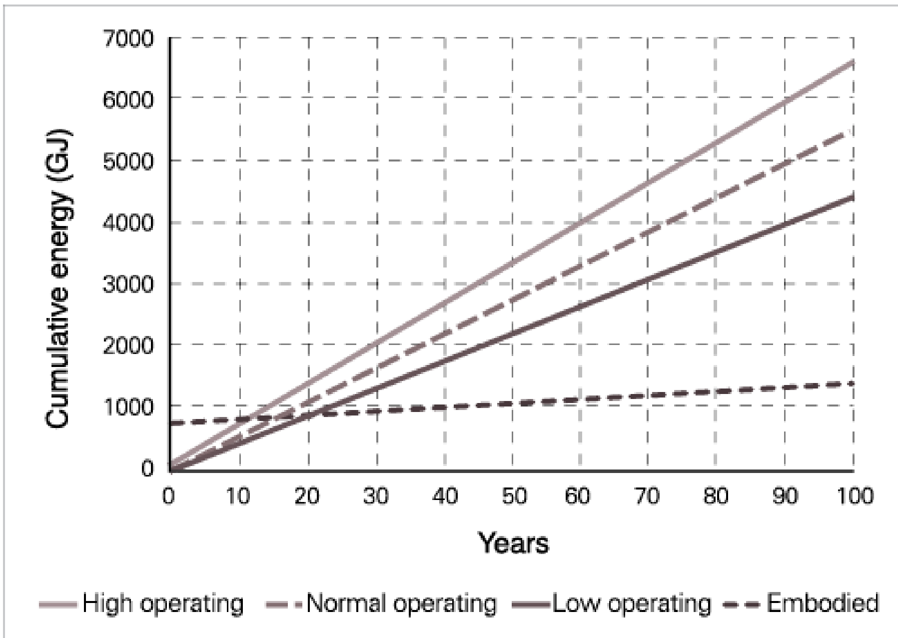


Figure 3. Operation and embodied energy comparison (Milne, 2013).

One of the major sources of this embodied energy is the production of materials like steel and concrete, which then relates to the release of carbon emissions. Not only would natural construction materials significantly reduce the levels of carbon dioxide being released into the atmosphere, they would also give off minimal to no toxic gases that some contemporary building materials produce (Keefe, 2005).

With society's current focus on conserving energy, more and more houses are being built to be energy efficient and therefore reducing the impact of the operational energy component of the structure. This decrease in operational energy instigates a higher percentage, of up to 50%, of the structure's total energy to be taken up by the embodied energy (Keefe, 2005). The drive now is to also lower the embodied energy of buildings by lowering the energy produced during the making of the construction materials.

Pacheco-Torgal (2012) has predicted that the energy demand of the world will increase by approximately 40% between the years of 2007 and 2030, due to the rising amount of people gaining access to electricity and the growing population. There is research being carried out in order to find ways of decreasing the energy associated with concrete and steel production. Metal production processes are being altered to achieve this goal of low energy consumption. Concrete processes are also being altered with by-product substitutes for cement such as fly ash and granulated blast furnace slag (Mehta, 2001). However, many more substantial changes must be implemented to achieve complete energy efficiency. If unfired earth and other alternative materials, such as mud brick, rammed earth and straw bale, can be used in construction, this can dramatically improve the sustainability of structures. Communities like the Earth Building Association of Australia are encouraging research on these alternative materials to ensure they have the structural capabilities that suit today's building regulations, and hence providing reliable materials that have negligible embodied energy costs.

2.4. Sustainable Construction Materials

Sustainable construction materials can be sourced from the natural environment or from the recycling of the mass amounts of waste produced by the society. Materials from the natural environment are centuries old and can continually be reused by future generations. Natural and earthen resources include:

- Straw bales,
- Mud brick,
- Cob,
- Wattle and daub, and
- Rammed earth.

The issues with growing consumption involving the use of plastics and non-biodegradable substances has caused large amounts of waste products being disposed of into the ground. These non-biodegradable products can be recycled for construction rather that being thrown out causing detrimental environmental impacts. Recycled materials that have been used for construction include plastic bottles and rubber tyres.

Natural and Earthen Materials

The most sustainable building materials are earth building materials. These materials have been used for centuries but have recently been neglected due to the development of stronger materials, such as steel and concrete. Rammed earth, mud brick and other earth materials are efficient materials that have been used throughout history. An example of an earth structure built with a combination of mud brick, rammed earth and compressed earth block is located in Mali, Africa, built in 1907 and is known as the largest dried earth building in the world. The village surrounding the Great Mosque of Djenne is also made out of earth and date back into the 14th century (Morton, 2014). The Great Mosque is shown in Figure 4.

Figure 4. The Great Mosque of Djenne built in Mali, Africa, 1907 (YALB, 2007).

Historical earthen buildings show signs of weathering and decay, however this is related to poor maintenance in recent years as people have moved to bigger cities and abandoned these earth structures (Bollini and Parodi, 2015). Earthen built structures require a high level of maintenance to control the erosive influences of rainfall, spalling and salts (Miccoli et al., 2014). Remains of earthen material buildings have been found in all parts of the world including the Middle East, Asia, Europe, Africa and the Americas. It has been estimated that currently 30-50% of the world's population live in earth built homes, proving that it can be used as a trustworthy construction resource (HB195, 2001). However, wealthier and highly developed areas of the world have abandoned earth materials due to the innovative, strong modern materials seen as the preferable choice. This is due to the minimal building codes available for earth materials causing it to be seen as a inferior building resource (HB195, 2001). Earthen building materials are now mainly being used by poorer and underdeveloped communities (Pacheo-Torgal and Jalali, 2012). The expertise associated with building with earth materials is a dying art due to this abandonment from modern society (Bollini and Parodi, 2015). Miccoli (2014) also agrees that the knowledge of earth building has been forgotten. Today's drive for sustainability indicates that we need to regain this expertise to drive down energy consumption levels.

Straw Bales

Straw bales are natural sustainable building alternatives that are made out of tubular stalk-like grasses composed of cellulose, hemicellulose, lignins and silica. The springy grass has high tensile strength and is quite resilient to vermin, fire and decay. The straw bales are constructed as loadbearing walls, as seen in Figure 5 below, and have a rendered earth finish (Downton, 2013a).

Figure 5. Straw bale construction (Glassford, 2015)

Straw bales are said to have good insulating characteristics with similar performance to fibreglass insulation blankets and a thermal resistance value

(R-value) larger than 10. Straw is dissimilar to hay as it cannot be used as feed and thus is considered a waste product. Using straw bales as a sustainable building material is therefore an ideal solution. Its renewable and biodegradable properties allow excess material and demolished building debris to be used as mulch. Not only are the renewable and biodegradable qualities helping the environment, it was found that the manufacturing of one tonne of concrete takes 50 times the energy of one tonne of straw bale (Downton, 2013a). Straw bale is a building material that provides a low carbon method of construction, and thus can be used to assist in reducing the carbon footprint of the construction industry.

Mud Brick

Mud brick is another material that can be 'borrowed' from the environment as it is made simply by mixing raw earth with water and placing into moulds to dry in the sun (Downton, 2013a), as seen in Figure 6.

Figure 6. Mud brick moulds (Downton, 2013a).

Mud bricks can contain fibres, such as straw, to assist with avoiding shrinkage and cracking, and, the bricks are held together in a structure with a mud mortor (HB195, 2001). Mud bricks were used to construct high rise buildings in Yemen that have been standing for centuries, proving that mud brick can be used successfully as loadbearing walls, given that the walls are the required thickness. The city of Shibam in Yemen was constructed entirely out of mud bricks approximately 1700 years ago and is still standing today (WO, 2012). This World Heritage Site of Shibam is shown in Figure 7.

Figure 7. City of Shibam, Yemen (WO, 2012).

Unlike straw bales however, mud bricks are known to provide insufficient insulation and in order to comply with the Building Code of Australia, insulation linings are required. In terms of embodied energy, mud bricks are considered to generate the lowest amount of energy out of all building materials (Downton, 2013a). Mud bricks are therefore also an appropriate alternative for the aim to reduce the world's carbon emissions.

Cob

Cob is one the oldest and simplest types of earthen building, which is made up of earth and plant fibres (Niroumand et al., 2013). The cob mixture is brought to a moisture content that is approximately equivalent to the plastic limit of the soil and the walls are built in stages of 1-1.2m high layers, allowing each layer of the wall to dry completely before the next layer is built on top (Miccoli et al., 2014; Niroumand et al., 2013). Cob is assembled in such as way that does not require any formwork or framework, other than wooden or stone lintels above windows and doors, creating moulded and curved wall shapes (Niroumand et al., 2013). The density and compressive strength of cob walls range from 1200 to 1700kg/m^3 and 0.5 to 1.5 MPa, respectively. However, these density and compressive strength values can be compromised due to the ability of rodents and insects to burrow into the walls (Miccoli et al., 2014). The remains of a cob building were found located in Phoenix, Arizona, called the Casa Grande, and was thought to have been built around 1200 to 1450 A.D. (Porter, 2010). With the majority of the building still standing after centuries, as shown in Figure 8, it is apparent that earthen building materials can be strong enough to build with.

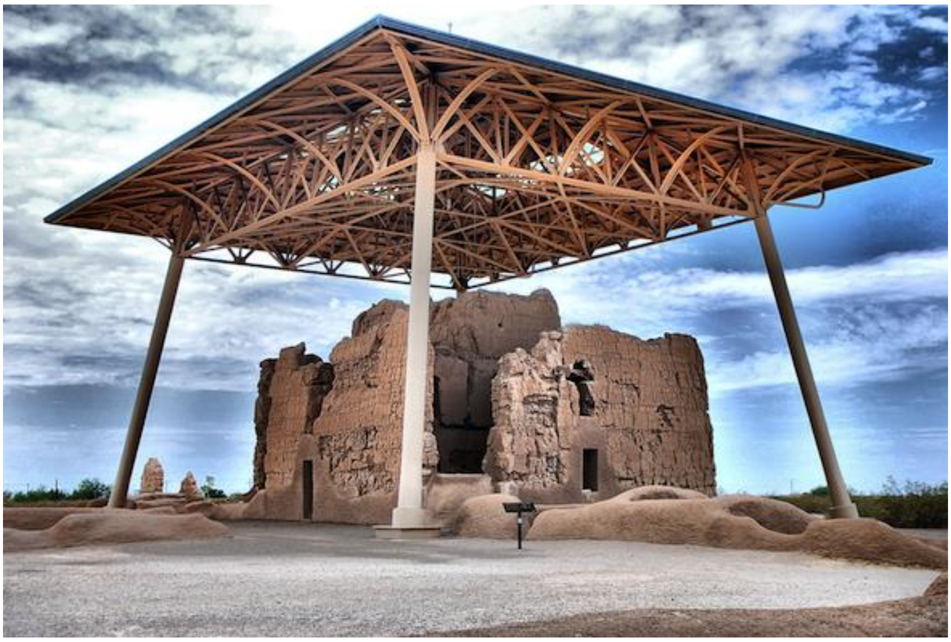


Figure 8. Casa grande, Phoenix Arizona (Porter, 2010).

Wattle and Daub

Wattle and daub is similar to cob, except that it has an additional woven structure made out of plant components on which the mud, cob-like mixture is smeared. The tree branch structural framework provides protection against destructive weather conditions, such as the harsh sun and heavy rain, and can also help resist seismic loads. The mud mixture is often based on organic materials, with materials such as dung used as a binder (Niroumand et al., 2013). This type of earthen building, shown in Figure 9, has been around for nearly 6000 years (Pacheco-Torgal and Jalali, 2012).

Figure 9. Wattle and daub earthen building (TC, 2007).

Rammed Earth

Rammed earth is a material constructed out of raw earth, which has been rammed, or compressed, in layers, to produce a dense, sandstone-like material. Rammed earth has been referred to as a man-made counterpart of sedimentary rock materials (Niroumand et al., 2013). The layering compaction method of rammed earth construction provides an appearance of layers in the wall as seen below in Figure 10.

Figure 10. Rammed earth wall (RESHI, 2015).

Rammed earth walls are built between two skins of formwork and are compacted in layer of approximately 250mm in thickness (Mahony, 2015). This formwork is removed after the construction of the wall has been completed (Downton, 2013a). Figure 11 shows the formwork used for rammed earth wall construction.

Figure 11. Rammed earth formwork (CAC, 2014).

Rammed earth walls typically range from 300mm to 600mm thick (Dong et al., 2014). Downton, 2013, states that unstabilised earth walls were traditionally built at 500mm thick with recent construction of rammed earth walls in Australia having a general thickness of 300mm, particularly for cement stabilised walls.

The relatively simple building method of rammed earth means that unskilled labour, such as those in poorer communities, can be used for construction (Ciancio et al., 2013). The Department of Housing in Western Australia has proposed this philosophy for the Aboriginal Housing program to assist those families who cannot afford extensive materials and building locations. The recruitment of unskilled labour used for rammed earth construction also helps provide job opportunities for the locals in these remote communities (Ciancio et al., 2013).

The thermal mass of rammed earth is high due the thicknesses of the walls, however the insulation properties are believed to be low and thus need additional insulation linings to comply with the Australian Building Code. This is an area that should be further researched, as supporters of rammed earth believe that rammed earth buildings provide a comfortable living space without insulation utilising its thermal mass (Taylor and Luther, 2004).

Recycled Materials

The increasing consumption of plastics, rubber and other non-biodegradable materials has led to a growing amount of waste products (Mansour and Ali, 2015). The increased demand of steel and concrete also contributes with mass amounts of by-products being produced during their intensive manufacturing processes. These waste products are being dumped into the ground creating infertile soils and hazardous influences on the ecological system (Mansour and Ali, 2015). These materials should be reused to prevent these harmful impacts on the environment, such as reuse in construction.

Plastic Bottles

The growing disposal of plastic bottles caused by industrial development and increasing population is creating an unhealthy environment with their non-biodegradable properties and the release of toxic chemicals (Mansour and Ali, 2015). Approximately 7800 plastic bottles are needed to build a home and around 220,000 are needed to build a school (Hattam, 2011). In Taiwan, approximately 2.4 billion plastic bottles are used and thrown out as waste each year, with only 4% of these bottles being reused and recycled (Messenger, 2010).

Plastic bottles are beginning to be reused as a building material, which are filled with either other waste or dry soil material. The bottles are laid like bricks, as shown in Figure 12, and mud is used as a mortar and render (Hattam, 2011).

Figure 12. Plastic bottle construction (Hattam, 2011).

Rubber Tyres

Rubber tyres are a non-biodegradable waste product with more than 48 million rubber tyres thrown out as waste in the UK each year (SBD, 2014). Sustainable Building Design, or SBD, (2014) discusses how tyres are slowly being introduced as a recycled building resource, promoting sustainability and minimising carbon. Earthship Biotecture (2015) have developed a sustainable village, known as the Earthship village, which is built as a prototype to represent how recyclable materials, including rubber tyres, can become building materials. The village is built out of 45% of recyclable materials, rubber tyres being among them (EB, 2015). A part of this Earthship village that was built out of tyres is shown below in Figure 13.

Figure 13. Tyre Construction in Earthship village (EB, 2015).

The construction method of rubber tyres involves tyres that are laid and then filled with compacted soil material. Layers of this tyre soil arrangement are constructed to produce wall that are then rendered with a mud or daub like substance (SBD, 2014).

