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**Evaluating the thermal performance of stabilized rammed earth walls in residential
buildings in Kathmandu valley**

by

Bibek K.C

A THESIS


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DEGREE OF MASTER OF SCIENCE IN
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DECLARATION

I hereby declare that the thesis entitled “Evaluating the thermal performance of stabilized rammed earth walls in residential buildings in kathmandu valley” submitted to the Department of Architecture in partial fulfilment of the requirement for the degree of Master of Science in Energy Efficient Buildings, is a record of an original work done under the guidance of Prof. Dr. Sushil bahadur bajracharya, Institute of Engineering, Pulchowk Campus. This thesis contains only work completed by me except for the consulted material which has been duly referenced and acknowledged.



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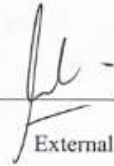
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ABSTRACT

This study evaluates the thermal performance of stabilized rammed earth (SRE) walls in residential buildings within Kathmandu Valley, Nepal, comparing them with traditional reinforced cement concrete (RCC) structures. The research addresses the growing energy demands and environmental challenges posed by conventional construction materials, emphasizing the need for sustainable alternatives. Through field measurements using HOBO data loggers and CO₂ recorders, indoor and outdoor temperature data were collected from SRE buildings (Dekaido Onseen and Madan Pustakalaya) and an RCC building over multiple days.

Results demonstrate that SRE walls exhibit superior thermal regulation, maintaining indoor temperatures consistently warmer than outdoor conditions by 1.09°C and 1.73°C at the respective sites. The high thermal mass of SRE walls enables effective heat absorption during the day and gradual release at night, reducing reliance on mechanical heating and cooling systems. In contrast, the RCC building showed less stable thermal performance, with larger temperature fluctuations and higher energy demands.

The findings highlight SRE's potential to enhance energy efficiency, lower carbon emissions, and improve indoor comfort in Kathmandu's climate. The study concludes that SRE is a viable, sustainable alternative to conventional materials, aligning with global goals for eco-friendly construction. Limitations include the use of basic data loggers and reliance on weather data from a distant location, suggesting avenues for future research with advanced tools and localized climate data.

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ABBREVIATION

(RE)	Rammed earth
(NRE)	Natural rammed earth
(SRE)	Stabilized rammed earth
(OPC)	Ordinary Portland Cement
(CO ₂)	Carbon dioxide
(CaO)	Calcium oxide
(CaCO ₃)	Calcium carbonate
(UNESCO)	United Nations Educational, Scientific and Cultural Oraganization
(GHGs)	Greenhouse gases
(CL)	Crushed limestone
(CSRE)	Cement Stabilized Rammed Earth
(IEA)	International Energy Agency
(IPCC)	Intergovernmental Panel on Climate Change

CHAPTER 1: INTRODUCTION

1.1 Background

Rammed earth (RE) buildings are gaining relevance worldwide for their reduced embodied energy due to the use of locally available materials and low amount of cement (Strazzeri & Karrech, 2022). Uses of earth for building purposes have gone through adaptation, modification, and innovation in the course of history. Throughout history, the use of earth for construction has undergone invention, adaptation, and alteration. This has been modified to house common people and to construct notable buildings from other civilizations. Earth construction is one of the oldest and most widespread building methods in the world. As a result, numerous significant earthen heritage sites and historic structures can be found globally. However, its use has largely declined in high-income regions, leading to limited academic focus on the material until recent years. Interest in earthen construction has grown within the academic community, partly due to the need for further scientific understanding to support the preservation of earthen heritage. Additionally, there is a growing awareness of the importance of reducing CO₂ emissions from the construction sector, which has further fueled this renewed attention (Mariscal et al., 2024). Around the world, rammed earth is used extensively as an antiquated building material (Strazzeri & Karrech, 2022). Raw earth construction boasts a rich and extensive history that spans over 9,000 years. Archaeological findings provide compelling evidence of its ancient origins, including mud houses that date back to around 4000 BCE in present-day Turkmenistan. Even earlier examples have been discovered in the Tigris River Basin, where structures were built as far back as 7500 BCE, demonstrating the long-standing relationship between early civilizations and earthen building techniques. Additionally, adobe blocks uncovered in Palestine have been dated to approximately 9,000 years ago, further highlighting the global and historical significance of earth as a construction material (Bhandaree & Tharmarajah, 2023). Earth has long been utilized as a versatile building material, adaptable to a variety of construction systems. However, its primary application has traditionally been in the construction of walls. This use of earth in architecture has been well-documented in numerous historical and archaeological sites around the world, showcasing its durability and cultural significance across different civilizations. The materials used in raw earth

construction typically include natural components such as fine clay, silt, and sand. These elements are abundant in nature and have been skillfully combined throughout history to create durable, functional, and climate-responsive structures. Modern researchers continue to study these materials in depth to better understand their properties, performance, and potential enhancements. Through ongoing scientific investigation, experts aim to optimize raw earth mixtures for greater strength, sustainability, and adaptability in contemporary architecture, while also preserving traditional building knowledge and promoting eco-friendly construction practices (Bhandaree & Tharmarajah, 2023). In recent years, interest in earth as a sustainable building material has grown considerably, largely due to its positive environmental impact. As a result, it has become the subject of a wide range of scientific research and academic studies, exploring its properties, potential improvements, and modern applications (Rio et al., 2021). Natural rammed earth (NRE) is a sustainable construction technique that involves compacting a processed earth mixture within a reusable engineered framework. Unlike most modern building materials, earthen materials and construction methods are locally sourced, require minimal processing, have a low carbon footprint, and promote environmental sustainability. Rammed earth walls are built by pouring the humid earth into a mould and compacting it until it is stiff enough and traditionally, the compaction process goes on by using a wooden rammer is performed (Mariscal et al., 2024). The use of earth as a construction material has been widespread across the globe since ancient times. Many researchers have highlighted the appealing characteristics of earthen buildings, including effective thermal and acoustic insulation, fire resistance, affordability, and ease of handling. In contemporary architecture, there is a renewed interest in earth due to its strong environmental benefits: low carbon emissions, absence of demolition waste, and the potential to incorporate industrial by-products or recycled materials as additives. Notably, several environmentally conscious architectural projects are embracing earth as a sustainable, modern building material (Mariscal et al., 2021). With the increasing emphasis on sustainable construction as a response to climate change, there is a growing interest in adopting earthen building techniques (Ramezannia et al., 2024). Unlike NRE, which consists of natural components such as clay and straw, modern rammed earth also referred to as stabilized rammed earth (SRE) has evolved in recent decades. SRE incorporates a binding agent (typically 5 to 10% cement, lime, or

bitumen) to improve the material's mechanical strength, ensuring compliance with construction regulations. However, while these binders enhance durability, they also diminish some of the environmental advantages associated with NRE. The rise in industrial development and population has resulted in a significant rise in energy demand. In 2009, the building sector emerged as one of the most energy-intensive industries, accounting for approximately 40% of the total energy consumption in both the United States and the European Union. This significant figure highlights the substantial impact that the construction, operation, and maintenance of buildings have on national and regional energy demands (Uprety et al., 2021). The energy used spans various activities, including the production and transportation of construction materials, the physical construction process, and the ongoing energy requirements for heating, cooling, lighting, and powering equipment within buildings throughout their lifespans. This level of energy use places considerable pressure on natural resources and contributes heavily to greenhouse gas emissions. As a result, the building sector has become a primary focus for energy efficiency initiatives and sustainable development strategies aimed at reducing overall energy consumption and minimizing environmental impact (Uprety et al., 2021).The construction industry plays a significant role in the consumption of natural resources and the use of energy across all stages of a building's life cycle. This impact begins with the extraction and processing of raw materials needed for construction, continues through the construction phase itself, and extends all the way to the building's operation, maintenance, and eventual demolition. At each of these stages, large quantities of energy are required, and valuable natural resources are depleted, contributing to environmental degradation and increasing carbon emissions. As a result, the building sector is recognized as one of the major contributors to global environmental challenges. Reducing its ecological footprint has become a critical goal in efforts to promote sustainability, resource efficiency, and environmental responsibility in both new construction and renovation projects (Strazzeri & Karrech, 2022).One of the most notable techniques involving earth is known as "rammed earth." This method involves compacting slightly moist soil where the moisture content is below the plastic limit into layers within reusable formworks. The compaction process creates dense, strong walls that offer excellent thermal mass and structural integrity. Rammed earth is increasingly recognized in modern construction for its low environmental

footprint and aesthetic appeal, making it an attractive option in sustainable architectural design (Rio et al., 2021).

1.2 Traditional and modern construction materials

Rammed earth (RE) construction is experiencing a resurgence of interest on a global scale, largely due to its numerous sustainable and environmentally friendly characteristics. One of the key advantages of this traditional building technique is its exceptionally low embodied energy, meaning that the amount of energy required to extract, process, transport, and assemble the materials is minimal compared to conventional construction methods. This makes rammed earth an appealing choice in the pursuit of greener, more energy-efficient buildings (Nabouch et al., 2016). Raw-earth construction material is one of the oldest and has been used since about 15000 BCE at the beginning of the settlements of mankind, but its use was widely developed during the creation of the first cities near the waterways (Luo et al., 2024). Almost 30% of the world's population lives in raw earth construction. Moreover, 10% of the sites inscribed in UNESCO are partly or totally composed of raw earth. In addition to its environmental benefits, rammed earth offers notable performance qualities that enhance indoor living comfort. Its significant thermal inertia allows it to naturally regulate indoor temperatures by absorbing heat during the day and releasing it slowly at night, reducing the need for artificial heating or cooling systems. This thermal mass contributes to a stable and comfortable indoor climate throughout changing seasons. Moreover, rammed earth has excellent moisture buffering capabilities, helping to maintain balanced humidity levels inside buildings, which promotes healthier indoor air quality. Aesthetically, rammed earth structures are also appreciated for their natural and earthy appearance, which often features warm tones and textured finishes that blend harmoniously with the surrounding environment. These combined qualities make rammed earth a compelling option for sustainable and visually appealing modern architecture (Nabouch et al., 2016).

The production of Ordinary Portland Cement (OPC) is widely recognized as one of the leading contributors to global carbon dioxide (CO₂) emissions. The manufacturing process involves heating a carefully blended mixture of raw materials primarily calcium carbonate

(limestone), along with silica, iron oxide, and alumina to an extremely high temperature of around 1450°C in a rotary kiln. This energy-intensive process generates CO₂ in two major ways: first, through the chemical decomposition of limestone (a process known as calcination), and second, from the combustion of fossil fuels used to achieve the required temperatures in the kiln. As a result, the environmental impact is substantial, with the production of just one ton of OPC releasing between 0.689 and 0.9 tons of carbon dioxide into the atmosphere (Bhandaree & Tharmarajah, 2023). Despite this, the use of raw earth has been marginalized, especially due to the overuse of concrete (Luo et al., 2024). The cement industry accounts for approximately 12–15% of the total energy consumed by the industrial sector worldwide. However, certain stages of cement production contribute to CO₂ emissions, primarily during the formation of clinker a vital cement component. In this process, carbonates, mainly limestone (CaCO₃), decompose under heat into oxides, predominantly lime (CaO), releasing CO₂. According to stoichiometric calculations, a specific amount of CO₂ is emitted for each unit of CaO produced. As a result, the cement industry could be responsible for up to 8% of global CO₂ emissions (Poudyal et al., 2025). Given the construction industry’s heavy reliance on cement as a primary binding material, finding a viable and sustainable alternative to OPC has become a critical and urgent challenge. Researchers and engineers around the world are actively exploring innovative solutions that can reduce or eliminate the carbon footprint associated with traditional cement production. These include the development of alternative binders, such as geopolymers, the use of industrial by-products like fly ash and slag, and the incorporation of natural materials that offer lower embodied energy. However, replacing OPC on a large scale is complex due to factors such as availability, cost, durability, regulatory standards, and performance under varying environmental conditions. Despite these challenges, the search for greener alternatives remains a top priority for achieving sustainability goals within the construction sector (Bhandaree & Tharmarajah, 2023).

In recent years, the demand for cement has seen a significant increase, especially in the aftermath of the devastating 2015 earthquake in Nepal, which led to the destruction of more than 500,000 buildings across the country. This disaster triggered a massive wave of reconstruction and infrastructure development, causing a sharp rise in cement consumption. While the global growth rate of cement consumption is estimated to be

around 3% annually, Nepal's demand is expanding at a much faster pace, with projections indicating an annual growth rate between 10% and 15%. This rapid increase highlights the country's accelerating need for construction materials to support its rebuilding efforts and ongoing urbanization (Poudyal et al., 2025). Of this total, 1.4 Gt CO₂ resulted from process-related emissions due to chemical reactions during calcination, 0.6 Gt CO₂ came from fuel combustion (direct emissions), and 0.3 Gt CO₂ was attributed to electricity consumption (indirect emissions) (Poudyal et al., 2025). The widespread use of concrete in construction has been accompanied by notable environmental drawbacks, particularly its high energy consumption and substantial carbon emissions. These negative impacts have contributed significantly to environmental challenges such as air pollution and the escalating problem of climate change. Concrete production requires enormous amounts of energy, both in the extraction and processing of raw materials and in the manufacturing process itself, which results in the release of large quantities of carbon dioxide (CO₂) into the atmosphere. As the world becomes increasingly aware of the environmental costs associated with traditional construction materials, there has been growing recognition of the need for more sustainable alternatives. In this context, rammed earth (RE) construction is experiencing a resurgence in popularity due to its environmentally friendly attributes. Unlike concrete, rammed earth requires far less energy to produce and has a much lower carbon footprint. It is made from natural, locally available materials such as clay, sand, and silt, which are compacted into formworks to create durable, efficient, and aesthetically pleasing structures. The environmental benefits of rammed earth, including its minimal embodied energy, ability to regulate indoor temperatures, and its use of renewable resources, have made it an attractive option for those seeking more sustainable building practices. As the construction industry seeks to mitigate its environmental impact, RE offers a promising alternative that aligns with global efforts to reduce carbon emissions and promote eco-friendly development (Zarasvand et al., 2023). Despite the growing demand, Nepal's domestic cement production has not kept pace consistently over the past two decades. The country's cement industry has faced various challenges that have hindered steady growth, including limitations in technology, infrastructure, and investment. The history of cement production in Nepal dates back to the 1950s, a time when the nation largely depended on neighboring India to meet its cement needs. Although Nepal has made

progress toward becoming more self-reliant in cement manufacturing, fluctuations in production capacity and efficiency still persist (Poudyal et al., 2025). To address the high energy demands and carbon footprint of cement production, governments, regulatory agencies, and international organizations are enforcing stricter policies worldwide. Energy consumption represents 50–60% of the total manufacturing cost in the cement industry, with thermal energy accounting for 20–25%. Therefore, a comprehensive energy analysis is crucial for identifying inefficiencies and implementing strategies to reduce energy consumption within this sector. On a global scale, the environmental impact of cement production remains a serious concern. In 2019 alone, the cement industry was responsible for emitting approximately 2.3 gigatons (Gt) of carbon dioxide (CO₂), making it one of the largest industrial sources of greenhouse gas emissions. This underscores the urgent need for sustainable alternatives and improved production practices in both global and local contexts to reduce the sector’s ecological footprint (Poudyal et al., 2025). To reduce the harmful influence of the building sector on our planet, one of the avenues considered is the development of materials that are less energy-consuming, more efficient, and more respectful of the environment (Luo et al., 2024). One of the most appealing aspects of rammed earth structures is their seamless integration with the surrounding natural environment. The materials used such as clay, sand, and silt are often sourced locally, allowing the buildings to harmonize with the local landscape both visually and environmentally. This connection to nature is particularly evident when rammed earth buildings are seen in clusters or arranged in various architectural configurations. From an architectural perspective, these structures possess a unique ability to blend into their surroundings, creating a sense of continuity and balance with the natural elements. Whether situated in rural areas, desert landscapes, or even urban environments, rammed earth buildings evoke a sense of timelessness, as if they have always been a part of the land. This integration not only contributes to the aesthetic value of the structures but also enhances the sense of place, making them feel as though they belong to the very soil from which they are made. The ability of rammed earth to adapt to different arrangements and architectural designs further amplifies its versatility, offering a sustainable and visually appealing alternative to more conventional construction materials (Yonzan & . Bajracharya, 2022). The construction industry plays a major role in global energy

consumption. According to the World Business Council for Sustainable Development, buildings account for 40% of total energy use, making the sector a key contributor to global warming due to the emission of greenhouse gases (GHGs). Researchers predict that by 2035, carbon emissions from buildings could reach 42.4 billion tons. Given the environmental impact of construction, it is crucial to implement measures that reduce energy consumption and GHG emissions. One of the most effective strategies is promoting energy-efficient buildings, which require less energy to operate. This, in turn, reduces the demand for energy production and helps lower GHG emissions, ultimately benefiting the environment (Bhattarai & Bhattarai, 2023).