Using recycled materials for construction reduces the waste that is dumped into the ground and is therefore considered to be a sustainable material. However, the embodied energy of these plastics and rubbers is 105.8 MJ/kg and 96.53 MJ/kg, respectively, compared to soil, which is 0.45 MJ/kg (Hammond and Jones, 2011). Therefore, earthen materials are the most sustainable substitute materials.

2.5. The Rammed Earth Case Study

This report focuses on the earth building material of rammed earth and discusses how some characteristics of this material need to be further researched and derived to produce a reliable building resource.

Many unstabilised rammed earth walls built throughout history have remained standing for centuries (Downton, 2013). This proves that the need for cement addition is not crucial. The development of ultra-strong materials, such as steel and concrete, has driven society to desire this level of strength for all constructions for reliability purpose. Consequently, people attempt to strengthen weaker, yet strong enough, materials with cement. It is evident by examples throughout history that rammed earth buildings constructed out of purely raw and natural materials have adequate capacities. In Weilburg, Germany, a six-storey loadbearing building was constructed out of rammed earth in 1826 (HB195, 2001). This example, photographed in Figure 13, shows that rammed earth walls can have the required capacities for building small to medium sizing buildings.

Figure 14. Historical six-storey rammed earth building in Weilburg, Germany (HB195, 2001).

To prevent this energy efficient construction method from dying out, the expertise used to build historical buildings, such as displayed in Figure 14, must be brought back into the current construction market and economic cycle (Bollini and Parodi, 2015). It is in the nature of economics for a product to reduce in price when the demand of the product increases; therefore further research must be carried out for rammed earth buildings to become more accessible and reliable. Bollini and Parodi (2015) explain that there is a significant drive for "the proper technical management of earth as a material, in the attempt to make the professional world, labour and clients trust it again."

Rammed earth is viewed as a weak material in comparison to materials like steel and concrete and thus the industry has attempted to strengthen the material with the addition of cement. Results have shown that stabilised rammed earth walls (containing cement) have better strength however for the environmental cost of the production of cement, the strength gained from this addition is not as worthwhile as some might think. Although unstabilised rammed earth walls are built thicker and tend to lose strength due to saturation and erosion from weather conditions, the energy conservation achieved from the use of this building material is considerably rewarding for the environment (Reddy and Kumar, 2010). As the content of cement increases, so does the embodied energy of the structure. Due to the current focus on sustainability, the cement content in rammed earth is to be minimised to ensure that the embodied energy consumed by the material is as low as possible. This relationship between the embodied energy of stabilised rammed earth walls and the varying amounts of cement used is shown in Figure 14.

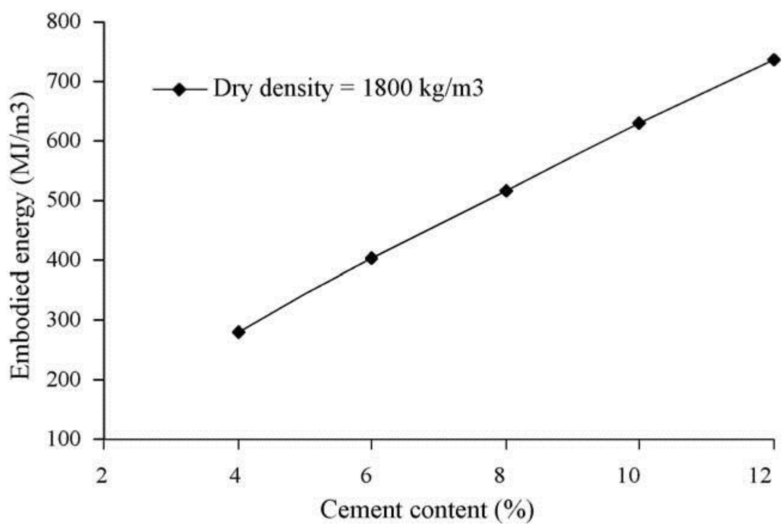


Figure 15. Embodied energy and cement content relationship (Reddy and Kumar, 2010).

A comparison by Pacheco-Torgal (2012) discusses the carbon content in rammed earth walls with varying cement. Whilst cement stabilized rammed earth is depicted as a low carbon alternative, a comparison shows how cement stabilised rammed earth can have almost triple the amount of embodied carbon than that of unstabilised rammed earth. The amounts of carbon dioxide (CO_2) produced with varying cement contents in rammed earth are shown in Table 2.2.

Table 2.2 — Carbon content of stabilised rammed earth, unstabilised rammed earth and stabilised earth blocks (Pacheco-Torgal and Jalali, 2012).

Wall Type	kg CO_2 eqv
Generic rammed earth	26
Cement stabilised rammed earth 8%	65
Cement stabilised rammed earth 9%	70

The soil properties of the material used to build the rammed earth walls are important as they describe how the wall might behave. Most sources rely on the particle distribution of the soil material, with the aim of obtaining particular amounts of clay, silts, sands and gravels, to achieve optimum compaction and interlocking of the soil particles (Ciancio et al., 2013). Other parameters, such as the plasticity index, and the linear shrinkage, should be considered to understand how the clay and silt particles will interact. Ciancio et al (2013) emphasises that compaction requires a small amount of clay, however to prevent shrinkage, the clay content must be higher. Ciancio et al (2013) also compares of the plasticity of the soil sample to the rammed earth walls. The soil sample has to be passed through a 425μm sieve to conduct the plastic and liquid limit tests, producing a material that is quite different to the soil mixture used to construct the walls. Therefore, testing for the plasticity index of a soil may not accurately define the properties of the rammed earth wall that is built out of the original soil mix. This inaccuracy is also a concern for the linear shrinkage testing, however it can produce some acceptable results regarding the clay reactivity (Ciancio et al., 2013).

The moisture of the soil is also an important parameter for when the wall is built. The moisture content needed for rammed earth construction is less than that of the plastic limit and closer to the optimum moisture content (Micolli et al., 2014). This low moisture content means that the soil particles are bound together by their interlocking, frictional capabilities and can produce a wall at or close to the maximum dry density (Ciancio et al, 2013).

Earth materials are not only successful in reducing embodied energy, they also assist in reducing energy produced by heating and cooling of indoor temperatures throughout the life of the structure. This heating and cooling energy consumption makes up for approximately 40% of the total energy produced in a household (Dong et al., 2014). Therefore, reductions in heating and cooling loads is an aspect that needs to focused on to achieve complete energy conservation. Rammed earth walls are known by supporters of rammed earth for their thermal mass properties, which can regulate indoor temperatures at a comfortable level. Despite this thermal performance reputation, experimental results have shown the opposite with rammed earth performing poorly when it comes to thermal resistance behaviour. This report investigates the thermal performance of rammed earth walls and conducts experiments to find dynamic and steady state thermal behaviour of this building resource.

2.6. Background Summation

It is clear that the current carbon footprint of the construction industry has a significant impact on the world's atmosphere. Contemporary construction materials, particularly steel and concrete, have intensive manufacturing processes that release substantial amounts of carbon emissions, contributing to global warming. With the growing focus on sustainability and energy conservation, the construction industry must look to reduce its production of carbon emissions.

Alternative earth building materials, such as straw bale, mud brick and rammed earth are materials that need to be explored as substitutes for these highly intensive contemporary materials. The lack of research and knowledge of earth building materials has created views that earth building materials are unpredictable and thus people are opting for the easier, comfortable, choice of steel, concrete or masonry. The research and development of earth building Australian Standards will greatly enhance their dependability and thus allow earth materials to be considered as mainstream construction materials.

Rammed Earth is the focus of this report with research and experimental procedures carried out to improve the understanding of this construction material. The thermal performance of rammed earth is an area of research that tends to be limited and varied. Further research of these thermal properties will help achieve a complete understanding of rammed earth's thermal behaviour. This knowledge can assist in understanding the thermal capabilities of rammed earth. It may also assist rammed earth buildings to be designed in an energy efficient way that reduces the building's operational energy associated with heating and cooling. This research contributes to the knowledge and understanding of rammed earth, enhancing the dependability of a low carbon building material that can potentially reduce the carbon footprint of the construction industry.

3. The Thermal Performance of Rammed Earth

The absence of reliable building codes for rammed earth appears to be holding society back from using this resource as a mainstream construction material. A deficiency in rammed earth regulations means that a large amount of research is required to recapture popular construction with rammed earth. The thermal performance of rammed earth is a characteristic that is considered a 'grey area' due to the disagreement in experimental results and human experience with rammed earth buildings (Bollini and Parodi, 2015).

Current construction regulations require only steady state thermal parameters to define the thermal behaviour of building materials, however steady state conditions do not depict the behaviour in realistic diurnal temperatures that buildings are exposed to. This study on the thermal performance of rammed earth will not only derive the steady state properties of rammed earth, but will also look at how rammed earth walls behave when exposed to dynamic temperature conditions.

Research of rammed earth's thermal performance can lead to reductions in embodied energy in construction and also reductions in operational energy. By understanding how this material behaves thermally, structures can be designed to take advantage of its thermal properties and thus reduce the need for heating and cooling energy in living spaces.

3.1. Steady State Thermal Performance

The steady state performance of a material is determined by exposing the internal and external side of the wall to static cold and hot temperatures, respectively. The main steady state parameter that is obtained from this type of testing is the thermal resistance value (R-Value). Other related parameters include the thermal transmittance and the thermal conductance.

Thermal Resistance (R-value)

Thermal resistance, often known as the R-value, is a property that describes the thermal behaviour of a material in steady state conditions. It relates to the difference in temperature of two faces of a material and the energy required to stabilise and maintain these constant temperatures (c-therm, 2015). Thermal resistance is calculated with the heat flow rate, q, in W/m^2 and the change in temperature, ΔT in degrees Celsius (°C), as shown in Eqn (1):

$$R = \frac{\Delta T}{q} \tag{1}$$

The thermal resistance of rammed earth has been shown to be quite low and thus relates to considerable amounts of heat released from the material over a period of time (Dong et al., 2014). The thermal resistance of rammed earth varies from wall to wall due to various soil grading, cement content, wall thickness, moisture content and other additional materials added to improve its structural properties. The R-values of cement stabilised rammed earth walls have been analysed by Hall and Allinson (2009) with differing wall thicknesses and additional insulating materials and various soil mixes. The walls tested contain a cement content of 6% as well as assorted amounts of gravel, sand, silt and clay (Hall and Allinson, 2009). These types of soil mixes used, labelled as Type 1, Type 2 and Type 3, for the rammed earth walls tested by Hall et al. (2009). The soil mixes include various amounts of gravels, sands, silts and clays, as seen in Table 3.1.

Table 3.1 — Soil properties of cement stabilised rammed earth walls (Hall and Allinson, 2009).

Mix Type	Soil component properties (kg/kg x 10)				
	14-6.3 mm gravel	<5 mm medium sand	Silts and Clays	Cement (%)	OMC (%)
Type 1	4	3	3	6	8
Type 2	6	1	3	6	8
Type 3	7	0	3	6	8

The thermal resistance testing of these walls were performed using steady state analysis. The types of walls tested in this experiment are 300mm thick (I) and 400mm thick (II) walls (Hall and Allinson, 2009). The results from these tests show that the soil grading of rammed earth walls have an impact on the thermal resistance behaviour of the wall. See Table 3.2 for the results.

Table 3.2 — Thermal resistance values for cement stabilised rammed earth walls (Hall and Allinson, 2009).

MIX TYPE	R-Value (m^2K/W)	
	Wall I	Wall II
Type 1	0.477	0.596
Type 2	0.540	0.660
Type 3	0.527	0.642

The information from Table 3.1 and Table 3.2 show that soil mixes with a variety of larger and finer particles performs better thermally than those made up of mostly finer soil particles. This improved thermal resistance is caused by the air pockets created between the larger and finer particles that fail to completely interlock. This study by Hall & Allinson (2009) proves that the thickness and soil types used in the construction for rammed earth walls have a significant impact on the thermal resistance performance of the material.

Hall & Allinson (2009) effectively show the thermal behaviour of rammed earth, however the inclusion of cement relates to a higher embodied energy. Due to the focus of society to find bigger, better and stronger materials, the addition of cement has become a common resource for the construction of rammed earth buildings. Historical rammed earth buildings that have been standing for centuries are built without cement, showing that unstabilised rammed earth building can be strong enough for what is required. Therefore the thermal behaviour of unstabilised rammed earth walls is an area that also needs to be researched.

Uninsulated rammed earth has been found to have low R-values. These low values relate to poor thermal performance and poor energy efficiency, which contradicts rammed earth's high thermal performance reputation. For a complete understanding of the thermal behaviour of rammed earth, the thermal mass and dynamic performance must also be considered.

Thermal Transmittance and Thermal Conductance

Thermal conductance is a property that is derived from steady state thermal testing and is the reciprocal of the thermal resistance value. The thermal transmittance is a similar parameter, however it also includes the material's heat transfer capabilities that come from convection and radiation (Ciancio et al., 2013). The thermal transmittance value, also known as the U-value, and the thermal conductance value, are defined by the quantity of heat flow per square meter (W/m^2) per 1 Kelvin (K) difference in temperature (IS, 2015). The thermal transmittance equation is simply the equation for thermal conductance with additional radiation and convection parameters added.

Thermal resistance, thermal conductance and thermal transmittance values essentially all describe the same steady state property. Due to Australian regulations using the thermal resistance value, or the R-value, this report focuses on the R-values of rammed earth walls. It also helps to simplify comparisons with dynamic thermal properties.

The existing steady state R-values of rammed earth relate to poor thermal performance, contradicting the view of supporters of rammed earth that rammed earth is an excellent thermal performer. Steady state and dynamic experiments of rammed earth must be correlated to engage a full understanding of the material's behaviour.

3.2. Insulation and Thermal Energy Requirements

The increasing amounts of greenhouse gas emissions has caused energy efficiency schemes to be developed. The Nationwide House Energy Rating Scheme (NatHERS) was established in the 1990s after Australia's commitment to the United Nations' climate change appeal (Daniel et al., 2015). The National Construction Code (NCC) has a Deemed-To-Satisfy (DTS) provision that provides regulations on minimum energy efficiency requirements for buildings for the various climatic regions in Australia (Dong et al., 2014).

The thermal performance of building materials is found with various software tools, such as AccuRate, that are based on steady state conditions. The results of this test are transformed into a star energy rating out of 10, where most areas of Australia must acquire a 6 star rating to comply with regulations (Daniel et al., 2015). This star rating method of energy efficiency enables the inefficiency of materials, such as rammed earth, to be counteracted with other thermal efficient materials (Dong et al., 2014). However, these compromises in other areas of the building, such as additional insulation and glazing, may be costly and unnecessary if it can be proved that rammed earth is a good thermal performer under dynamic thermal loads. This dynamic testing should be considered in energy efficiency rating schemes as it reflects realistic behaviour. Daniel et al. (2015) agrees that rammed earth houses are perceived to have good thermal performance, which contradicts their poor measured performance. The measured thermal performance of rammed earth for energy efficiency ratings have been known to neglect the thermal mass and lag time of earthen materials like rammed earth (Daniel et al., 20150).

The thermal resistance value required by the NCC is 2.8 m^2K/W (Dong et al., 2014). Typical R-values for a 300mm thick rammed earth wall range between 0.35 and 0.70 m^2K/W which are substantially less than the value required. Therefore, according to the DTS provision, additional insulation (with an R-value between 0.5 and 1.0 m^2K/W) is required for a 300mm thick rammed earth wall with a surface density of 540-660 kg/m^2 (Dong et al., 2014). Insulation is usually placed within the rammed earth walls, however this reduces the structural capacity of the wall and increases the difficulty associated with the construction of the wall. Due to the halved thickness of the wall leafs, the moment capacity of the wall is reduced to 25% of the moment capacity of its original thickness (Dong et al., 2014).

Dong et al. (2015) performed a study on insulation within rammed earth walls using a basic model house as shown below in Figure 16.

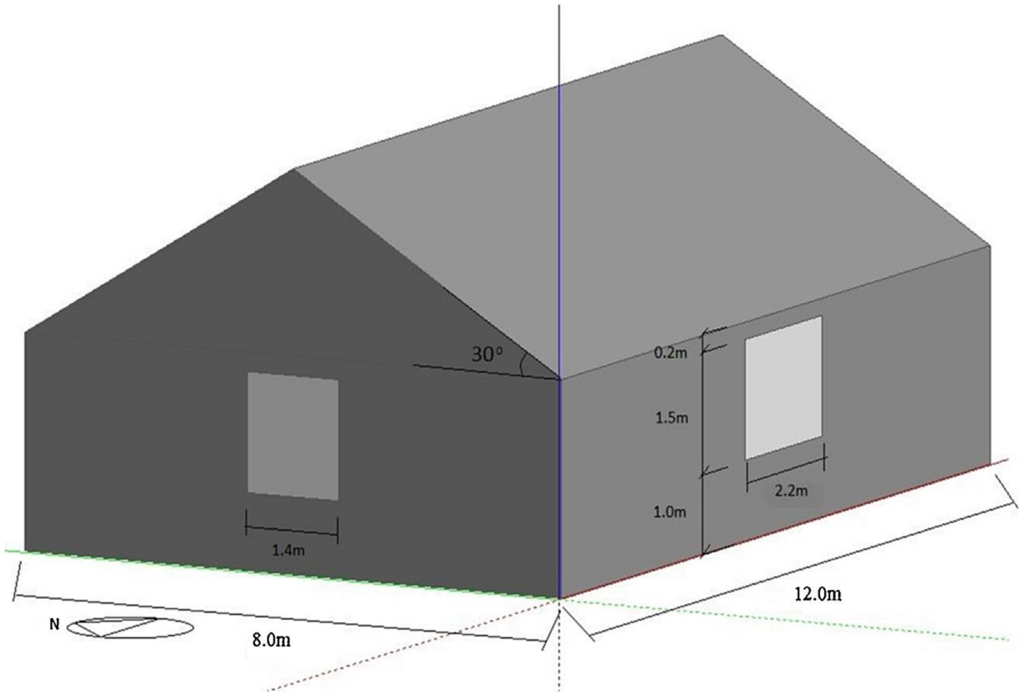


Figure 16. Basic model house for insulated rammed earth wall tests
(Dong et al., 2015)

This investigation focuses on reducing heating and cooling loads and optimizing the design of a rammed earth building. Various insulation and wall thicknesses were tested to determine the impact that each of these factors has on the thermal abilities of the wall. The walls tested consisted of walls with varying rammed earth thicknesses and constant insulation thicknesses. Another experiment was then performed with constant rammed earth thicknesses and varying insulation thicknesses (Dong et al., 2015). These wall types are shown in Figure 17 and 18, respectively.

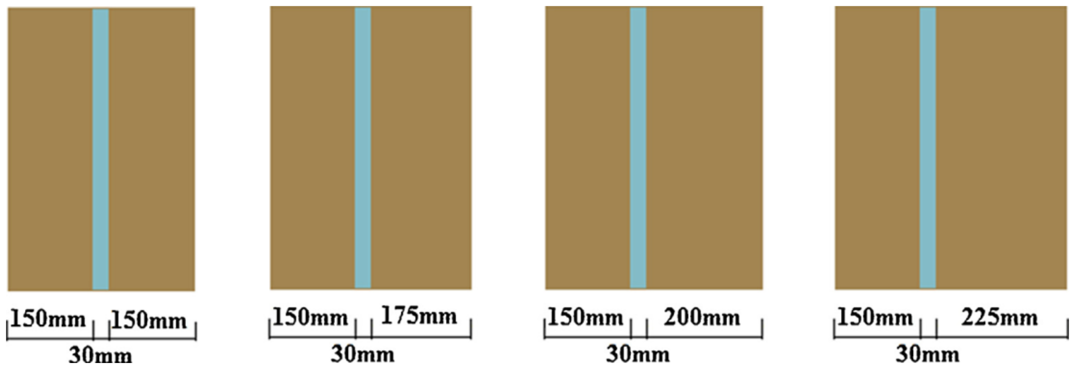


Figure 17. Increasing rammed earth thickness with constant insulation thickness (Dong et al., 2015).

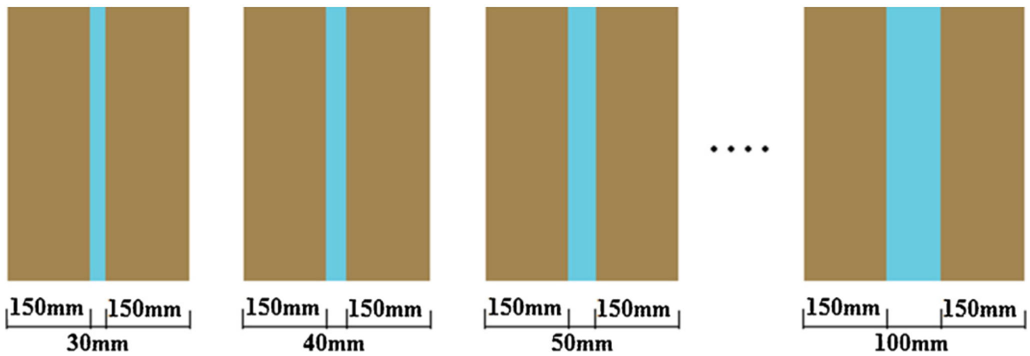


Figure 18. Increasing insulation thickness with constant rammed earth thickness (Dong et al., 2015)

There were many design factors that influenced this experiment such as window shading, window size, window to wall ratios, positioning of the house and location of the house. In general it was found that the thickness of the insulation had a substantial impact on the heating and cooling loads of the walls. This reduction in heating and cooling loads correspond to higher energy efficiency and thus a more sustainable product according to regulations in the NCC. Heating and cooling loads decrease as the thickness of the insulation cavity increase, as shown in Figure 19 (Dong et al., 2015).

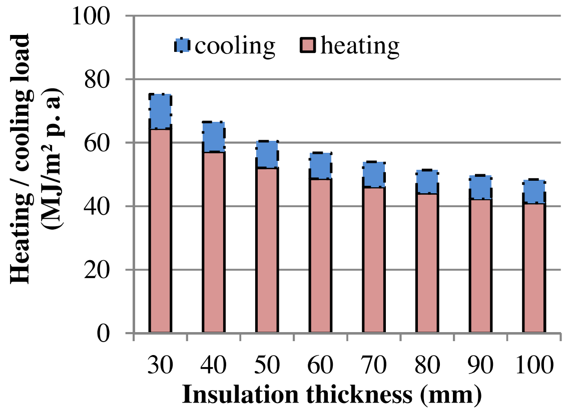


Figure 19. The decrease of heating and cooling loads due to insulation thickness (Dong et al., 2015)

This study by Dong et al (2015) also discovered that in comparison to the insulation, increasing the thickness of the rammed earth wall leafs had an insignificant impact on the heating and cooling loads of the house, as demonstrated in Figure 20 below.

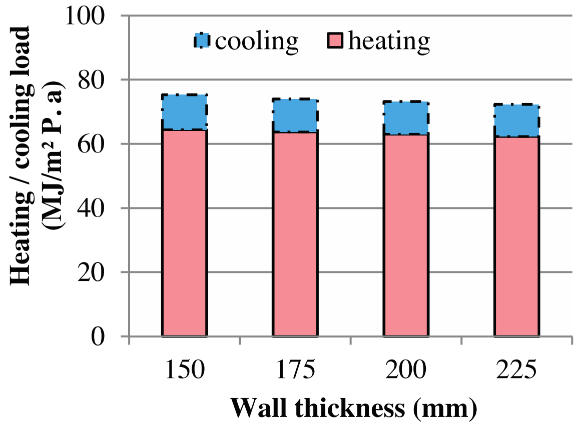


Figure 20. Impacts of rammed earth wall thickness on heating and cooling loads (Dong et al., 2015)

Although the insulation has increased the R-value of the material, it has reduced the thermal mass of the wall due to the inclusion of insulation in the centre of the wall. Instead of only focusing on the adjusting R-values to comply with energy efficiency schemes, the thermal mass of the building must be considered before deciding whether the wall needs insulation. Insulation is considered necessary when only the thermal resistance values of rammed earth are considered, which depict rammed earth as being a poor thermal performing material. Integrating steady state and dynamic thermal testing of rammed earth walls may prove that additional insulation is, in fact, unnecessary. It is important to gain a complete understanding of the behaviour of the material in its raw state (uninsulated and unstabilised) before additional substances are added. This topic of insulation shows how the strive of society is to create the strongest and best performing materials rather than focusing on what materials are good enough for what is required. This is based on the current regulations only incorporating steady state thermal testing, when arguably this gives an incorrect description of how materials behave thermally. If Australian regulations integrated the dynamic thermal performance as well as steady state results, a true depiction of how materials behave can be presented. Given that dynamic testing of rammed earth walls agrees with the common perception that they are good thermal performers, insulation may not be required.

3.3. Dynamic Thermal Performance

Current regulations in Australia use packages, such as NatHERS and NCC's DTS provision, to evaluate the energy efficiency of domestic buildings. The AccuRate and FirstRate software measures this energy efficiency by accounting for location, climate, surrounding environment and construction materials. These software tools use steady state models and thus can produce inefficient readings (Alterman et al., 2014).

The dynamic thermal performance is a property that describes a material's behaviour when it is subject to diurnal temperature fluctuations. This dynamic behaviour improves the understanding of how materials perform in real climatic conditions. The current building regulations that require steady state thermal properties, such as thermal resistance, have been found to be inadequate for complete design of energy efficient buildings (Arendt et al., 2011). A high thermal resistance or R-value, which depends on insulating properties only, does not relate to efficient dynamic thermal performance . The neglect of dynamic thermal properties relates to miscalculations of the energy demand and thus can cause energy inefficiency (Arendt et al., 2011). It seems that a more correct method of thermal testing would be to expose the material to diurnal temperatures; similar to those it will be exposed to in a realistic situation, rather than testing it with impractical steady state conditions. The parameters associated with dynamic performance include thermal mass, insulation and ventilation. Consideration of these parameters can lead to an understanding of the complete thermal performance in real dynamic conditions and therefore lead to a sustainable future in building (Alterman et al., 2014).

Thermal Mass

Thermal mass is a characteristic that describes how materials absorb, store and release heat energy. This property is used to regulate internal temperatures of buildings and houses creating comfortable living and working spaces. Ideally the diurnal extremes, otherwise known as day and night temperatures, are averaged and a near constant internal temperature is achieved by thermal mass properties. A material with a high thermal mass absorbs and stores relatively more heat from the sun keeping the internal spaces cool. This stored heat energy is then released when the exterior temperature drops throughout the night, warming up or maintaining the internal temperature. This rate of heat being absorbed and released is known as the thermal lag. The thermal lag of a material depends on conductivity, thickness, insulation and the internal and external temperature differences. The thermal lag of materials like rammed earth or mud brick can be between 24 hours to seven days (Reardon, 2014). The thermal lag times of various modern and earthen materials are compared in Table 3.3 below.

Table 3.3 — Thermal lag figures for various materials (Reardon, 2014).

Material (Material Thickness)	Time Lag (hours)
Double brick (22)	6.2
Concrete (250)	6.9
Autoclaved aerated concrete (200)	7.0
Mud brick/ adobe (250)	9.2
Rammed earth (25)	10.3
Compressed earth blocks (250)	10.5

The comparison presented in Table 3.3 shows that rammed earth has a longer thermal lag time than concrete and thus implies that it performs better in the activity of absorbing and storing heat.

With their various levels of thermal mass, some materials release heat energy soon after they have absorbed it while others can retain the heat for 10-12 hours, as shown in Table 3.3. The type of thermal mass needed depends on the climate in which the structure is being built. In general, a high thermal mass is desirable as it is these materials that delay heat flow, however for tropical climates with diurnal temperature changes at around 7-8°C are better suited with low mass construction (Reardon, 2014).

According to past experiments, rammed earth has a poor thermal performance, however supporters of rammed earth walls believe that rammed earth has excellent thermal capabilities (Taylor and Luther, 2004). Materials with high thermal mass can regulate temperatures better than other contemporary building methods. This regulation of temperatures is shown in Figure 21, where heavy buildings are buildings with high thermal mass and light buildings have low thermal mass.

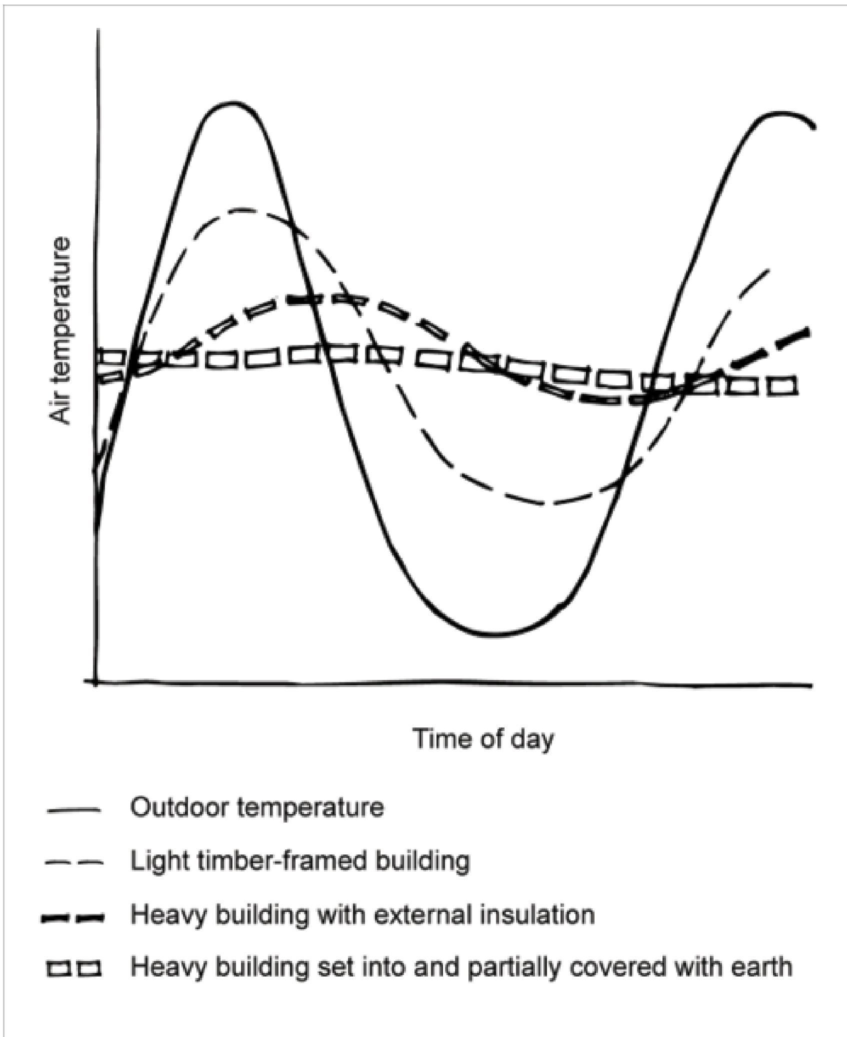


Figure 21. Temperature regulation of thermal mass in heavy and light weight buildings (Reardon, 2014).