1.3 Stabilized rammed earth

Stabilized rammed earth (SRE), often referred to as modern rammed earth, has emerged over the past few decades as an advanced variation of traditional rammed earth (NRE). This innovative approach involves incorporating a binder, typically ranging from 5 to 10% by weight, into the earth mixture. Common binders include cement, lime, or bitumen, which serve to improve the material's mechanical properties. The addition of these binders significantly enhances the structural strength and durability of rammed earth, making it more suitable for meeting the stringent requirements of modern construction codes. This advancement allows for greater flexibility in building design and opens up possibilities for using rammed earth in a wider range of construction projects, including those with higher load-bearing demands (Ramezannia et al., 2024). However, while SRE offers improved performance, it also comes with certain trade-offs in terms of sustainability. The inclusion of binders such as cement or bitumen diminishes some of the environmental benefits that are inherent to traditional non-stabilized rammed earth (NRE). The production of cement and other binders contributes to increased carbon emissions, reducing the overall ecological advantage of using earth as a building material. While SRE maintains many of the positive attributes of rammed earth such as good thermal insulation and moisture regulation the environmental impact of the binders used in the mixture highlights the need to balance performance with sustainability. Consequently, the adoption of SRE should be carefully considered, weighing its enhanced mechanical properties against the potential reduction in its environmental benefits (Ramezannia et al., 2024). In modern rammed earth construction, stabilizers such as cement have been increasingly utilized to enhance the

engineering properties of the material. The addition of cement helps improve the strength and structural integrity of the earth mixture, making it more suitable for contemporary construction standards. Over the past few years, the use of cement in rammed earth has gained popularity worldwide due to its accessibility and ability to provide the necessary strength characteristics required for various building applications. The typical cement content in modern rammed earth construction ranges from 6% to 10%, which is generally sufficient to meet the strength requirements for most projects. However, while cement improves the compressive strength of rammed earth, it does not necessarily ensure long-term durability, which remains a challenge for this construction method (A et al., 2025). Research studies have shown that a cement content of around 6% offers the best balance between strength and sustainability, providing enhanced compressive strength without significantly compromising the material's eco-friendly advantages. On the other hand, cement content exceeding 15% begins to shift the composition toward a lean concrete mix, which is not advisable for sustainable construction due to the environmental impact of cement production. Excessive use of cement reduces the overall environmental benefits of rammed earth, as it introduces higher embodied energy and carbon emissions. Consequently, while cement stabilization can be beneficial in certain applications, it is important to carefully control its proportion in the mix to maintain both the material's structural performance and its environmental sustainability (A et al., 2025). The substrate materials can vary and may include crushed limestone (CL), in modern applications like SRE and waste granular materials, or fibrous particles, used alongside or in place of soil. SRE contains 5 to 10% stabilizers, such as cement, lime, or bitumen to meet the physical and mechanical requirements of construction codes (Ramezannia et al., 2024). Lime-stabilized rammed earth (LSRE) plays an important role in enhancing the properties of traditional rammed earth by utilizing lime as a stabilizer. One of the key factors in the effectiveness of lime stabilization is the activation of pozzolanic reactions, which occur when lime interacts with the fine particles in the soil. These reactions contribute to the hardening and strengthening of the material over time. In LSRE, the finer the soil particles (fines content), the more pronounced the pozzolanic reaction, which in turn leads to higher compressive strength. This is because the finer particles provide a greater surface area for the lime to react with, resulting in a more solid and durable structure (Baibordy et al.,

2025). As the fines content increases, the lime can more effectively bind the soil particles together, improving the overall strength of the rammed earth mix. This enhancement makes LSRE a more robust material compared to non-stabilized rammed earth, offering better resistance to stresses and loads. The pozzolanic reaction not only strengthens the material but also contributes to its durability and long-term performance, making LSRE an attractive option for modern sustainable construction. Additionally, this process allows lime-stabilized rammed earth to maintain many of the environmental benefits associated with traditional rammed earth while improving its mechanical properties, making it suitable for a broader range of construction applications (Baibordy et al., 2025). Cement Stabilized Rammed Earth (CSRE) has various issues and needs further investigation and solutions, due to water absorption in the pores of RE has caused loss of strength that affects its durability and structural integrity (A et al., 2025). Beyond cement as a stabilizer, Alker technology offers an alternative method for enhancing traditional earthen materials. This approach utilizes earth containing approximately 8% clay, stabilized with gypsum and lime. Research by and Pekrioglu highlights its advantages, including improved workability and mechanical properties. Gypsum is known for its ability to facilitate rapid hardening in building materials, allowing for quicker setting times and efficient construction processes. In contrast, lime works by extending the workable time of the material, providing more flexibility during the construction process and allowing workers to handle and adjust the mixture more easily before it sets. This combination of gypsum and lime creates a balance between fast-setting properties and extended workability, making the material more adaptable for various construction needs (Ramezannia et al., 2024). Moreover, the incorporation of additional materials such as waste marble dust and polypropylene fibers into Alker a type of building mix can significantly enhance its mechanical properties. Waste marble dust, which is a by-product of marble processing, serves as a supplementary material that improves the mix's overall strength and durability. Polypropylene fibers, on the other hand, contribute to the material's structural integrity by reinforcing the mixture, preventing cracks and improving its resistance to tensile stresses. Research has shown that when these fibers are included, the compressive strength of the material can increase by up to 112.9%, while its flexural strength resistance to bending can be enhanced by 41%. This combination of additives not only boosts the material's mechanical performance but also

contributes to sustainability by repurposing waste materials, making it an excellent option for more durable and environmentally responsible construction (Ramezannia et al., 2024).

1.4 Importance of Thermal Performance in Buildings

The building sector, which includes both residential and commercial properties, is responsible for about one-third of the world's total energy consumption and carbon dioxide (CO₂) emissions. This significant contribution to global energy use and emissions highlights the sector's pivotal role in the fight against climate change. Looking ahead, energy demand within the built environment is expected to increase by 55% by the year 2050, driven by factors such as population growth, urbanization, and evolving building standards. Given this projected rise in demand, achieving meaningful reductions in energy consumption across the sector will necessitate large-scale energy efficiency measures, targeting both the design and operation of buildings (Tian et al., 2015). In recent years, there has been growing interest in researching the energy performance of entire building stocks rather than focusing solely on individual buildings. This shift in focus reflects a recognition that addressing energy consumption at a broader scale across entire building portfolios has the potential for greater impact. However, compared to studies that examine the energy performance of single buildings, fewer studies have tackled the challenge of modeling and analyzing the collective energy behavior of entire building stocks. This area of research remains relatively new, and much work remains to be done in developing effective methods and tools to assess and optimize the energy performance of building stocks as a whole. Understanding the dynamics of energy use across large groups of buildings is essential to implement large-scale efficiency strategies that can help meet global sustainability goals (Tian et al., 2015). Heat transfer through building envelopes plays a crucial role in the overall energy consumption of structures. The building sector is one of the most energy-intensive industries, primarily due to the high energy demand required for maintaining comfortable indoor temperatures, especially for cooling during the hot summer months and heating during the colder winter months. This significant energy consumption places considerable pressure on both environmental resources and energy systems. To address these challenges, reducing the thermal loads and overall energy consumption of buildings is crucial. Achieving this goal largely depends on strategies that minimize the conduction of heat through building materials, regulate temperature

fluctuations caused by external weather conditions, and extend the time delay between the peak temperatures on the outer surfaces of walls and roofs and those on the interior surfaces. These strategies help reduce the need for mechanical heating and cooling systems, ultimately lowering energy consumption (Toufigh & Samadianfard, 2022).As climate conditions continue to vary and energy demands rise, it becomes increasingly important to focus on enhancing the thermal performance of building materials. Further research in this area is essential to better understand how different materials and construction techniques can effectively reduce heat transfer and improve temperature stability within buildings. By advancing our knowledge of thermal insulation, heat storage, and heat transfer properties of materials, we can develop more energy-efficient building designs that not only improve comfort but also contribute to significant energy savings and a reduction in carbon emissions. This ongoing research is a key factor in creating sustainable buildings that are better equipped to handle the challenges posed by climate change and energy scarcity (Toufigh & Samadianfard, 2022). The energy performance of building stock at a national level has been analyzed in various countries, including Ireland, Greece, Portugal, the UK, and the USA. Similarly, global sensitivity analysis on an energy model of England's housing stock was conducted, identifying wall insulation and demand (setpoint) temperature as the most influential uncertain parameters. Key factors influencing energy performance include wall insulation, lighting demand, exposed wall area, and operational schedules. The impact of energy-saving measures is typically assessed by evaluating how changes in these variables affect overall energy consumption (Tian et al., 2015).

According to the International Energy Agency (IEA), the building sector which includes residential buildings, non-residential structures, and the broader construction industry accounts for a significant portion of global energy consumption, contributing to nearly 36% of the total energy used worldwide. In addition to its substantial energy demands, this sector is also a major source of greenhouse gas emissions, responsible for approximately 39% of the global emissions. This includes emissions from various stages, such as the construction of buildings, their operation (heating, cooling, lighting, etc.), and the materials used in the building process. The impact of this sector on both energy use and emissions underscores the urgent need for more sustainable building practices, energy-efficient designs, and eco-friendly materials. Reducing the environmental footprint of the building sector is essential

in the global effort to combat climate change and achieve a more sustainable future (Luo et al., 2024). On a global scale, the construction industry plays a significant role in the consumption of energy, accounting for more than 34% of the total energy used worldwide. In addition to its substantial energy demands, the sector is also a major contributor to global carbon dioxide (CO₂) emissions, responsible for approximately 37% of the total emissions. A notable portion of these emissions, around 10%, is attributed to the manufacturing of building materials and products. This includes the energy-intensive processes involved in producing materials such as cement, steel, and glass, which require vast amounts of energy and lead to significant greenhouse gas emissions. As the construction industry continues to grow and urbanization expands, these figures highlight the urgent need for more sustainable practices within the sector to reduce its environmental impact. Efforts to improve energy efficiency, reduce emissions, and promote the use of eco-friendly materials are crucial in mitigating the industry's contribution to climate change and ensuring a more sustainable future for construction (Ramezannia et al., 2024). The thermal performance of buildings, and therefore building materials, is of the utmost importance for their sustainability, as it contributes to overall thermal comfort as well as the reduction of energy consumption to achieve that state (Real et al., 2024). Rammed Earth (RE) construction provides excellent thermal performance, particularly when used in the right climatic and technical settings. Under specific environmental conditions, such as regions with significant temperature fluctuations between day and night or areas with extreme climates, RE's ability to regulate indoor temperatures becomes a significant advantage. The natural materials used in RE construction such as clay, sand, and silt possess high thermal mass, meaning they can absorb, store, and slowly release heat. This characteristic helps to maintain a stable indoor temperature, reducing the need for active heating or cooling systems (Strazzeri & Karrech, 2022).

1.5 Kathmandu Valley Climate and Housing Challenges

The global climate is undergoing significant changes that are having diverse effects across various sectors, influencing different regions in unique ways. As a result, it is anticipated that the Kathmandu Valley will experience similar climate-related impacts, though the specific effects may vary depending on local conditions and vulnerabilities. According to the Intergovernmental Panel on Climate Change (IPCC, 2013), global temperatures have

already risen by approximately 0.3 to 0.6°C when compared to historical levels recorded in 1900. This trend of rising temperatures is expected to continue, with projections indicating that by the year 2100, global temperatures could increase by anywhere between 1.4°C and 5.8°C. These temperature changes are likely to bring about shifts in weather patterns, with potential consequences for local ecosystems, agriculture, water resources, and infrastructure in the Kathmandu Valley. The rising temperatures and changing climatic conditions will likely amplify existing environmental challenges, making it essential for the region to prepare for and adapt to the anticipated impacts of climate change. Addressing these issues will require careful planning and the implementation of strategies aimed at mitigating the effects of global warming and enhancing the resilience of local communities (Shrestha et al., 2020). The Kathmandu Valley is home to three major cities-Kathmandu (the capital), Lalitpur, and Bhaktapur and is regarded as the most developed region in the country. As a result, people from across the nation migrate to the valley in pursuit of better opportunities and an improved quality of life. This population influx has led to rapid and unplanned construction of infrastructure and residential buildings. Previous studies indicate that built-up areas in the valley have expanded significantly, rising from **5.10% to 26.06%**. Additionally, research suggests that Kathmandu and Lalitpur have experienced substantial urban growth over the past three decades, which may have contributed to the rise in urban temperatures in the core areas of the valley (Shrestha & Shimizu , 2021). A key contributor to the increase in urban temperatures is the extensive use of construction materials that are impermeable, such as concrete, asphalt, and glass. These materials have high thermal mass, meaning they absorb and retain heat from the sun, which in turn raises the temperature of the surrounding environment. Unlike natural surfaces like soil or vegetation, these man-made materials reflect very little sunlight and tend to trap heat within the urban landscape. As a result, cities experience what is known as the "urban heat island effect," where built-up areas become significantly warmer than their rural counterparts. The combination of heat absorption and low sunlight reflection causes these materials to retain heat for extended periods, especially during the day and throughout the night, further exacerbating the urban temperature rise. This phenomenon not only increases energy consumption due to higher cooling needs but also contributes to greater discomfort and health risks for city residents, making it essential to consider alternative, more sustainable

materials in urban development to mitigate these effects (Shrestha & Shimizu , 2021), thus Rammed earth possesses significant advantages compared to other building materials such as concrete, steel, and wood: exceptional thermal insulation and humidity regulation properties, cost-effectiveness, a straightforward construction process with low energy consumption, and recyclability. Therefore, rammed earth building is widely distributed (Zarasvand et al., 2023). In naturally ventilated buildings, thermal energy consumption is significantly influenced by HVAC operation and window usage during the heating season. For instance, lowering the temperature setpoint from **20°C to 19°C** can lead to a **9%–10%** reduction in energy demand (Ubachukwu et al., 2025).

Nepal has traditionally had a relatively low level of urbanization, with much of the population residing in rural areas. However, in recent years, the country has experienced a rapid surge in urban growth, with more and more people migrating to cities in search of better opportunities. This fast-paced urbanization has placed considerable pressure on existing infrastructure and resources, as many urban areas still lack adequate amenities and services to support the growing population. Despite these challenges, by 2012, the urban population of Nepal had reached 66.08%, reflecting a significant shift toward urban living. This growth indicates a marked change in the demographic trends of the country, highlighting the increasing importance of addressing urban planning, housing, and infrastructure needs to accommodate the expanding population. The rapid urban growth underscores the need for sustainable development strategies to ensure that urban areas can meet the demands of their residents while maintaining quality of life and environmental sustainability (Basnet & Bajracharya, 2024). However, the growth is dynamic in recent years, and energy consumption from the construction sector has increased by 25.08% in the fiscal year 2078/79 BS (Basnet & Bajracharya, 2024). Rammed earth construction is one such approach that utilizes local materials and has a lower environmental impact, as it consumes less energy and has lower emissions (Basnet & Bajracharya, 2024). Furthermore, with the emergence of environmental movements and increased awareness of environmental issues among professionals involved in building processes, rammed earth is once again being viewed as a global and future-oriented solution to the problems that construction poses regarding environmental conservation, building life cycles, and the carbon footprint of construction materials (Arto et al., 2024). Earth-built houses offer

several benefits, showcasing long-term sustainability by lowering resource use and cutting greenhouse gas emissions. These buildings offer exceptional thermal and acoustic insulation properties, helping to maintain a comfortable indoor environment by regulating temperature and reducing noise transmission. The thermal insulation ensures that heat is retained in the colder months and kept out during the warmer months, contributing to energy efficiency and a reduction in the need for artificial heating or cooling systems. Similarly, the acoustic insulation helps create a quieter, more peaceful environment by minimizing the impact of external sounds, which is particularly valuable in noisy urban areas (Arenas & Shafique, 2024). Additionally, these structures foster a sense of community by encouraging cooperative construction methods, where local residents or groups work together to build the structures. This collaborative approach not only enhances social bonds and teamwork but also empowers individuals by involving them in the creation of their living spaces. By using traditional or locally adapted techniques, the process promotes shared ownership and responsibility, leading to stronger community ties and a deeper connection to the built environment. The combination of sustainable construction and community engagement makes these structures a valuable model for more resilient and connected living spaces (Arenas & Shafique, 2024).

1.6 Importance of research

The building sector plays a major role in global energy consumption and carbon emissions, making it a critical area for potential reductions in overall environmental impact. Together, the construction and operational phases of buildings contribute to approximately 30% of the world's total energy consumption and around 27% of the emissions generated by the energy sector. This substantial share highlights the significant environmental footprint of the building industry, which not only consumes large amounts of energy but also contributes heavily to pollution and greenhouse gas emissions. As buildings continue to be major consumers of energy, it becomes increasingly important to adopt sustainable building practices in order to mitigate these impacts. Incorporating energy-efficient technologies, using low-carbon materials, and implementing green building designs can significantly reduce both energy use and carbon emissions, helping to address the global challenges of climate change and environmental degradation. By making sustainability a priority in the construction and operation of buildings, the industry has a tremendous opportunity to

contribute to global mitigation efforts and work toward a more environmentally responsible future (Basnet & Bajracharya, 2024). Reinforced Cement Concrete combined with brick masonry has emerged as a popular choice for residential construction. However, the materials used in these structures have high embodied energy and carbon emissions, making current construction practices increasingly unsustainable. This study highlights the need for adopting sustainable alternatives, such as Rammed Earth Construction, which has the potential to serve as an immediate substitute for conventional methods (Basnet & Bajracharya, 2024). Ensuring thermal comfort within living spaces is a key factor in enhancing daily productivity and well-being, as it directly impacts an individual's ability to function effectively throughout the day. Reducing the duration of uncomfortable temperature conditions, such as extreme heat or cold, plays a vital role in achieving this goal. Rammed earth houses are particularly effective in providing this kind of comfort due to their natural ability to regulate temperature. The materials used in rammed earth construction, such as clay, sand, and silt, have high thermal mass, which helps absorb and retain heat, thereby keeping indoor temperatures more stable and reducing the need for artificial heating or cooling systems (Kulshreshtha et al., 2020). Moreover, the use of locally available construction materials and building techniques that are specifically designed to align with rural lifestyles, local topography, and climate conditions can offer significant advantages. These approaches ensure that the built environment is better suited to the surrounding natural conditions, enhancing both comfort and sustainability. In addition, these materials and techniques often demonstrate greater resistance to natural disasters, such as earthquakes or floods, making them more resilient in the face of environmental challenges. This combination of factors positions these types of construction methods as viable solutions to the growing housing shortage, particularly in rural areas. By integrating traditional building practices with modern sustainable design, we can address both the need for housing and the demand for more environmentally and culturally appropriate construction methods (Kulshreshtha et al., 2020). When optimal thermal conditions are maintained, they contribute to better health, increased confidence, and improved efficiency in both physical and cognitive tasks and optimization of thickness of rammed earth wall counters dependencies on other non-energy efficient methods of heating and helps save energy while maintaining comfort. (Yonzan & . Bajracharya, 2022).