Research has shown that lightweight walling systems with high R-values and low thermal mass have quicker responses to outside diurnal temperatures than those materials with high thermal mass and lower R-values (Alterman et al., 2014).

Materials with high thermal mass should be coupled with efficient designs to allow for the changes between winter and summer. In winter, the heat energy is absorbed, stored and released. Through summer, there must be openings, such as windows and doors, in appropriate places to allow ventilation and breezes through to draw out all the heat energy being released by the material. Rammed earth is considered to have a high thermal mass and therefore is seen as a desirable building resource when it comes to comfortable living temperatures and energy efficiency.

Parameters of Dynamic Thermal Performance

Dynamic thermal behaviour can be expressed by the time lag, the decrement factor and thermal diffusivity of the material.

Time Lag

The thermal time lag, φ, of a material is calculated by finding the difference in time between the peak external temperature and the peak internal temperature, see Eqn (2):

$$\varphi = \tau_{external} - \tau_{internal} \tag{2}$$

where τ is the time at which the peak surface temperature is recorded within a period of 24 hours (Gagliano et al., 2014).

Decrement Factor

The decrement factor, f, is the ratio of amplitude decrease that occurs during a period of diurnal temperature swings and this ratio is calculated with the internal and external temperature differences, see Eqn (3):

$$f = \frac{T_{internal\,max} - T_{internal\,min}}{T_{external\,max} - T_{external\,min}} \tag{3}$$

where T is the temperature recorded on the surface of the material (Gagliano et al., 2014).

Thermal Diffusivity

The thermal diffusivity (a_t) describes how quickly materials adapt their temperature to the surrounding temperature . It is a function of the thermal conductivity (κ), the specific heat capacity (c) and the material density (ρ), see Eqn (4):

$$a_t = \frac{\kappa}{\rho c} \tag{4}$$

The specific heat capacity is a property that relates to the thermal mass and the thermal capacitance and describes the energy needed for the internal temperature of the material to increase by one degree (Alterman et al., 2014).

Recent Italian regulations have been released that show the ranges for the time lag and decrement factor values that provide bad to excellent thermal ratings. These ranges are shown below in Table 3.4.

Table 3.4 — Values for time lag/shift and decrement factor according to Italian regulations (Gagliano et al., 2014)

Time Shift	Decrement Factor	Rating
Ψ>12	f<0.15	Excellent
12≥ Ψ>10	0.15≤f<0.30	Good
10≥ Ψ>8	0.30≤f<0.40	Middle
8≥ Ψ>6	0.40≤f<0.60	Sufficient
Ψ≥6	f≤0.60	Bad

The range of time lag and decrement factor values shown in Table 3.4 provide an indication of how well materials will perform thermally. Simple regulations like these could be developed or adapted to suit the Australian climate to provide a way of including the dynamic performance of materials in energy efficiency assessments.

Dynamic Thermal Response (T-value)

Another parameter that suitably sums up the dynamic performance of materials is the Dynamic Thermal Response value, otherwise known as the T-value. This value involves both thermal resistance and thermal mass recorded in cyclic diurnal temperatures. This T-value can be found through laboratory testing using an adapted ASTM standard guarded hot box test, which was originally created for steady state testing. This modified apparatus simulates dynamic temperatures on one side of the wall and records the uncontrolled temperature on the other side of the wall (Alterman et al., 2014). The hot box apparatus is displayed in Figure 22 below.

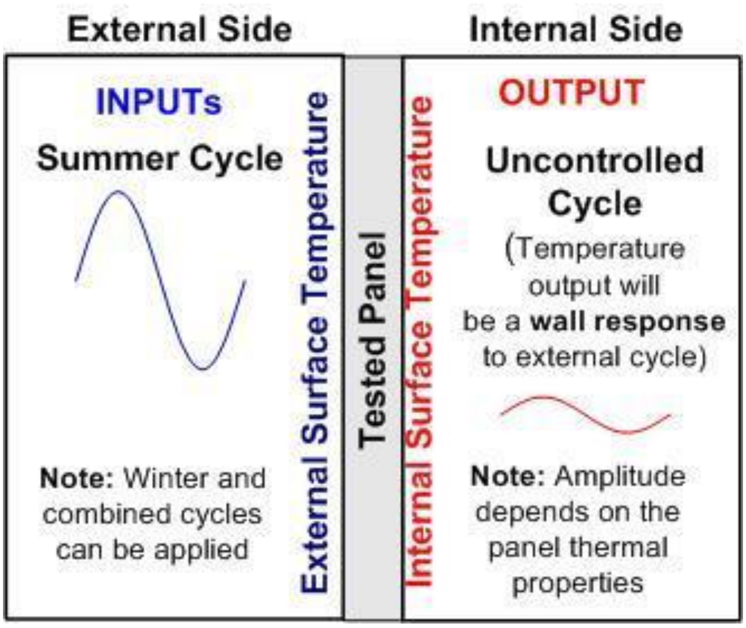


Figure 22. Modified hot box rig (Alterman et al., 2014).

The temperatures obtained from the "external" and "internal" sides of the wall of a period of time are then graphed with external temperatures on the horizontal axis and internal temperatures on the vertical axis. A principal axes line is then to be drawn on the elliptical shape formed by the plotted points. The inclination or angle of the principle axes line is the T-value for the material (Alterman et al., 2012). High T-values are produced by materials that have experienced minimal decrease in the amplitude of internal temperature. An example of a material with a high T-value is shown in Figure 23.

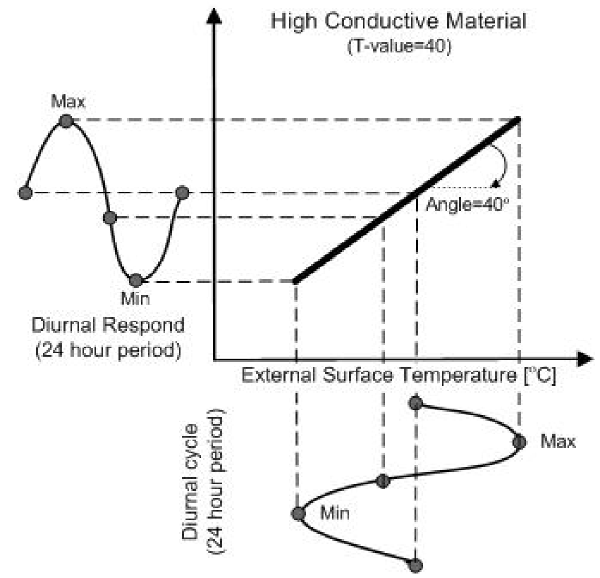


Figure 23. High T-value example (Alterman et al., 2012).

For materials with low T-values, the amplitude of the intermal temperature wave decreases significantly creating reduced fluctuations in internal temperature. An example of this T-value (due to the lower angle) is shown in Figure 24.

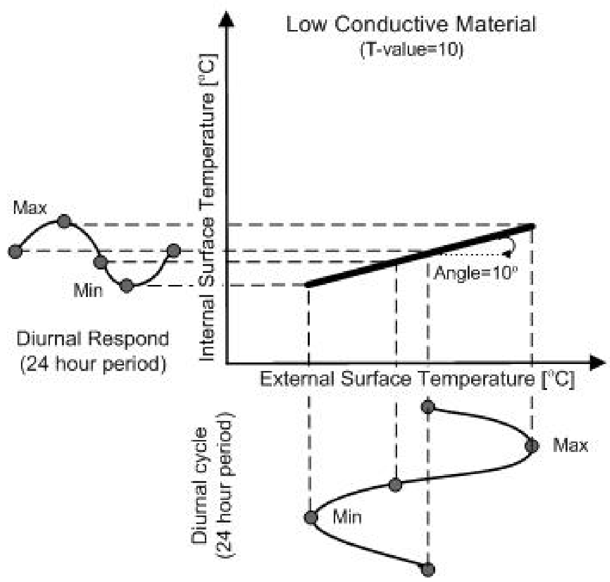


Figure 24. Low T-value example (Alterman et al., 2012).

Lower T-values or the angles of inclination relate to materials that have high thermal efficiency, whereas T-values that approach 45 degrees are poor thermal performing materials (Alterman et al., 2014).

An analysis of natural ventilation and heat flow, performed by Taylor and Luther (2004), was conducted on a two-storey university building that was built with rammed earth walls that were 300mm thick. It was found that there is a decrease in heat flux amplitude on the internal surface of the walls compared to the external surface. The analysis of this behaviour in this study has proved that R-values alone are inaccurate for assessing thermal performance and the large thermal capacity of rammed earth walls enhances this thermal behaviour (Taylor and Luther, 2004). The high thermal mass of rammed earth suggests that it would perform well under thermal dynamic simulation. Table 3.3 states that rammed earth has a thermal lag time of 10.3 hours which is more than that of concrete and masonry (Reardon, 2014). The R-values and T-values of unstabilised rammed earth must be compared to determine the accuracy of the R-values required for current energy efficient regulations and establish whether rammed earth is indeed a good thermal performer.

3.4. Dynamic Thermal Performance of Contemporary Materials

There is a lack of knowledge on the dynamic performance of unstabilised and uninsulated rammed earth. Having a better understanding of dynamic thermal performance would enable a broader understanding of the thermal behaviour of rammed earth. Research on other materials provides evidence that dynamic thermal performance can show true insight to how building materials actually behave under thermal loading.

Alterman et al. (2014) tested masonry walls and concrete panels with differing insulating properties. The masonry walls were tested using four full scale housing test modules with varying masonry types of cavity brick (CB), insulated cavity brick (InsCB), insulated lightweight masonry (InsLW) and insulated brick veneer (InsBV). These modules were exposed to seasonal conditions, where internal and external conditions were monitored using 105 sensors fitted in each module. These module tests were conducted for 8 years with data recorded every 5 minutes (Alterman et al., 2014). The internal surface temperatures versus external surface temperatures plot is presented in Figure 25, showing ellipses for each of the wall types.

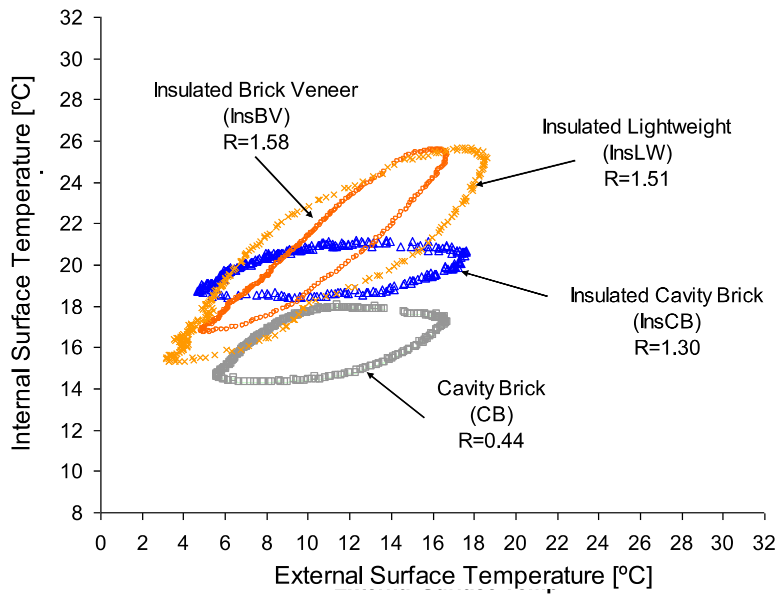


Figure 25. Masonry wall internal vs. external surface temperatures (Alterman et al., 2014).

The T-values obtained from Figure 23 are compared to the respective R-values show that insulated and uninsulated cavity brick are good thermal performers, compared to insulated brick veneer and insulated lightweight masonry, see Table 3.5. The R-values of the uninsulated and insulated cavity brick are the two lowest values and therefore proves that high R-values should not be relied upon when determining whether a material is a good thermal performer.

Table 3.5 — T and R values of masonry walls (Alterman et al, 2014).

Wall Type	T-Value	R-Value [m^2K/W]	Comments
Cavity brick	12.8	0.44	Good thermal performance
Insulated cavity brick	8.4	1.30	Good thermal performance
Insulated Brick Veneer	35.8	1.58	Poor thermal performance
Insulated Lightweight	32	1.51	Poor thermal performance

The comparison between the thermal performances of materials in Table 3.5 indicates that the thermal rating depends on the dynamic T-value. Although, rammed earth existing R-values imply that it is a poor thermal performer, the high thermal mass and time lag of rammed earth suggests that it would have a low T-value and therefore relate to good thermal performance.

A study on concrete panels was conducted by using the modified thermal rig to compare the impact of insulation on the internal and external faces of the panels. The concrete panels were 2.4 m x 2.4 m with a high thermal mass, weighing 2000 kg and an R-value of 0.09 Km^2/W. The insulation used is a polystyrene panel with a low thermal mass and an R-value of 0.67 Km^2/W. The walls were tested using a dynamic input to produce a realistic scenario and provide reliable results of its thermal performance (Alterman et al., 2014). The results of this hot box experiment are shown in Figure 26.

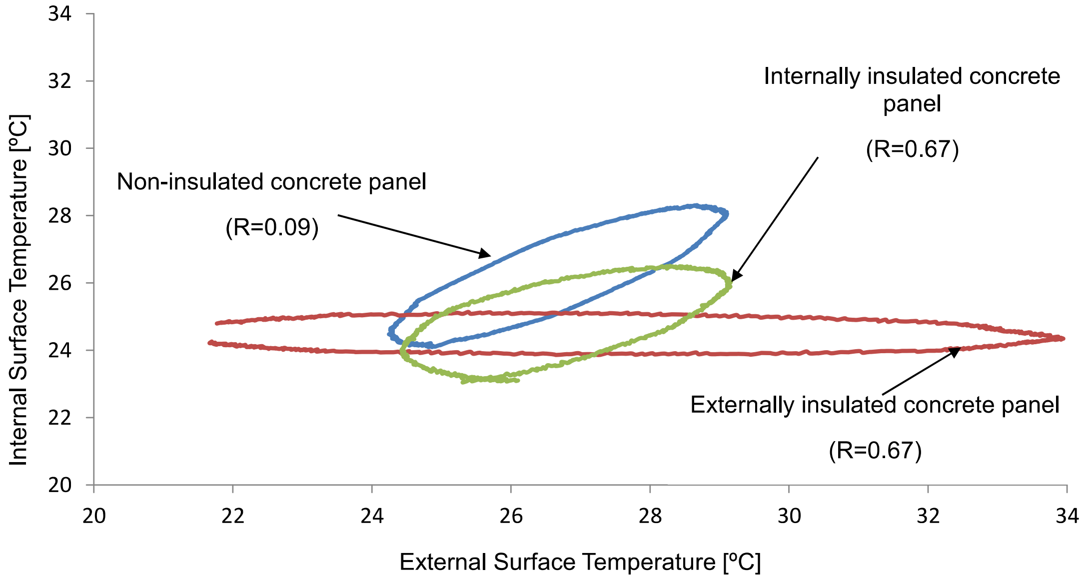


Figure 26. Internal temperatures vs. external temperatures of concrete panel experiment (Alterman et al., 2014).