1.7 Problem statement

Kathmandu valley has a growing problem and keeping comfortable condition of houses in different weather is a challenge. Most house are built with bricks and concrete, and do not keep indoor temperature stable so we need to rely on heating and cooling systems which leads to high energy use and costs. Also, there is limited research on the comparison of stabilized rammed earth wall and RCC residential building particularly regarding thermal performance, energy efficiency, and cost-effectiveness.

1.8 Objective

To evaluate the thermal performance of stabilized rammed earth walls in residential buildings. It focuses on analyzing thermal properties, assessing energy efficiency, indoor comfort, structural stability, and environmental feasibility.

1. The study aims to evaluate the thermal performance of stabilized rammed earth walls in residential buildings.
2. To Analyze thermal properties, comparing stabilized rammed earth and RCC building wall assessing energy efficiency, indoor comfort.

1.9 Topic validity

The study highlights the significant impact of green building standards on construction practices, emphasizing the importance of integrating sustainability into the design and development of buildings. It explores how these standards influence various aspects of construction, including energy efficiency, resource usage, and environmental impact. The findings suggest that adopting green building practices can lead to more sustainable, environmentally friendly, and energy-efficient structures. Additionally, the study provides recommendations for construction practices that align with these standards, offering valuable insights into how the industry can shift towards more eco-conscious methods. By implementing these suggested practices, the construction sector can contribute to reducing its carbon footprint, improving the quality of buildings, and promoting long-term sustainability in the built environment (Strazzeri & Karrech, 2022). It helps to addresses global concerns about energy efficiency, and carbon reduction in the construction industry (Luo et al., 2024). The emphasis of the study is on renewable

materials such as bamboo and stabilized rammed earth, which are increasingly gaining attention due to the growing demand for environmentally sustainable building solutions. These materials align with the global shift toward more eco-friendly construction practices that minimize environmental impact while promoting resource conservation. The study further contributes to the advancement of construction techniques by investigating hybrid materials that combine the benefits of these renewable resources. These innovative building approaches have not been widely explored or represented in existing literature, making this research a valuable contribution to the field. By examining the potential of hybrid materials, the study opens up new possibilities for sustainable construction, encouraging the use of natural, low-impact materials that can help reduce the carbon footprint of the building sector. This exploration of alternative materials not only supports the transition to greener building methods but also inspires new ideas for the future of construction, fostering innovation in the industry (Zarasvand et al., 2023). Findings will provide insights for architects, builders, and policymakers in designing energy-efficient, low-cost housing. Due to the availability of materials and established testing methods for thermal performance and structural analysis gives idea on rammed earth importance (Luo et al., 2024). Promotes affordable, sustainable housing in regions where traditional materials are costly (Zarasvand et al., 2023). The use of raw earth materials presents a promising opportunity for sustainable construction due to their low environmental impact and the potential for improving building efficiency. These materials, such as clay, silt, and sand, are naturally abundant, energy-efficient, and have a minimal carbon footprint compared to conventional building materials. Their incorporation into construction practices offers an eco-friendlier approach to building design. However, the full potential of raw earth materials can be further maximized by integrating them with other sustainable building techniques. One such approach is the use of hybrid construction methods, which combine raw earth materials with advanced solutions like passive ventilation strategies. These techniques help to optimize energy use by leveraging natural processes, such as air flow, to regulate indoor temperatures without the need for mechanical heating or cooling systems. By combining raw earth materials with these innovative, energy-saving strategies, buildings can achieve greater sustainability, improved comfort, and reduced reliance on external energy sources, making them more efficient and environmentally responsible in

the long run (Belarbi et al., 2024). The thermal performance study demonstrates that the building's high thermal mass plays a crucial role in maintaining a consistent indoor temperature throughout the day and night. This characteristic allows the building to absorb and store heat during warmer periods and gradually release it when temperatures drop, effectively stabilizing the interior climate. As a result, the need for artificial heating or cooling is significantly reduced, leading to a more energy-efficient environment. By minimizing temperature fluctuations, the building's thermal mass helps to lower the overall energy consumption, making it less reliant on energy-intensive systems. This not only enhances the comfort of the occupants but also contributes to reducing the building's carbon footprint, promoting long-term sustainability. The ability of the building to naturally regulate its temperature through the use of materials with high thermal mass is a key factor in reducing energy requirements and supporting eco-friendly building practices (Basnet & Bajracharya, 2024). The simulation results, obtained through the use of Ecotect software, reveal a significant reduction in heating loads for rammed earth walls when compared to traditional masonry construction. This indicates that rammed earth, with its superior thermal mass, is more efficient in regulating temperature and reducing the need for additional heating. The software analysis highlights how rammed earth walls are better at absorbing and storing heat, then gradually releasing it, maintaining a more consistent indoor temperature. In contrast, masonry walls, while effective to some extent, do not perform as efficiently in terms of heat retention and temperature regulation, leading to higher heating demands. As a result, rammed earth walls can contribute to a considerable decrease in energy consumption for heating, offering a more sustainable and cost-effective building solution. This comparison underscores the benefits of using rammed earth as a construction material for enhancing energy efficiency in buildings (Uprety et al., 2021). Mud being locally available material, its use would lessen the impact on environmental condition which results from transportation emission (Pandey et al., 2017). Mud-based construction uses considerably less water than cement-based construction. Modern houses account for 29% of the total water consumption in construction, whereas traditional houses not only demand less water but also have a lower cost per unit area compared to modern houses (Pandey et al., 2017). The property of rammed earth structure and its superior thermal performance as a result of high thermal mass and temperature stabilizing shows its

signification use in building practices (Yonzan & . Bajracharya, 2022). The findings provide valuable insights into how rammed earth structures can offer superior thermal performance compared to both traditional and modern building methods, all while maintaining optimal thermal comfort. The study suggests that, due to the high thermal mass of rammed earth, these structures are capable of more effectively regulating indoor temperatures, reducing the need for artificial heating and cooling systems. This natural temperature regulation helps create a more comfortable living environment without compromising energy efficiency. By absorbing and slowly releasing heat, rammed earth walls ensure that temperatures remain consistent, even in extreme weather conditions. As a result, these structures not only enhance energy savings but also contribute to a more sustainable approach to building design, offering a practical and eco-friendly alternative to conventional construction methods (Yonzan & . Bajracharya, 2022).

CHAPTER 2: LITERATURE REVIEW

2.1 Historical Background

Although earth building techniques have developed uniquely in different regions around the world, they share several common characteristics that are universally present. Despite variations in materials, design approaches, and cultural influences, many traditional earth construction methods exhibit similar principles, such as the use of locally sourced materials, passive climate control, and sustainable building practices (Uprety et al., 2021). Asia is considered as the roots of earth construction also it is performed in Himalayan regions of Nepal. Traditional rammed earth structures in Nepal, particularly in the Annapurna region and Mustang, showcase the effective use of local materials for climate-responsive and thermally comfortable designs (Yonzan & . Bajracharya, 2022). For more than 10,000 years, earth has served as one of humanity's most enduring and reliable building materials. Even today, approximately 30% of the world's population continues to live in structures made from earth-based materials. Its widespread use can be attributed to several key qualities most notably, its natural abundance, ease of use, and remarkable versatility in adapting to different climates and cultures. From mud huts and homes to rammed earth walls and earth construction reflects a deep relationship between humans and their environment (Pandey et al., 2017). Rammed earth construction dates back to the origins of civilization. The rise of agriculture near major rivers marked a turning point in human history, giving the formation of permanent settlements. Fertile river valleys provided not only the means for cultivating crops but also ideal conditions for earth-based construction due to the plenty of suitable soil. Archaeological findings suggest that the technique of building with earth emerged independently in several ancient river valley civilizations, including those along the Tigris and Euphrates, Nile, Indus, Jordan, Murghab, and Yellow Rivers. The reliance on locally sourced earthen materials reflects an early form of sustainable architecture that has tied to both the environment and available resources. (Uprety et al., 2021). By approximately 5000 BC, Mesopotamia experienced a significant shift in building practices, moving from the use of hand-shaped bricks to more uniform, cuboid forms. In contrast, rammed earth construction techniques were absent in South America prior to their introduction by European settlers (Uprety et al., 2021). Rammed

earth has been a building technique since the development of early civilizations, especially in areas lacking timber and stone (Strazzeri & karrech, 2023). Mud is used extensively for walling and roof insulation in traditional buildings, showcasing its sustainable properties and the shift from traditional to modern construction methods calls for an assessment of their implications on the environment and society (Pandey et al., 2017). Subsoil suitable for earth construction is commonly found in many parts of the world, especially in areas where natural resources like timber and stone are not available. The availability of earth makes it as good optional material for building, particularly in rural or resource-limited regions. Additionally, the minimal need for use of complex tools and low transportation cost, contributes to its cost-effectiveness. Earth can often be sourced directly from or near the construction site, reducing expenses and environmental impact. Its ease of preparation and application also makes its use to local communities, which also allows unskilled laborers to participate in the building process. These factors together make earth a practical, cost-effective choice for construction across various places (Kulshreshtha et al., 2020). Traditional construction methods (e.g., brick kilns) contribute significantly to carbon emissions, necessitating sustainable alternatives like rammed earth, thus its construction requires less than 10% of the energy input compared to fired clay or concrete masonry (Strazzeri & karrech, 2023).