The T-values obtained from Figure 20 for the non-insulated, internally insulated and externally insulated concrete panels are 36.3, 23.2 and 0.6, respectively. These results show that even though the R-value of internally and externally located insulation is the same, the dynamic thermal performance of the walls show that insulation performs better when located on the external face of the wall (Alterman et al., 2014).

The above studies prove that researching the dynamic thermal performance of materials is worthwhile as it can prove how these materials will perform in real life. Although rammed earth has been found to have a very low thermal resistance value, this research on masonry and concrete proves that the thermal resistance should not be relied upon as the sole property for determining how a material performs thermally. Therefore, the dynamic thermal behaviour of rammed earth is an area that needs to be researched in order to confirm the hypothesis that rammed earth is good thermal performer.

3.5. Literature Summation

The thermal performance of building materials is a crucial property that can reduce the operational energy of a building throughout its lifespan. Low embodied energy-building materials are the way of the future and earth building materials are not only low in embodied energy, but are also known to be excellent thermal performers. Buildings have been built with earth for thousands of years, however the dying art of earth building and the development of highly processed modern materials has caused this building method to be deemed unreliable. Research and experimentation of these earth materials will enhance the reliability of this energy efficient material.

Studies on the thermal mass and steady state thermal properties of rammed earth have been conducted, providing contradictory results. The high thermal mass indicates that rammed earth is a good thermal performer, whereas the low thermal resistance suggests that the material is a poor thermal performer. The need for additional insulation in walls is based on steady state parameters, such as the thermal resistance, and dynamic thermal properties are neglected. The aim for adding insulation is to prevent any heat energy from flowing through to the internal spaces of buildings, however this may not be the appropriate approach.

Experimentation with the dynamic simulation of diurnal temperatures provides details on how the materials will perform in realistic situations. The dynamic thermal response factor, or the T-value, is what can sensibly determine the true thermal performance of building materials. Dynamic testing of materials incorporates the steady state thermal parameters of thermal resistance and thermal transmittance with the thermal mass and time lag factors. This dynamic testing has been used to assess materials like masonry and concrete and these experiments have proven that the dynamic thermal behaviour is an important parameter to consider when it comes to assessing thermal performance.

Dynamic thermal testing of rammed earth walls is an area that has not yet been assessed. Given that it is a common perspective that rammed earth walls perform well thermally, the dynamic thermal assessment is a possible way to prove it and contradict its low R-value that has previously been found.

The integration of dynamic thermal properties in Australian regulations is a concept being pursued, as dynamic simulation will determine how materials perform in real cyclic temperatures of day and night. Further research of the dynamic thermal performance of various materials must be undertaken improve the reliability of this notion.

4. Experimental Analysis

4.1. Objectives of Experimentation

Rammed earth, like many other earth building materials, is a low energy resource that is currently being neglected due to the lack of understanding of the material. Broadening the knowledge of rammed earth can lead to the development of a building code and therefore presenting it as a reliable mainstream product. Even modern materials went through the process of being researched and assessed before their building codes were produced. Earth materials are being dismissed for their perceived "useless" qualities in comparison to strong modern materials such as steel and concrete. However, due to recent views of society being structured around sustainability and energy efficiency, there is now a drive for materials that are energy efficient and strong enough.

Whilst some research has already been carried out for the strength of rammed earth walls, very little research has been undertaken on the thermal performance of rammed earth. The broad objective for this project is to produce experimental results for thermal performance and determine how the walls behave thermally. Included in this analysis is the derivation of steady state and dynamic thermal properties and comparing the two. After gauging the thermal performance of rammed earth, it is then to be compared with existing beliefs and findings with respect to its compliance (or otherwise) with Australian energy efficiency regulations.

A rammed earth wall is to be built on campus with the ideal dimensions for the thermal experimental apparatus with the type of soil and water content tested and noted. The first thermal experiment will be the steady state analysis, with the objective of determining the thermal resistance value (R-value). The same wall will then be used for dynamic thermal simulation in order to derive the dynamic thermal response value (T-value).

4.2. Experimental Apparatus and Equipment

The apparatus used in this project includes the equipment used to construct to wall, test the soil material and examine the thermal performance.

Wall Construction Equipment

The rammed earth wall was built inside of wooden formwork and compacted with pneumatic tamper connected to a compressor. A photograph of a pneumatic tamper is shown in Figure 27.

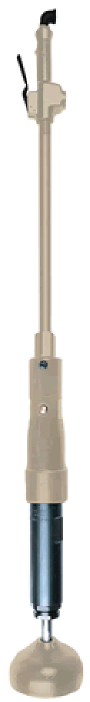


Figure 27. Pneumatic tamper (Jackhammers, 2011).

The specimen frame is the support for the wall including the insulation need around the perimeter of the wall (ASTM, 2011). The rammed earth wall was built on a structural steel 300mm parallel flange channel with timber cut to size for packing between the bottom of the wall and the steel channel so the wall is at the right height for the thermal rig testing. A layer of polystyrene foam was placed between the layers of timber to prevent heat losses from escaping through the bottom of the wall. Insulation batts are then used to cover the edges of the packing support system. A photograph of this support system is shown in Figure 28.

Figure 28. Rammed earth wall support and packing beam (Netherton, 2015).

Formwork, similar to concrete formwork, is constructed around the support and held into place with washers and nuts screwed onto reinforcement bars that run through holes on either side of the formwork.

Soil Testing Equipment

Soil tests were conducted to define the soil used to build the rammed earth wall. The tests performed include a particle distribution test, maximum dry density and optimum moisture content, liquid limit and plasticity index. These soil tests were conducted in accordance with AS 1289.1. The main equipment used include weighing scales, particle sieves with aperture sizes ranging from 37.5mm to 75μm, a 152mm cylindrical metal mould, a hand drop compactor, Casagrande liquid limit apparatus and a semi-cylindrical trough shrinkage mould. The soil material used for the rammed earth construction, called 5C5 Screened overburden, was sourced from a local quarry, Quarry Products Newcastle (QPN).

Thermal Performance Apparatus

The thermal testing of the rammed earth wall is conducted using a thermal rig, otherwise known as a standard hot box. This hot box is used for both steady state and dynamic analysis by varying the temperatures on either side of the wall. ASTM International, 2011, describes the two separate sides of the hot box as the metering chamber and the climatic chamber. The metering chamber is known as the hot side of the box, where hot temperatures are applied through a heat input. The climatic chamber, also known as the cold side, is the side opposite to the metering chamber and provides cooler conditions similar to those of internal temperatures (ASTM, 2011). The surface and air temperatures on either side of the box are recorded. The metering chamber and climatic chamber are displayed in the diagram in Figure 29, showing the direction of heat flow.

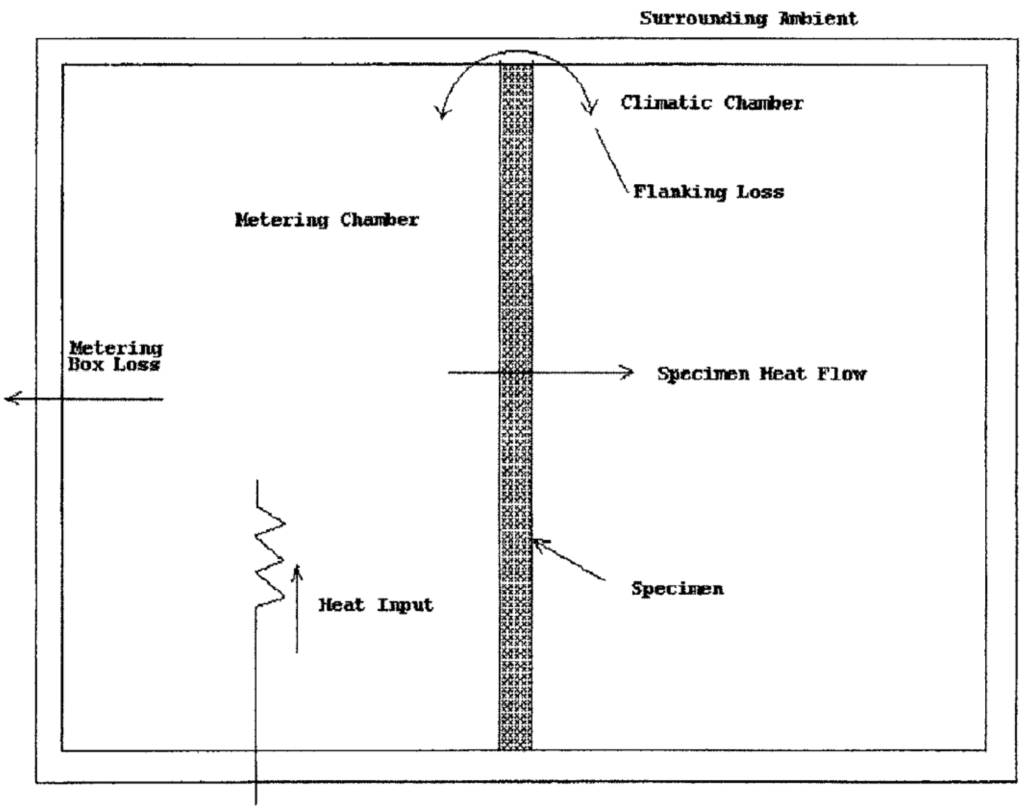
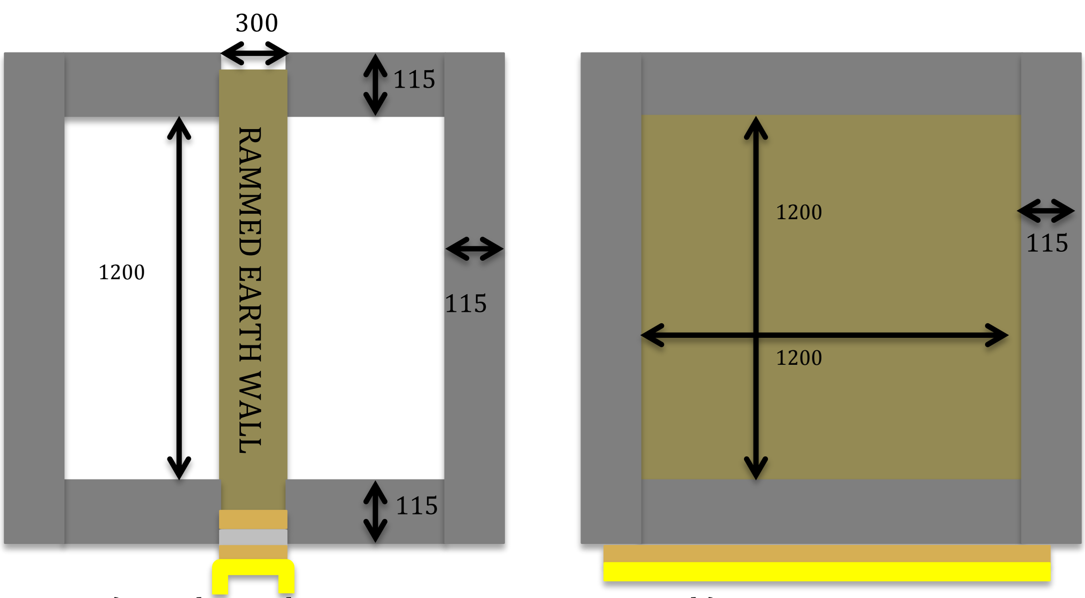


Figure 29. Hot box apparatus diagram (ASTM, 2011).

The flanking loss indicated in Figure 29 is the rate of heat exchange between the metering and climatic chambers caused by the two-dimensional transfer of heat at the boundary of the test wall and the surrounding metering chamber wall (ASTM, 2011). This flanking loss is prevented using insulation panels to cover the 300mm thick edges of the rammed earth wall.

The hot box used is a masked hot box, which means that the wall specimen is the same size as the metering box. The dimensions of the hot box used to conduct this experiment are presented in Figure 30 with the rammed earth wall clamped inside the apparatus.



a) North-South Section

b) East-West Section

Figure 30. Hot Box apparatus dimensions.

A data logger is used to record the time rate of the net heat flow and the temperatures on each side of the wall are recorded using T2 type thermocouples attached to the both surfaces of the wall. A heating element connected to a temperature controller is used to heat the air during the experiments on the hot side of the box. Julaba Recirculating Coolers are used during the steady state test to maintain a constant temperature. The computer software used to accumulate the results from the data logger and temperature regulators is called Julabo EasyTemp Professional.

4.3. Experimental Procedure

The procedure of this experiment includes the construction of the rammed earth wall, the laboratory testing on the soil used and the steady state and dynamic thermal performance testing using the standard hot box. Photographs documenting the procedure of the wall construction and thermal testing are presented in Appendix A.

Wall Construction

The support system, or specimen frame, was to be built with timbers and polystyrene cut to the width and length of the wall. These timber planks and the polystyrene sheet are laid on the 300mm parallel flange channel, ensuring that the polystyrene is laid between the timber planks. Eyelets are drilled into the flanges of the channel on each corner with lifting lugs screwed into each hole for future movement of the wall.

The rammed earth timber formwork is rested on the lifting lugs on each side of the support system and was held together with 600mm reinforcement bars in four corners of the timber formwork. Small PVC piping was cut to the required width of the wall, 300mm, and threaded onto the reinforcement bars between the formwork to ensure that the formwork was held apart at a consistent distance for the height of the wall. The formwork is constructed similar to that of a bearer and joist flooring system. Timber 'joists' are rested on top of the reinforcement bars on the external side of the formwork. Steel plate washers and nuts are used to screw onto the reinforcement bars to secure the timber 'joists' and formwork into place. A timber board is cut to the width and proposed height of the wall with two timber 'bearers' nailed to each edge, maintaining the 300mm wall width. This piece of formwork is slotted upright in against the reinforcement bars on either side edge of the wall, ensuring that they are level and the steel washers and nuts are tightened to secure its location. As the rammed earth wall is compacted, timber formwork boards are built onto the existing formwork in a similar way. The photograph in Figure 31 shows the building stages of this formwork arrangement.