2.2 Stabilized Rammed Earth (SRE) Walls

In modern applications such as SRE, the substrate material can vary and may include alternatives like crushed limestone, waste granular materials, or fibrous particles, which can be used either alongside or instead of soil. Additionally, to comply with construction codes' physical and mechanical requirements, SRE typically incorporates 5 to 10% stabilizers, such as cement, lime, or bitumen. The ideal soil for lime stabilization should have a plasticity index between 20% and 30% and a liquid limit ranging from 25 to 50, making lime particularly effective for stabilizing expansive soils (Ávila et al., 2022). However, while chemical stabilizers like cement enhance SRE's embodied energy, they also introduce challenges related to recyclability, vapor permeability, and moisture buffering capacity. Beyond cement, Alker technology offers an alternative by stabilizing earth with approximately 8% clay using gypsum and lime. This method, as highlighted in

research studies, enhances workability and mechanical strength, with gypsum promoting rapid hardening and lime extending the material's workable duration (Ramezannia et al., 2024). Cement is the most widely used stabilizing agent in rammed earth construction, valued for its ability to significantly improve the strength and durability of the material. In certain cases, lime is used as an alternative stabilizer, particularly in regions where traditional or low-carbon building methods are preferred. The process of using these stabilizers whether cement or lime into the earth mixture gives 'stabilized rammed earth.' This technique improves the structural integrity, water resistance, and can have long lifespan of the walls, making them more suitable for a variety of climates and environmental conditions. Additionally, stabilization allows rammed earth to be used in more demanding construction projects, including multi-story buildings and infrastructure exposed to weathering. While modern stabilizers dominate today's practices, research continues into natural and sustainable alternatives that offer similar benefits with lower environmental impact. Common stabilizers types include Portland cement, air lime, barley straw fibers, and date palm fibers (Koutous & Hilali, 2021). Soil for stabilized rammed earth construction should generally be free of humus and plant matter to prevent future deterioration and in certain conditions; materials such as dry straw can be added to the soil mix (Ávila et al., 2022). The incorporation of a stabilizer can lead to an increase in the embodied energy of rammed earth. Notable research on the embodied energy of stabilized rammed earth was conducted by, who analyzed energy consumption in the manual construction of cement-stabilized rammed earth walls. Their findings indicated that compaction energy rises as the clay fraction in the soil mix increases, highlighting the importance of clay content as a key parameter. However, they also noted that the energy used in the compaction process is minimal compared to the energy content of cement (Serrano et al., 2013). Studies have shown that incorporating cement into rammed earth mixtures can enhance their strength by nearly 70% compared to lime, making it a much more effective stabilizing agent. This significant difference stems from the fact that lime mortar generally possesses only about one-third of the compressive strength of cement mortar. Due to this notable performance advantage, cement has become the preferred stabilizer in modern rammed earth construction. In many cases, it is used in combination with other additives such as natural fibers, fly ash, or gypsum. These supplementary

materials further contribute to the improvement of the mechanical properties, thermal stability, and overall durability of the finished structure (Jiang et al., 2024). For unstabilized rammed earth (URE), the ideal soil mixture should contain about 20% to 35% clay and silt together, while sand should be around 50% to 75% of the total composition. This ensures that the mixture has enough strength and stability without needing added binders. When it comes to stabilized rammed earth (SRE), the soil should mostly be made up of sand and fine gravel. Only a small amount of clay is needed—just enough to help hold the mix together while a bit of silt helps fill the tiny gaps between particles. In stabilized mixes, materials like cement or lime are added to act as the main binder, which means the natural stickiness or binding power of the clay becomes less important. These additives make the structure stronger and more durable, especially in places with changing weather (Ávila et al., 2022).

2.3 Thermal Performance of Rammed Earth Walls

Around 30% of the global population lives in rural areas, where rural construction accounts for approximately 60% of the total built environment. Enhancing the thermal performance and energy efficiency of rural residential buildings is a critical objective. Studies conducted in northwest Sichuan have shown that rammed earth walls significantly reduce the impact of external environmental conditions on indoor spaces while also providing excellent humidity regulation (Jiang et al., 2024). Keeping indoor temperatures comfortable is very important for creating a healthy and efficient workspace where people can focus and perform well. At the same time, it's also important to use less energy in commercial buildings like offices, shops, and factories because these buildings use a lot of power for heating and cooling. By lowering energy use, we can significantly reduce the amount of greenhouse gases released into the atmosphere, which helps fight climate change. So, finding ways to keep buildings comfortable without using too much energy is good for option (Taylor et al., 2008). Due to limited advancements in research on rammed earth materials and construction techniques, traditional rammed earth buildings in China still face challenges related to structural safety, durability, and thermal and moisture performance. Therefore, enhancing the composition of rammed earth materials and improving their properties are essential for broader application and the widespread adoption of rammed earth construction (Jiang et al., 2024).

2.4 Energy Efficiency and rammed earth Construction

Brick kilns are a major source of air pollution, releasing huge amounts of harmful gases into the atmosphere every year. They emit around 500,000 tons of dangerous pollutants like carbon monoxide, nitrogen oxides, and sulfur dioxide, along with about 829 million tons of carbon dioxide. These gases not only contribute to global warming but also have serious effects on human health. Breathing in polluted air from brick kilns can lead to health problems, especially for people living nearby. In addition, these emissions harm the environment by damaging ecosystems, increasing air pollution, and contributing to climate change (Uprety et al., 2021). High thermal mass provides excellent insulation, making it a key component of passive design strategies and maintains thermal comfort, reducing the need for active heating and cooling systems (Yonzan & . Bajracharya, 2022). Consequently, researchers are increasingly focusing on earth-based construction, which is a low-cost, sustainable material requiring less than 10% of the energy input needed for manufacturing fired clay and concrete masonry units. Earthen materials exhibit remarkable heat retention capabilities, utilizing both passive and latent heat storage mechanisms (Uprety et al., 2021). In Nepal, many homes are built using a mixture of mud and mortar, often combined with cement or bricks. This method is a reflection of the traditional construction practices that have been used in the country for generations. The use of mud, being available material, along with more modern materials like cement and brick, helps create durable and cost-effective homes. This construction system has been passed down through the years; giving local knowledge with new technologies that is suitable for rammed earth construction (Basnet & Bajracharya, 2024). This allows buildings to absorb heat from the sun during the day and release it gradually at night, helping to maintain a comfortable temperature without relying on external heating or cooling. Rammed earth construction, in particular, is a great way to save energy because it requires less energy to produce compared to building materials like concrete or steel. Rammed earth has a special ability to absorb heat from the sun during the day and release it slowly at night. This helps keep the indoor temperature stable, reducing the need for artificial heating or cooling. By naturally storing and releasing heat, rammed earth promotes passive heating and cooling, meaning the building can stay comfortable without using much energy. This not only saves money on energy bills but also helps protect the environment by reducing the need for air conditioning

or heating systems (Strazzeri & karrech, 2023).Rammed earth provides both strong structural support and environmental benefits, making it a great choice for building sturdy, load-bearing structures up to four stories high, even in areas prone to earthquakes. It's naturally fire-resistant, waterproof, and able to withstand different weather conditions, ensuring long-lasting condition. Over time, rammed earth has become a well-established and sustainable building method used all around the world. This construction technique has been improved and adapted to perform even better and to fit in with the environment, making it a reliable option for eco-friendly buildings (Yonzan & . Bajracharya, 2022). Rammed earth (RE) walls are created by pressing earth between vertical molds, which can be made of wood or metal. The earth is then compacted using a rammer, either manually or with a machine, to create layers about 15 cm thick. In the past, workers used hand-operated rammers to compact the earth, but today, most of the process uses more powerful pneumatic rammers. These machines speed up the building process and help make the material dense, resulting in stronger, more durable walls (Nabouch et al., 2016). Rammed earth is made up of a mix of clay (15-25%), sand (50-60%), and gravel (15-20%). Sometimes, a small amount of stabilizer, like cement (3-5%), is added to improve strength. Only a little bit of water (8-12%) is needed to make the mix in workable. The mixture is then compacted into the desired shape using basic tools and simple methods condition, usually within wooden or metal molds. This process, known as tamping which helps to create solid, durable walls without needing advanced machinery (Uprety et al., 2021). In many rural areas, compacted earth is still a popular material for building walls because it is affordable and locally available. However, compacted earth walls have some weaknesses, such as poor flexibility and low resistance to forces that try to push or pull them apart. To overcome these problems, bamboo is used as a reinforcement material. Bamboo is known for its strong ability to resist stretching or pulling forces, making it an ideal addition to improve the strength and durability of compacted earth walls (Luo et al., 2024). An environmental impact study of bamboo revealed that it has a very low effect on the environment. Specifically, it produces very little greenhouse gas emissions and uses minimal energy during its growth and processing. This makes bamboo a highly eco-friendly material, as it contributes very little to global warming or energy consumption compared to many other building materials (Basnet & Bajracharya, 2024). This means that

using rammed earth not only helps reduce energy costs over time but also has a smaller environmental impact, as it consumes less energy to create and process the materials (Uprety et al., 2021).

2.5 Passive design strategy and energy Performance of Rammed Earth

Bioclimatic studies show that rammed earth is an ideal material for keeping buildings comfortable without relying on artificial heating or cooling, no matter the climate. When compared to traditional masonry buildings, simulations have shown that rammed earth structures especially in tropical areas require less energy for heating and cooling. This is because rammed earth naturally helps maintain a steady indoor temperature, keeping it cooler in hot weather and warmer in cooler conditions, reducing the need for air conditioning or heating systems (Strazzeri & karrech, 2023). In sustainable building design, passive strategies focus on making the most of natural resources and the building's structure to improve energy efficiency. This includes elements like the walls, roof, windows, shape, and placement of the building to help reduce energy use. Over the last ten years, a lot of research has been done on these passive strategies, showing how important they are for creating buildings that are both energy-efficient and kind to the environment. One study emphasizes the need to look at these strategies as a whole, rather than separately, to build structures that are not only energy-saving but also environmentally sustainable (Zong et al., 2024). Rammed earth has much lower embodied energy compared to materials like fired brick or cement. This means that producing rammed earth requires less energy, which makes it a more environmentally friendly option. In addition, buildings made from rammed earth can stay comfortable without needing air conditioning or heating systems. This is possible because passive cooling strategies, such as natural ventilation and thermal mass, help regulate indoor temperatures naturally, keeping the building cool in hot weather and warm during cooler times (Strazzeri & karrech, 2023). As energy use in buildings continues to rise, builders are turning to more sustainable and cost-effective construction methods that also offer long-lasting durability. The construction industry, which is responsible for most of the new buildings, accounts for 36% of global energy consumption and 51% of electricity usage. To address this, rammed earth materials, when combined with cement for stabilization, have been shown to provide better thermal efficiency than traditional masonry materials. This means that buildings made with stabilized rammed

earth can stay cooler in the summer and warmer in the winter, reducing the need for artificial heating and cooling (Uprety et al., 2021). For example, stabilized rammed earth (SRE) has a longer time lag (14.63 minutes) and a higher R-value (0.37 W/m·K) compared to masonry (time lag: 14.53 minutes, R-value: 0.10 W/m·K). These properties highlight the strong thermal mass of SRE materials. Additionally, rammed earth structures reduce carbon dioxide emissions during both construction and their operational lifetime (Uprety et al., 2021). As construction increasingly depends on materials that aren't sourced locally, it creates both environmental and financial problems. Transporting these materials over long distances uses more energy, increases costs, and contributes to pollution. Additionally, the absence of proper technical oversight often leads to buildings not performing as well as they should. This can affect both the physical durability of the building and the way it fits with the community's cultural needs and lifestyle (Pandey et al., 2017). Rammed earth is a sustainable construction material known for its thermal properties. Its thermal conductivity typically ranges from 0.5 to 1.4 W/m·K, depending on factors such as density, moisture content, and any added stabilizers. This range indicates that rammed earth provides moderate thermal insulation, helping to maintain comfortable indoor temperatures by slowing down heat transfer. Additionally, its high thermal mass allows it to absorb heat during the day and release it at night, contributing to passive heating and cooling strategies in buildings (Ávila et al., 2022). Rammed earth walls offer thermal insulation properties similar to traditional ceramic bricks and outperform common materials like concrete in this regard. To further enhance their thermal performance, incorporating thermal energy storage materials, such as bamboo reinforcement, has proven its effectiveness. Bamboo's structural advantages, combined with its integration into rammed earth, contribute to improved thermal efficiency. This approach not only boosts the material's strength but also its capacity to regulate temperature, making it a sustainable and efficient choice for construction (Ávila et al., 2022).

2.6 Rammed Earth as a Sustainable Building Material

Rammed earth, an ancient construction method, is experiencing a revival due to its environmental benefits and natural temperature-regulating properties. This technique involves compressing layers of soil typically composed of clay, silt, sand, and fine gravel

within wooden molds to form sturdy walls. To enhance the strength and durability of rammed earth structures, modern practices incorporate stabilizing agents like lime and blast furnace slag. Additionally, integrating natural fibers such as jute, coconut, bamboo, and *Arundo donax* aims to improve seismic resistance and flexibility (Ruiz et al., 2024). Rammed earth construction utilizes locally available materials, primarily soil, making it an environmentally friendly and cost-effective building method. In modern prototype houses, the material composition typically includes stones (47%), mud (23%), and reinforced cement concrete (RCC) (28%). In contrast, traditional prototype houses predominantly consist of mud (56%), stones (37%), and timber (7%). This shift towards RCC in modern constructions reflects a trend towards incorporating more durable and robust materials. However, it's important to note that the effectiveness of these materials can vary based on local availability, cultural practices, and specific structural requirements (Ciancio & Beckett, 2013). However, the effectiveness of these fibers is a topic of ongoing discussion, as they can potentially introduce weak points within the structure. Stabilizing rammed earth with materials like cement has proven effective in enhancing its properties, making it a more reliable and sustainable building option. Embracing rammed earth construction aligns with sustainable development goals, offering an eco-friendly alternative to conventional building materials. By carefully selecting materials and incorporating appropriate stabilizers and reinforcements, rammed earth can be adapted to meet modern construction standards while minimizing environmental impact. (Ruiz et al., 2024). According to the properties of the excavated soil, the size of the sand and the mix design are determined. The mixture of the dry soil, coarse sand and cement gives the shot earth and dry mixture is 7:7:2 ratio by its weight. (Ciancio & Beckett, 2013).

CHAPTER 3: METHODOLOGY

3.1 Research Paradigm

This study adopts post-positivism because the study involves measuring and analyzing the thermal performance of rammed earth walls which relies on empirical data, experimentation, and simulations.

3.2 Ontology

The study assumes that the thermal performance of walls is an objective reality that can be measured, but it acknowledges that environmental conditions, construction techniques, and material properties may introduce variations.

3.3 Epistemology

The epistemology is nature of Knowledge which is derived through experiments, thermal performance measurements, and statistical analysis. The study seeks to establish cause-effect relationships based on observable data.

3.4 Axiology

While the study aims for objective, data-driven conclusions, it holds value in promoting sustainable construction practices and improving energy efficiency in Kathmandu Valley's residential buildings.

3.5 Methods

3.5.1 Simulation Modeling:

Tools: Rhino modeling software will be used to model the rammed earth building typology. Grasshopper with plugins like Ladybug and Honeybee will be used for simulation of thermal performance of the building.

Process: Rhino will be used to create the model of rammed earth building. Weather data from Tribhuvan International Airport (TIA) will be retrieved which will be morphed accordingly using dragonfly. Research aims to leverage Grasshopper plugin within the Ladybug Tools suite, to evaluate the comparative effectiveness of rammed earth wall in

order to obtain thermal performance of the building. The study will develop scenarios with rammed earth wall and focus on their impact on the indoor temperature of the building with respect to outdoor weather conditions, which will relate to temperatures, energy consumption for cooling, and outdoor thermal comfort.

3.5.1.1 Boundary condition

Wall typically experiences conduction through the material and convection and radiation both on inner and outer surfaces. Roof is more exposed to solar radiation and has higher temperature fluctuations. Door and window have thin walls with less insulation than other walls, which include convection at surfaces and solar radiation transmission.

3.5.1.2 Energy plus weather file (EPW)

An EPW (Energy Plus Weather) file is a standardized file format used to provide climate and weather data for building energy simulations, especially in tools.

3.5.1.3 Thermal zone

A thermal zone is a space within a building that is thermally consistent and controlled by a single thermostat or HVAC system.

3.5.1.4 HVAC system

HVAC stands for Heating, Ventilation, and Air Conditioning. It's a system used to regulate indoor environmental comfort by controlling the temperature, humidity, and air quality in residential, commercial, and industrial buildings.

3.5.2 Data Collection and Analysis:

Variables: temperature, energy usage, indoor temperature profiles.