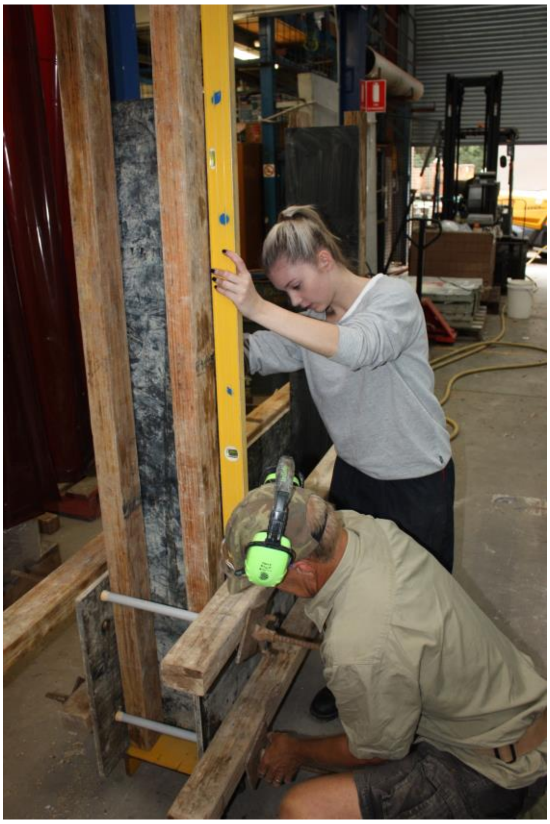


Figure 31. Formwork construction (Netherton, 2015).

The soil material for the rammed earth wall was examined and adjusted using appropriate materials to obtain a rough desirable particle distribution. This soil adjustment was heavily based on the experience of the contractor, Luke Mahony. To achieve the required optimum moisture content for the wall compaction, water is added and mixed through the material until the appropriate consistency is found. The drop test is performed, where a handful of soil is compacted by hand and dropped from shoulder height, to confirm that the moisture content is correct. Ideally, the hand compacted ball of material should break into only a few clumps, rather than shatter into many pieces. Once the correct moisture content is achieved, the material can be shovelled into the formwork. The shovelfuls of material are thrown against the formwork boards to build up the material on the outer edges of the wall and allowing the larger particles to fall into the centre of wall, which prevents any air pockets from forming around the larger soil particles on the surface of wall. Soil material is added until a layer of approximately 250mm is formed. A pneumatic tamper is connected to the compressor and is used to compact the

250mm layer of material, ensuring that corners and edges are also compacted, see Figure 32.

Figure 32. Compacting layers of soil between formwork (Netherton, 2015).

This process of shovelling and ramming soil layers is repeated until the required height of the wall is achieved. After the wall has been completed, the formwork is stripped to allow the wall to dry.

Soil Laboratory Testing

The laboratory testing of the material determines the properties of the soil, which can describe how it will behave when it is constructed into a rammed earth wall. Important characteristics that can determine the wall performance are the soil particle sizes and shrinkage. Other characteristics that affect the wall's construction include the optimum moisture content, liquid limit and plasticity index. If the material tested provides a sound basis for rammed earth construction, then these properties can be compared to materials from quarries with the intention of finding a similarly suitable material without the need for manual mixing of various types of soils.

Particle Size Distribution

The particle distribution test is conducted accordance with the standard sieving particle size distribution tests in AS 1289.3.6.1. The sieve aperture sizes used to determine the particle distribution of the soil used in this project are 37.7mm, 26.5mm, 19mm, 13.2mm, 9.5mm, 6.7mm, 4.75mm, 2.36mm, 1.18mm, 600µm, 425µm, 300µm, and 150µm.

Moisture Content

The moisture content of the material used for the rammed earth wall construction can be found using the oven drying method expressing in AS 1289.2.1.1. The water content is the difference between the wet and dry sample expressed as a percentage of the dry soil sample (SA, 2005).

Optimum Moisture Content and Maximum Dry Density

The optimum moisture content is the amount of water needed to assist the material in filling voids with smaller soil particles for optimal compaction. If a material has a water content greater than the optimum moisture content, it can cause voids to be filled with water. In contrast, a material with a lower water content can cause voids to be filled with air. The optimum moisture content and maximum dry density are found using the standard compactive effort test in AS 1289.5.1.1. Soil samples with differing water contents are compacted in the cylindrical metal mould. The recorded weights and dimensions of the compacted samples can be used to calculate the bulk density, ρ_{bulk}, of the sample, using the following equation (SA, 2003).

$$\rho_{bulk} = \frac{weight\ (grams)}{volumne\ (m^3)} \tag{5}$$

The moisture content, w, of each sample is determined using the oven drying method and expressed as a percentage. The dry density, ρ_{dry}, is then calculated by using equation (6) stated below (SA, 2003).

$$\rho_{dry} = \frac{\rho_{bulk}}{(1 + \frac{w}{100})} \tag{6}$$

The results for each compaction sample with various water contents are plotted on a dry density versus water content graph. An approximate parabolic curve is then drawn through the four data points, where the peak of the parabola is the point of optimum moisture content and maximum dry density (SA, 2003).

Liquid Limit

The liquid limit is the state at which a soil material changes from a plastic state to a liquid (SA, 2009). It is determined using the four point Casagrande method as described in AS 1289.3.1.1, where samples that are passed through a 425μm sieve have varying water contents and are placed in the cup of the liquid limit apparatus and a groove is created through the middles of the sample. The pivoting handle on the liquid limit apparatus is used to apply blows to the grooved material until the groove in the material join. The water content needed to achieve 25 blows is the liquid limit of the material, expressed as the water content percentage (SA, 2009).

Plastic Limit

The plastic limit describes the water content of a soil material when it transitions from a semi-solid to a plastic state (SA, 2009). The standard test method for the determination of the plastic limit is located in AS1289.3.2.1. This parameter is determined by adding water to a soil sample that has been passed through a 425μm sieve and allowing the mixture to cure for 12 hours or more. The wet soil samples are then rolled into a strip with a 3mm diameter. If the material crumbles before a 3mm diameter is achieved, then more water must be added, and if the material easily achieves a 3mm diameter, then there is excess water in the sample. Strips of material must continue to be rolled out of the material until it crumbles at a 3mm diameter. The moisture content at this state is defined as the plastic limit (SA, 2009). The plasticity index is a soil is the difference between the liquid limit and the plastic limit (Merriam-Webster, 2015).

Linear Shrinkage

The linear shrinkage of a material is the percentage of how much the soil sample shrinks at its liquid limit (SA, 2008). The procedure for deriving the linear shrinkage of a soil sample is found in AS1289.3.4.1. Similar to the liquid and plastic limit tests, the soil sample must be passed through a 425μm sieve. The liquid limit moisture content is added to the sample and the sample is then left to cure for a minimum of 12 hours. After curing, the sample is placed in a greased, 250mm semi-cylindrical trough, ensuring that all voids and air bubbles have been filled. The soil is then left to dry at room temperature for 24 hours, and then transferred to an oven until the sample is completely dry. The distance that the sample has shrunk is expressed as a percentage over the total length of the sample (SA, 2008).

Thermal Performance Experimentation

The thermal performance of the constructed rammed earth wall is determined using a ASTM standard hot box to simulate both steady state and dynamic conditions. The wall was clamped in the hot box, as shown in Figure 33.

Figure 33. Rammed earth wall undergoing tests in the thermal hot box (Netherton, 2015).

The results of these tests are then used to calculate the thermal resistance (R-value) and the dynamic thermal response (T-value) to conclude on the thermal behaviour of rammed earth.

Steady State Thermal Testing

The rammed earth wall is shifted into position with a crane and nine T2 type thermocouple wires are attached to the surface of each side of the wall. Insulation panels are cut to size and placed on the edges of the wall to prevent any losses. Thermocouple sensors are also attached to the insulation panels on the edges of the wall to allow any losses to be accounted for in the results. Thermocouple sensors are attached to the internal and external surfaces of the hot box, as well as nine thermocouples to measure the air temperatures in each hot box chamber. The hot box apparatus is clamped onto the rammed earth wall, ensuring that all edges are sealed and the ends of the thermocouple sensors are extended outside of the hot box. The thermocouple ends are connected to a data logger for temperatures to be recorded during the experiments.

A temperature controller attached to a heating element on the hot side of the thermal box is turned on and is set to a temperature of 30 degrees Celsius. The cold side of the box has Julaba Recirculating Coolers that are set at a temperature of 18 degrees Celsius. A short code is written in the Julabo EasyTemp Professional software that specifies what temperature values are to be obtained from the experiment via the data logger. The thermal experiment is then left to run for approximately three days for the temperatures to equalise, to create a steady state condition and to achieve a acceptable level of accuracy. The exact time required for the test to stabilise varies and depends on the properties of the testing wall and the ambient temperature conditions at the preliminary and final stages of the test (ASTM, 2011).

The standard test method used for the hot box apparatus explains that to calculate the thermal resistance of the material, the net heat transfer through the material is to be established. This is determined by the net heat input in the metering chamber and is adjusted to account for the heat flow through the wall of the chamber and the flanking loss. The heat flow through the walls of the thermal box is prevented with insulation on the chamber walls. Heat losses through these chamber walls can be further reduced by controlled the external air temperatures, however this cannot be done for this experiment and therefore the minimisation of losses is dependent on the insulation of the walls (ASTM, 2011).

Dynamic Thermal Testing

The dynamic test is carried out similarly to the steady state experiment, except that the temperature settings on the temperature controllers are adjusted to simulate diurnal temperature changes. The cold chamber of the hot box is set to have no temperature regulation and only the heat flow coming through the wall specimen and the surface and air temperatures are recorded.

The T-value is found by graphing one wave of the internal surface temperature against one wave of the external surface temperature. An elliptical shape is formed on the graph from which the inclination of the neutral axis is noted and is described as the dynamic thermal response, or the T-value.

4.4. Expected Results

Particular results are expected from the experimentation of rammed earth's thermal performance. In addition to this, the tests conducted for the soil properties are also expected to be similar to the soil characteristics provided by the quarry that provided the material.

Soil Laboratory Testing

The properties of the soil material determined by the laboratory tests are required to meet guidelines that are proposed by The Australian Earth Building Handbook. These guidelines provide per cent ranges of sand and gravel, silt, and clay that are recommended for rammed earth construction. These recommended ranges are shown in Table 4.1 below.

Table 4.1 — Recommended Material Properties (HB195, 2001).

Material Property/Type	**Range**
Sand and Gravel	45-75%
Silt	10-30%
Clay	Up to 20%
Liquid Limit	Less than 35-45%
Plasticity index	Less than 15-30%
Dry Density	1700 – 2200 kg/m^3

The expected characteristics of the quarry soil material complied with the guidelines shown in Table 4.1. The quarry material, named 5C5 screened overburdened, was presented with characteristics as stated in Table 4.2.

Table 4.2 — 5C5 Screened Overburdened quarry material properties (Qualtest, 2015).

Material Property	Value
Liquid Limit	24%
Plasticity Index	13%
Optimum Moisture Content	13.1%
Dry Density	1730 kg/m^3

The particle size distribution related to this quarry material shows a satisfactory spread of finer particles. The spread is shown in the particle size distribution curve is displayed in Figure 34.

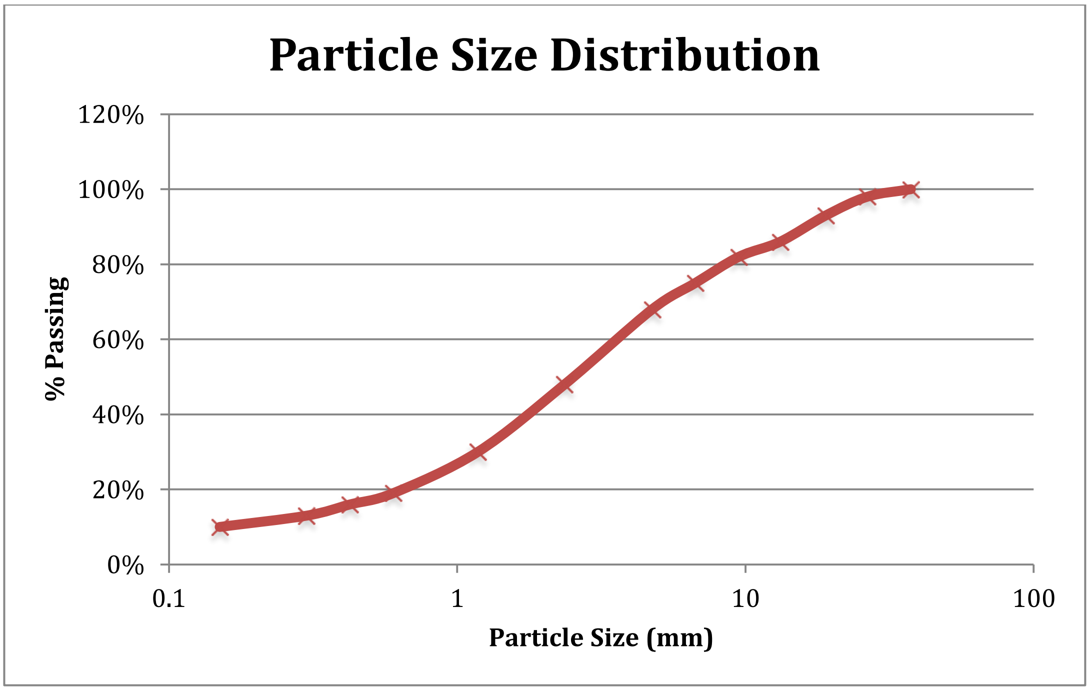


Figure 34. Particle size distribution curve of 5C5 Screened Overburdened quarry material (Qualtest, 2015).

The soil laboratory tests are predicted to produce these ideal material properties, providing a good basis for rammed earth construction.

Thermal Performance Values

The aim of this experiment is to compare the steady state and dynamic test results with the intent of proving that rammed earth is a good thermal performer despite low existing R-values. The R-values that are expected from this experiment are similar to that of existing data. Various existing thermal resistance data shows that this experiment should produce an R-value between 0.35 and 0.70 m^2K/W. Although there has been limited research on the dynamic thermal performance of rammed earth walls, its high thermal mass suggests that it will be a good dynamic thermal performer. The high thermal lag time obtained as a result of this high thermal mass also suggests that this is true.

The time lag for rammed earth is expected to be approximately 10.3 hours as expressed in Table 3.3. The predicted T-value depends on the decrement factor, which is the ratio between the internal and external surface temperatures describing the decrease in amplitude of the temperature fluctuations. Table 3.4 gives an indication of what the decrement factor should be for a good or excellent thermal performing material. For rammed earth to be classified as a good thermal performer, the decrement factor is between 0.15 and 0.30, which translates to a internal temperature change of 1.5 - 3°C when there is an external temperature change of 10°C. Using this basis, a set of predicted results were developed to show what the T-value of these results would be. For simplicity and the purposes of demonstration, the predicted results were shown as linear rather than sinusoidal, however it still shows an estimate for the T-value. The data used to approximate this T-Value is shown in Table 4.3.

Table 4.3 — Estimated T-value data.

ESTIMATED T-VALUE		
Hour	**External side (10 degree temperature change)**	**Internal side (3 Degree temperature change)**
1	30.0	20.0
2	29.2	19.8
3	28.3	19.5
4	27.5	19.3
5	26.7	19.0
6	25.8	18.8
7	25.0	18.5
8	24.2	18.3
9	23.3	18.0
10	22.5	17.8
11	21.7	17.5
12	20.8	17.3
13	20.0	17.0
14	20.8	17.3
15	21.7	17.5
16	22.5	17.8
17	23.3	18.0
18	24.2	18.3
19	25.0	18.5
20	25.8	18.8
21	26.7	19.0
22	27.5	19.3
23	28.3	19.5

The internal temperature changes were plotted against the external temperature changes. This plot shows a low angle of inclination or T-value, demonstrating a good thermal performer, see Figure 35.

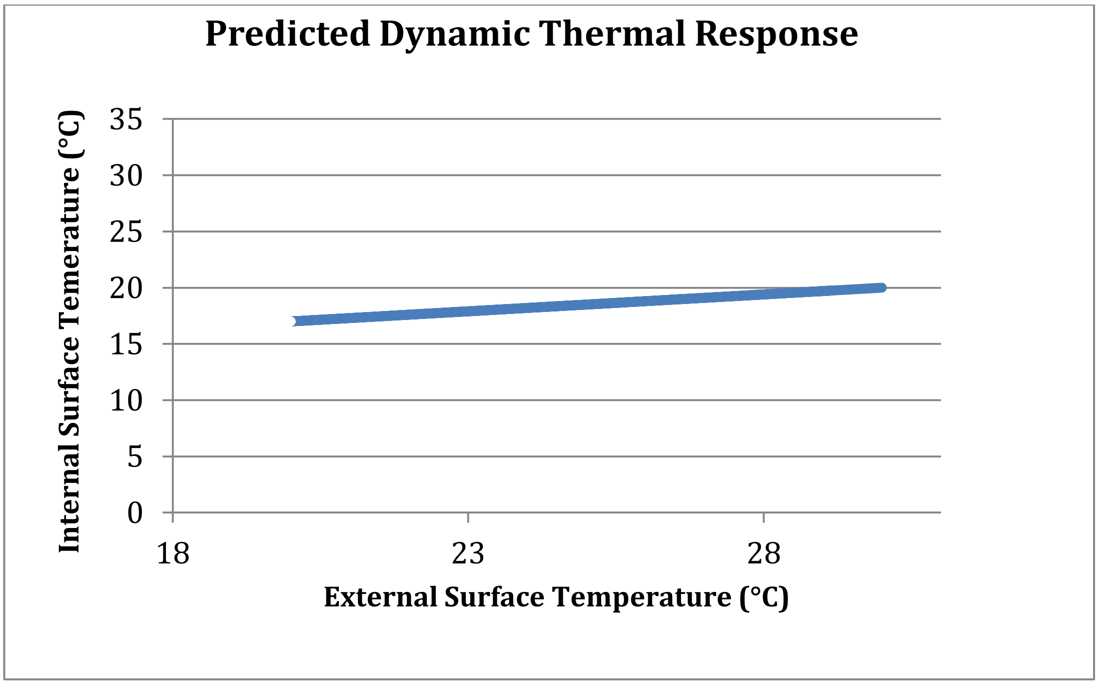


Figure 35. The predicted Dynamic Thermal Response for rammed earth.

The inclination angle, or dynamic thermal response derived from Figure 35 is 16.7°. This low value relates to good thermal performance and thus is the approximate expected result for the dynamic thermal testing of rammed earth.

4.5. Issues and Observations

There were some problems that arose during the experiment that may influence results. The main issues that occurred were involved with the construction and laboratory testing of the soil material. This was based around the problem that properties of the soil that was received did not match what was expected.

During the construction of the rammed earth wall, the soil material was assessed by the rammed earth contractor. The material had minimal adhesive properties, therefore would fail the drop test and shatter into many pieces. There were many particles around 2mm in size and not enough finer particles. This issue was improved by adding a brickie sand to the mixture to facilitate the interlocking of particles when the material is compacted. The proportions of this mix were two parts of the original material (5C5 Screened Overburdened) and one part of the brickie sand. This addition amended the material however the mixture was still lacking in silt and clay particles. There was some speculation about whether or not the material would bind together enough for the wall to remaining standing.

The laboratory testing on the material proved that the material received from the quarry was significantly different to the material that was expected. The particle size distribution of the expected soil compared to the received soil show distinct variations in the amounts of finer particles. In addition to this, the liquid limit, plastic limit and therefore the plasticity index could not be determined due to the lack of silt and clay particles. The material sample for these liquid and plastic limit tests is to be passed through a 425μm sieve. Firstly, approximately 15 kg of the mixed material (two parts original soil, one part brickie sand) had to be sieved to obtain a 300 gm sample. This small proportion of the original material would not accurately describe the behaviour of the wall. Secondly, the material that did pass this 425 μm sieve size consisted of mostly fine sands and minimal clay and silt, therefore the liquid and plastic limit tests were unable to be conducted. Given that the liquid and plastic limit tests could not be conducted with the original material, it proves that the material received was an inadequate material. The results of these laboratory tests are presented in the Section 4.6 of this report.

There was an issue regarding the moisture of the rammed earth wall, with condensation produced during the experiments potentially damaging the hot box apparatus. Due to problems with the inadequate soil material, the formwork around the wall was left on for a prolonged period of time to give the wall a better chance of standing up and not crumbling. The solution to this problem was to wrap the wall in a 100 micron thick plastic that can prevent the condensation from the wall reaching the hardware attached inside the hot box. Some difficulties were also faced with attaching the thermocouples to the damp wall. The thermocouples were fixed the to wall with strips of tape that were wrapped around the wall. The moisture of the wall may also inhibit results from producing thermal values that would reflect the thermal ability of dry rammed earth walls. However, since both steady state and dynamic tests are being conducted on the same wall, the comparison between steady state and dynamic thermal analysis can provide a better understand of the thermal performance of rammed earth walls.

4.6. Experimental Results

Soil Laboratory Tests

The experimental results for the soil laboratory testing includes the particle size distribution, moisture content of the wall soil sample and the optimum moisture content and maximum dry density test. The data from these experiments is shown in Appendix B.

The particle size distribution experiment was performed on the original soil and the mixed soil (two parts original soil and one part brickie sand). These two material types are compared and assessed whether the, brickie sand improved the particle distribution. The particle size distribution of the two soil types as well as the expected particle distribution of the 5C5 Screened Overburdened quarry material is shown in Figure 36.

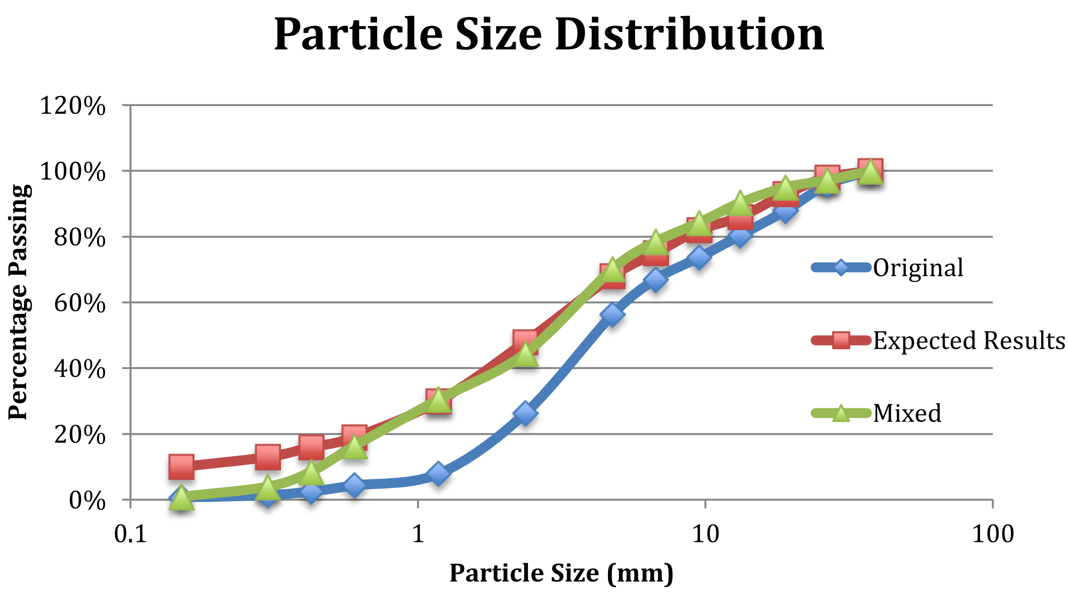


Figure 36. Particle size distribution curve.

The moisture content of the soil used for the rammed earth wall construction was found using the oven drying method. Three samples of the rammed earth wall material were taken at the beginning, middle and end of the wall construction to establish the average water content used throughout the height of the wall. The optimum moisture content of the soil was also determined using the standard compactive effort test. The optimum water content and the maximum dry density were determined through this test. The optimum moisture content (OMC) and maximum dry density (MDD) are determined from the graph in Figure 37.

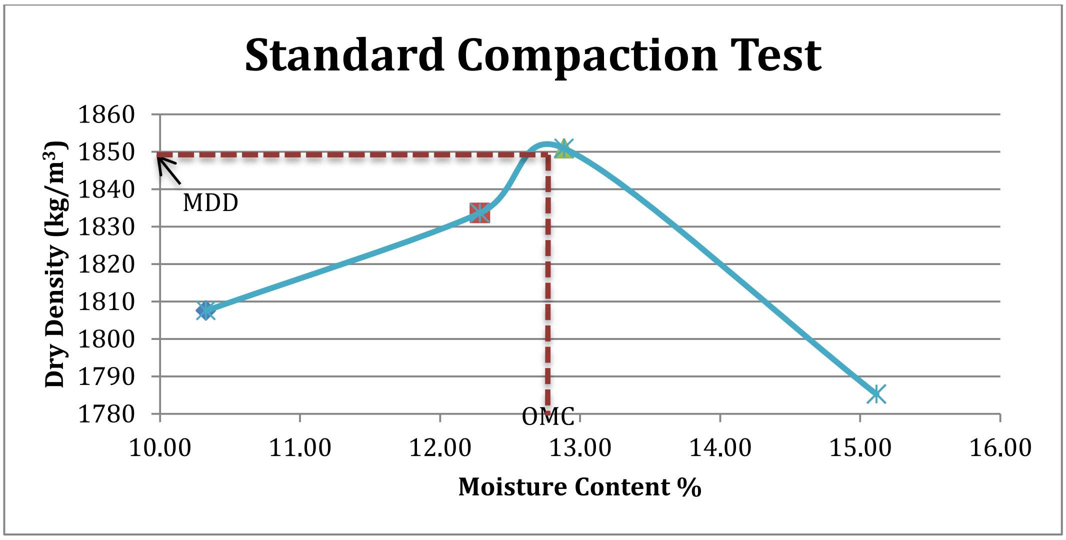


Figure 37. Standard compaction test results.

The rammed earth wall soil average moisture content, the optimum moisture content and the maximum dry density are shown in Table 4.4.

Table 4.4 — Moisture contents and maximum dry density.

Material Property	Value
Average Wall Moisture Content	13.2%
Optimum Moisture Content	12.8%
Maximum Dry Density	1852 kg/m^3

As discussed in Section 4.5, the liquid and plastic limits, and therefore the plasticity index, were unable to be determined due to the insufficient silt and clay content in the mixed material. This minimal clay and silt content was also noted when the drop test was performed, with the material shattering into many pieces rather than breaking into only a few clumps held together by the clay and silt particles. This lack of clay and silt could influence the wall's structural capacity and may also impact the thermal performance results.

Steady State Thermal Performance

Thermal resistance values are derived from the steady state thermal performance test conducted in the hot box apparatus. The surface and air temperatures were recorded and are present in Appendix C. There are three types of R-values that can be determined from this test, including the overall, surface to surface and surface to air thermal resistance. The surface-to-surface and surface to air (for hot and cold side) R-values should add together to equal the overall thermal resistance. The current and voltage of the temperature regulated heating element on the hot side and the fan and cooler on the cold side are recorded, as well as the temperatures of the metering walls and insulation panels, in order to calculate the heat flow through the specimen wall. The metering wall losses and the flanking losses are taken away from the net heat flow due to the fan and the heater. This heat flow, Q, is then used to calculate the thermal resistance values. The full calculations for the heat flow and the R-values are presented in Appendix D. The thermal resistance values shown in Table 4.5 are the results of these calculations.

Table 4.5 — Calculated thermal resistance values.

Thermal Resistance Type	R-value (m^2K/W)
Overall	0.35
Surface to Surface	0.14
Surface to air (hot side)	0.14
Surface to air (cold side)	0.06

The R-value that is to be compared against existing results is the overall R-value. The calculated overall R-value is within the range of expected R-values mentioned in Section 4.5, however is on the lower range of the expected results. This lower thermal resistance could relate to the dampness of the wall, with moisture aiding the heat flow through the specimen. Testing the wall again when it is completely dry would determine if this was true. The plastic that covered the wall during experimentation may have also hindered the results. It is however still in the expected range.

Dynamic Thermal Performance

With a material that has been tested to have a low thermal resistance value, it is interesting to note how it behaves when exposed to a dynamic environment. The dynamic thermal performance is found by exposing one side of the wall to cyclic temperature changes and recording the temperature changes on the other side of the wall. The air and surface temperatures that were recorded from each side of the wall are shown in Figure 38, depicting the true thermal behaviour of the rammed earth wall. The full data from this test is shown in Appendix E. The cold air and surface temperatures represent internal temperatures of a structure, whereas the hot air and surface temperatures symbolize external diurnal temperatures.

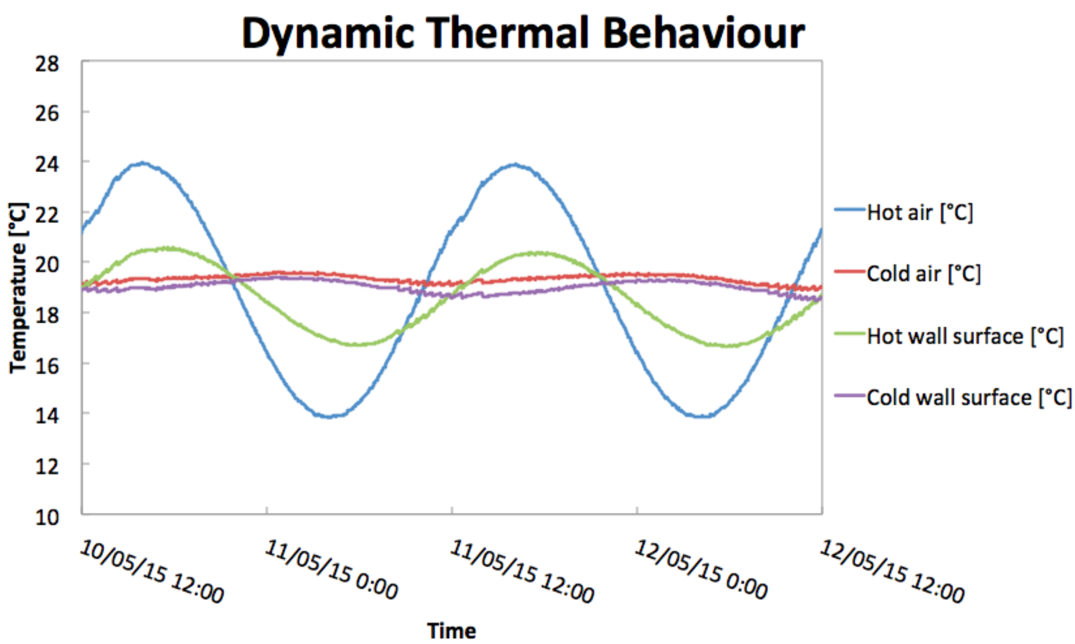


Figure 38. Dynamic thermal behaviour.

The graph displayed in Figure 38, shows that the external cyclic temperatures have a little affect on internal temperatures. This indicates that the material has good thermal performance qualities. The time lag of the material and the decrement factor have been calculated and are shown in Table 4.6.

Table 4.6 — Time lag and decrement factor results for rammed earth.

Thermal Property	Value
Time Lag	10.7 hours
Decrement Factor	0.06

The dynamic thermal response factor, or T-value, is determined by graphing one full sinusoidal curve of the internal temperatures against a full curve of external temperatures. The data for this dynamic thermal response is presented in Appendix F. The plot forms an elliptical shape of which the neutral axis represents the T-value. The elliptical shape formed from the data produced from this experiment, shown in Figure 39, has a flattened shaped due to the minimal internal temperature changes.

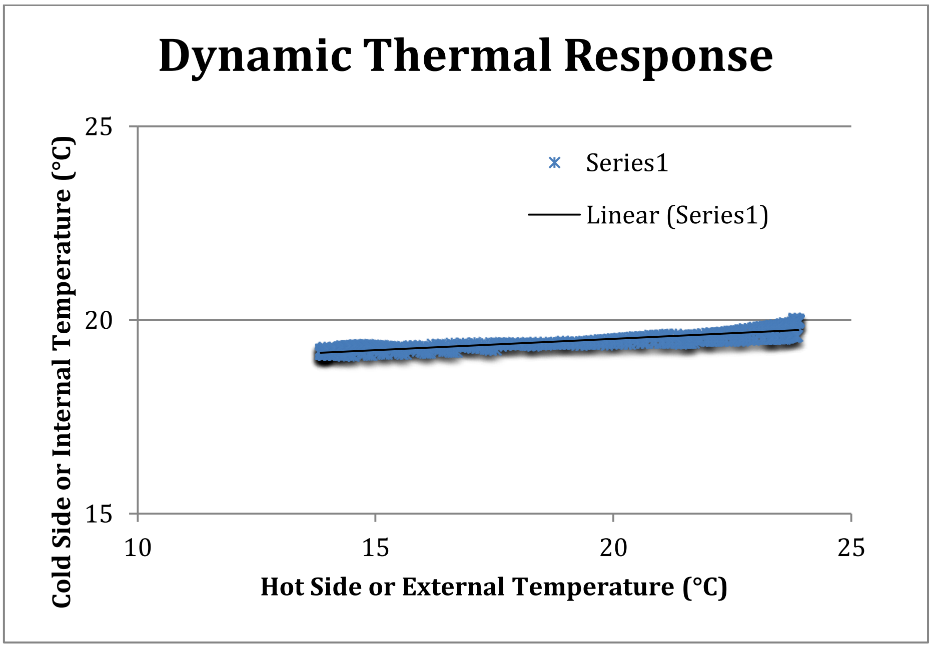


Figure 39. Dynamic thermal response.

The low inclination angle of the neutral axis, or the trendline, of the graph produces a T-value of 3.3. The high value for time lag and low values for the T-value and decrement factor indicate that the rammed earth wall was a good thermal performer. These ideas are further analysed in the discussion in Section 4.7.

4.7. Discussion

The results obtained from the soil particle size distribution show that the material received was substantially different to that was expected. The soil mix received had substantially less fine particles, hindering the material's ability to interlock. The mixed soil material, with the addition of brickie sand, gave a better particle size distribution curve that was closer to that of the expected material.

Although the addition of brickie sand improved the particle distribution, the material still lacked in clay and silt content, as discovered by the inability to perform the liquid and plastic limit tests. This lack of clay and silt particles can cause the material to crumble when compacted, rather than holding together. The drop test demonstrated this when the ball of hand compacted material shattered into many pieces, showing the material's failure to bind together. This can relate to a weaker material that may have lower strength capacities. Whilst the strength of the interlocked particles is not necessarily a factor that affects the scope of this project, it is crucial, however, that the material is sufficient for rammed earth construction. The main concerns with this project were the potential failure of the wall. Although the soil material was considered inadequate, it is important to note that the wall remained standing despite these inadequacies. Compression tests were conducted on cylindrical rammed earth samples that were made out of the same soil material used for the thermally tested wall. These compression tests found that rammed earth made out of this so-called inadequate material can take 0.5 MPa (Gray-Thompson, 2015). This strength translates to a capacity of 15 tonnes per metre in length. Although, rammed earth may not be as strong as concrete or steel, this capacity of 15 tonnes per metre is enough for small-scale constructions. Therefore, unstabilised rammed earth is indeed adequate for construction.

The thermal resistance, of 0.35 m^2K/W, found in this project agrees with the existing range of rammed earth thermal resistance. The Australian Earth Building Handbook provides a range of R-values between 0.35 and 0.70 m^2K/W, in which the calculated thermal performance of this project lies. The calculated R-value is on the lower scale of the expected results, which may have been a result of the residual moisture in the wall due to the incomplete drying process. The moisture may have aided the heat flow through the rammed earth specimen during the experiment. As expected, this low R-value does not comply with NCC's thermal resistance requirement of greater than 2.8 m^2K/W. However, this perception of inadequate thermal performance is transformed through the dynamic thermal testing results.

The dynamic thermal performance of rammed earth is proven to be excellent with internal temperatures maintained at a near constant temperature whilst external temperatures fluctuate. The rammed earth wall specimen was found to have a decrement factor of 0.06 and a time lag of 10.7 hours. This time lag value is similar to the expected value expressed in Table 3.3. Since Australian energy efficiency schemes neglect dynamic thermal performance, these decrement factor and time lag values can be compared against standards that have been set in Italy as shown in Table 3.4. This table shows that the results of this thermal experiment on the rammed earth wall represent good to excellent thermal performance. A time lag of 10.7 hours relates to good thermal performance, whilst a decrement factor of 0.06 relates to excellent thermal performing qualities.

The T-value of the rammed earth specimen was found to be 3.3, which describes a low conductive material that is known to perform well when exposed to diurnal temperature changes. This T-value is lower than what was expected; proving that rammed earth is indeed a excellent thermal performer. Although the thermal resistance is low, relating to poor performance, the low T-value proves that rammed earth is an excellent thermal performer. Comparisons between cavity brick R-values and T-values in Table 3.5 support the view that good thermal performers can have low R-values. Concrete panels have a very low thermal resistance of 0.09, similar to that of rammed earth, which categorises them both as poor thermal performers. However, when the dynamic thermal behaviour is considered, uninsulated concrete panels have a T-value of 36.3. This high T-value relates to poor thermal performance, whereas rammed earth is considered to have excellent dynamic thermal qualities. It was found that rammed earth performs the best thermally when compared to uninsulated cavity brick, insulated cavity brick and concrete panels, see Figure 40.

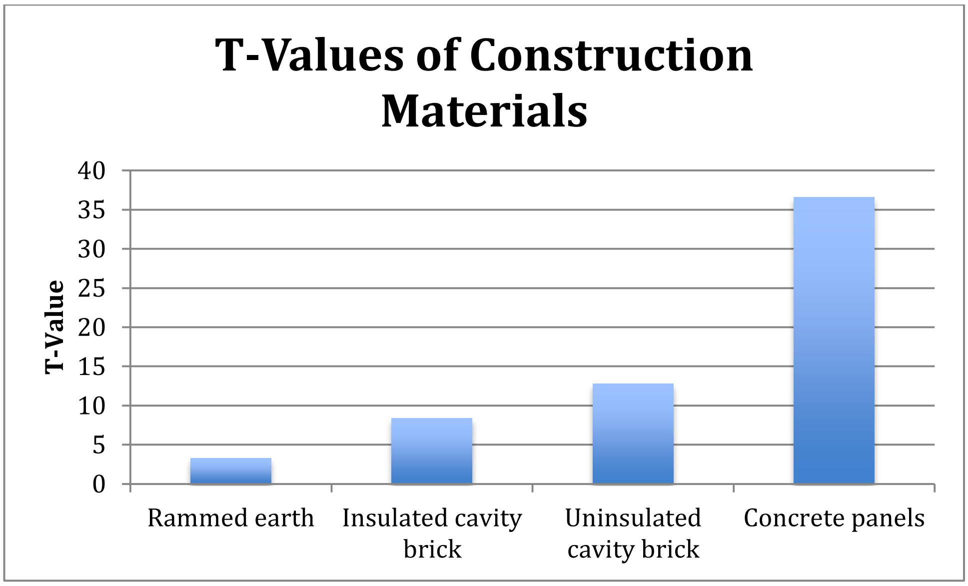


Figure 40. T-values of construction materials.

Therefore, rammed earth can be confirmed to have not only a lower embodied energy than modern materials, but also has lower operational energy than modern materials. This proves that the R-value cannot accurately describe how materials behaviour in realistic diurnal temperatures. Therefore, it is important for energy efficiency schemes to consider the dynamic thermal performance of materials to determine how materials will truly behave in diurnal climatic conditions.

The results from this experiment have been successful in showing trends that were similar to what was expected. The testing process, however, can still be fined tuned to produce precise results that can be relied upon by Australian standards. The ambient temperature could be monitored and held constant to limit losses and provide more accurate temperature readings. The rammed earth wall must also be given the appropriate amount of time to completely dry out, as it would in a rammed earth structure. This would also help with attaching the thermocouple sensors, as it is easier to attach tape to a dry wall, improving the surface temperature readings. The most important improvement that could be made to the testing procedure is to repeat the tests. These repeated tests should not only be conducted on the same wall, but also other wall of the same thickness and material to find a consistent result. This would increase the accuracy and dependability of the outcomes on thermal performance.

4.8. Experimental Summation

This experimental investigation successfully proved that rammed earth is a good thermal performer, contradicting existing views based on steady state thermal performance. Although there were issues associated with the soil material (as used), the wall was still able to present good thermal behaviour results and that this bodes well for other walls. Whilst the rammed earth wall may not have a great deal of strength capacity due to the inadequate soil properties, it is important to note that despite this inadequacy the wall was still able to be built and remains standing. The strength of this rammed earth wall is unknown, however the strength capacity of this wall can be found in the future to determine whether this poor soil material can still produce a wall with adequate strength. The tests conducted on the cylindrical rammed earth samples made out of the same soil proved that this material has a capacity of 15 tonnes per metre. This means that the rammed earth wall could hold more than 20 tonnes of vertical load, which is definitely suitable for small-scale constructions.

As expected, the steady state thermal testing on the rammed earth wall produced a low thermal resistance value correlating to poor thermal performance. The dynamic testing proved this test method as insufficient for determining the thermal behaviour of materials, demonstrating that the rammed earth specimen did indeed have good thermal performance characteristics.

The experimental objectives were met, not only proving that rammed earth is good thermal performer, but also proving that dynamic thermal characteristics should be considered in Australia's energy efficiency rating schemes. The excellent thermal behaviour of rammed earth shows that building with this earthen material can reduce the operational energy of a structure. This low operational energy combined with the low embodied energy associated with rammed earth demonstrates that rammed earth is an outstanding sustainable material.

5. Conclusion

Modern construction materials pose an increasing threat to the environment via substantial emissions of carbon dioxide from their energy intensive manufacturing and construction methods. Rapid development, combined with a growing population, means that the demand for these materials is expected to grow, and exponentially so. Not only will the world suffer drastic environmental challenges, resource scarcity is a prominent issue, particularly for materials like cement and steel. The finite amount of raw materials combined with the exponential demand growth can lead to outcomes that are not only damaging to the environment but will also cause the construction to grind to a halt. Measures must be taken to reduce the harmful impacts of these modern materials and provide renewable and sustainable alternatives.

Earthen materials are ideal substitutes for small to medium scale constructions, reducing carbon emissions and prolonging the use of non-renewable materials like steel and cement. Earth building materials require negligible embodied energy and also require low operational energy due to their superior thermal performance. Rammed earth possesses good thermal performance characteristics, however the steady state thermal resistance or R-values required by Australian energy efficiency schemes are not in accordance with the materials actual thermal superiority when tested dynamically. There is speculation about the inaccuracy of steady state analysis and the need for dynamic thermal analysis to determine the true thermal performances of materials. These current energy efficiency schemes (using only steady state parameters) are holding back earthen materials from being classified as a complete sustainable material.

A steady state and dynamic thermal analysis of a 300mm thick rammed earth wall was conducted to establish a full understanding on its thermal behaviour. As expected, the steady state and dynamic tests demonstrate contradictory results with steady state R-values showing poor thermal performance and dynamic T-values showing good thermal performance. A comparison between this rammed earth wall specimen and concrete panels proved that even though two materials can both be seen as poor thermal performers when steady state conditions are considered, the dynamic analysis can prove which material is truly a better thermal performer. This comparison proved that rammed earth is a good thermal performer, whilst the concrete panels were considered poor performers for both steady state and dynamic analysis. Rammed earth was also compared against an insulated cavity brick wall. Rammed earth's thermal performance was found to surpass the performance of insulated cavity brick wall. These comparisons show that concrete panels and insulated cavity brick walls have T-values 11 and 4 times larger than rammed earth's T-value, respectively. This proves that rammed earth has superior thermal performance. It clarifies that the dynamic thermal response of materials should be taken into account when analysing the thermal performance for energy efficiency schemes. Dynamic thermal analysis shows an accurate depiction of thermal behaviour and should be considered as a more appropriate test method as structures are exposed to dynamic diurnal conditions throughout their lifespan.

The conclusion that rammed earth is a superior thermal performer proves that building with this earthen material can significantly reduce the operational energy of the structure. The near stable temperatures achieved inside the building decreases the need for additional heating and cooling, which is the main contributor to energy consumption in structures. This low operational energy combined with low embodied energy presents rammed earth as an ideal sustainable material for future construction.

6. Further Research

There are many areas of this project that can be researched further. The experimental results of this project have been a good indication that rammed earth is indeed a good thermal performer based on dynamic simulation. This is revolutionary research that needs to be further investigated to produce consistent and reliable dynamic results that can be incorporated into future energy efficiency schemes.

Further tests should be conducted on the rammed earth wall specimen used in this project after it has been allowed to dry completely. The absence of moisture could slightly impact on the thermal results. This secondary test should also aim to minimise the errors associated in the experimentation of this project, including controlling the ambient temperature and repeating the test at least three times produce a consistent result. Extended testing should be conducted on walls built with the same material, walls built with other soil materials and walls with varying thicknesses. These tests can produce a variation of thermal behaviour results that can enhance the industry's understanding of rammed earth's thermal behaviour.

The compatibility of the soil material is a crucial element that may not only vary thermal results, but can also determine the strength capacity of rammed earth. Modern materials have been researched to produce a variety of categories that all have differing strength capabilities. Steel, for example, can vary between hot-rolled, cold-rolled, cast or drawn, each having different ductility and strength abilities. Similar research can be carried out for rammed earth on different soil types with different strength and thermal capacities associated with each soil type. Defining a wide range of soil types that can be used for successful rammed earth construction can allow design of rammed structures to be flexible with incorporating locally sourced soils. For example, if local soils are weaker, than the walls could be designed to be thicker. The first step is discovering the properties of these varying soil types.

There are other areas of rammed earth that must be researched, including bending strength, compression strength, shear strength, and weathering for rammed earth walls, slabs and footings. Further research in these specific areas can lead to an Australian Standard for the raw rammed earth material. Regulated rammed earth construction will assist it in becoming a reliable, mainstream product that can contribute to sustaining the environment for future generations.

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8. Appendices