Primary Data

Temperature data was measured using data loggers for indoor and outdoor temperature data.

The indoor and outdoor temperature at Dekaido onsen at Budhanilkantha was recorded for eight days continuously, and data recording was done in one-hour intervals. The total set of data collected was 193 data points.

Similarly, the indoor and outdoor temperature at Madan pustakalaya at patan dhoka, was done for eight days continuously and recording of data was done in the interval of one hour. The total set of data collected was 114 amounts of data.

Lastly, the indoor and outdoor temperature at Residential building at Maitrinagar kirtipur, was done for one day continuously and recording of data was done in the interval of one hour. The total set of data collected was 26 amounts of data.

Secondary Data

Meteorological Data:

Hourly weather data, including air temperature, humidity, wind speed, and solar radiation, will be sourced from reliable databases online.

Material Properties:

Key material properties of the rammed earth wall such as its thickness, thermal conductivity, and density will be sourced from scientific literature, established material property databases, and official manufacturer specifications. Gathering this data from multiple credible sources ensures that the input values used in the analysis are both accurate and representative of real-world conditions. This approach helps in enhancing the precision of thermal performance simulations and supports the reliability of the overall study.

3.5.3 Validation:

Calibration of Model Outputs:

The simulated indoor temperature outputs, obtained in response to varying outdoor temperature conditions, will be cross-checked against actual local weather data. This validation process is essential to confirm the accuracy and reliability of the simulation results. By comparing modeled data with real-world measurements, the study aims to ensure that the simulations realistically reflect local climatic conditions, thereby enhancing the credibility and applicability of the findings.

Cross-Validation with Literature:

To ensure the credibility of the results and determine how well they apply to the local context, the findings of this study will be viewed alongside those from similar research. By identifying consistencies or differences with existing studies, the transferability of the results can be better understood, helping to establish whether the insights gained are applicable beyond the immediate study setting.

3.5 Research process



3.5 Equipment used for data collection

3.5.1 Hobo data logger

Hobo data logger is a weatherproof data logger with an internal temperature sensor with Bluetooth technology for easy setup and data download directly to mobile device or Windows computer running Onset's free HOBOTEMP connect app. This logger delivers high-accuracy measurements in harsh outdoor environments. Hobo data logger is a convenient wireless setup which has a Bluetooth range of 100-foot range. It helps to take data in hard-to-reach locations and gives visual alarms. Access real-time data effortlessly using Onset's free HOBOTEMP connect app and seamlessly share downloaded data from mobile device or windows computer software. With an impressive accuracy of $\pm 0.2^{\circ}\text{C}$, this device delivers precise and dependable measurements.



Figure 1 HOBOTEMP data logger

3.5.2 CO₂ recorder

CO₂ Data Loggers are commonly used to monitor the high concentration of carbon dioxide across indoor air quality or safety environments. In addition, many data loggers also provide temperature, relative humidity, particulate matter, and dew point - which can come as great additions when monitoring indoor spaces. The most important thing in using a CO₂ data logger, is the ability to access your data points of CO₂ concentration remotely, without

needing to plug into an actual system. Most CO₂ Data Loggers monitor and record the CO₂ concentrations to indicate potential CO₂ hazard points or alert individuals when air quality levels are poor and ventilation is required.



Figure 2 CO₂ Data Loggers

CHAPTER 4: CASE STUDY

A case study on Dekkaido Onsen located at Budhanilkantha, Kathmandu, Madan pustakalya at patan, Lalitpur and RCC building at Maitrinagar, Kirtipur and data was collected in room of RCC residential building at Maitrinagar, Kirtipur.

4.1 Dekkaido Onsen

Dekkaido Onsen is a Japanese restaurant which is inspired by modern rammed earth technique which is load bearing structure with thatched roof. The room temperature and surrounding temperature was recorded for eight days by using data loggers.



Figure 3 Dekaido Onsen for collection of indoor and outdoor temperature

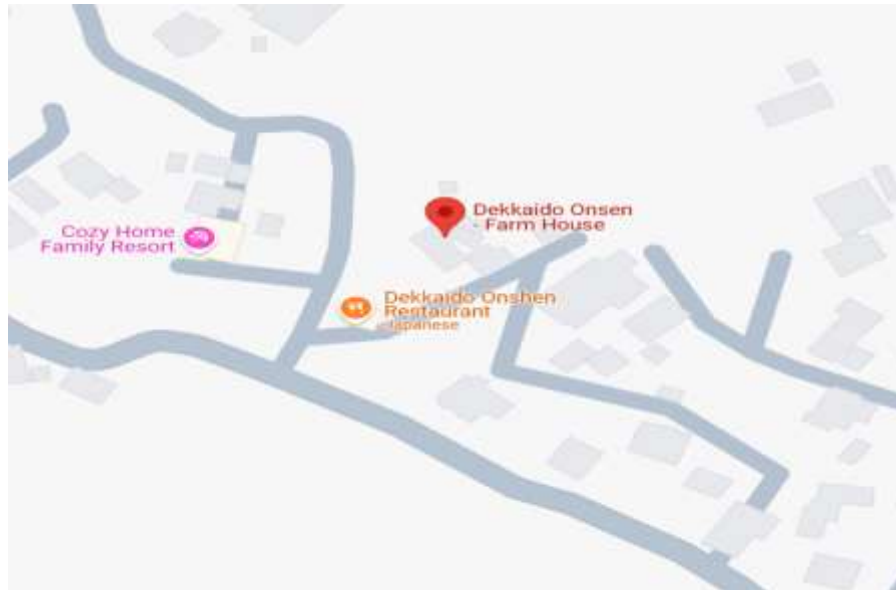


Figure 4 Source google map

4.2 Madan Pustakalaya

Madan Pustakalaya is a library building that is made from stabilized rammed earth with thatched roof and is located at patan dhoka, Lalitpur. The room temperature and surrounding temperature was recorded for six days by using data loggers.



Figure 5 Madan Pustakalaya for collection of indoor and outdoor temperature



Figure 6 Source:google maps

The field data at Madan pustakalaya was taken for six days in which inside and outside temperature of building was recorded.

4.3 RCC building

RCC building at Maitrinagar is south facing two story building having 9” thick brick wall. The room temperature and outside temperature were taken for one day by using data loggers.



Figure 7 RCC building Maitrinagar

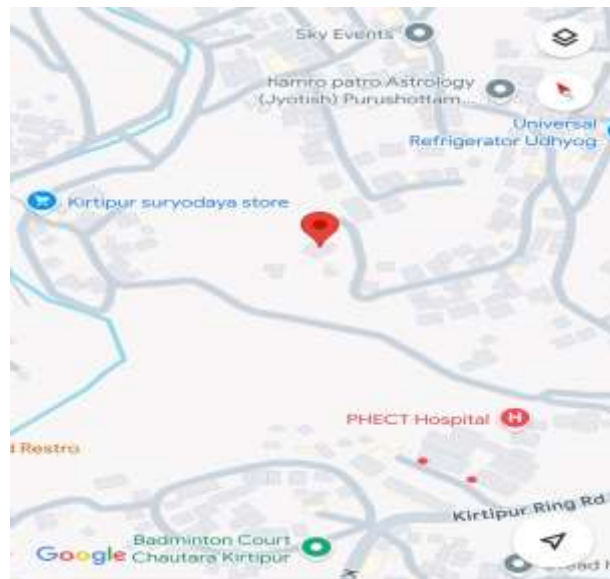


Figure 8 Source: Google map

The building is located at Maitrinagar, kirtipur which is a two storey RCC building. The field data at RCC building was taken for six days in which inside and outside temperature of building was recorded.

4.4 Tools and equipment at case studies

The instrument that are used for collecting indoor and outdoor temperature are Hobo data logger and CO₂ recorder.



Figure 9 Co2 recorder used to collect outside temperature at Dekaido Onseen



Figure 10 Hobo Data logger used to collect indoor temperature at Dekaido Onseen



Figure 11 Hobo data logger for recording outer temperature at Madan Pustakalaya



Figure 12 Co2 recorder used for recording inside temperature at Madan Pustakalaya

CHAPTER 5: DATA ANALYSIS, DISCUSSION AND FINDINGS

5.1 Indoor Temperature:

The measure of thermal conditions within an enclosed space, such as a room or building. It reflects the ambient warmth or coolness experienced by occupants and is influenced by factors such as insulation, ventilation, heating, and cooling systems. In the context of rammed earth walls, indoor temperature is affected by the thermal mass and insulation properties of the wall material.

5.2 Outdoor Temperature:

The measure of the thermal conditions in the open environment outside of buildings. It varies throughout the day and night due to weather conditions, solar radiation, humidity, and wind. Outdoor temperature serves as a reference point for comparing the thermal performance of indoor environments.

Following charts shows the different temperature difference between indoor and outdoor temperature in two case study building (i.e. Dekaido Onseen and Madan pustakalaya) which illustrates the effect of thermal mass of stabilized rammed earth wall at different time period.

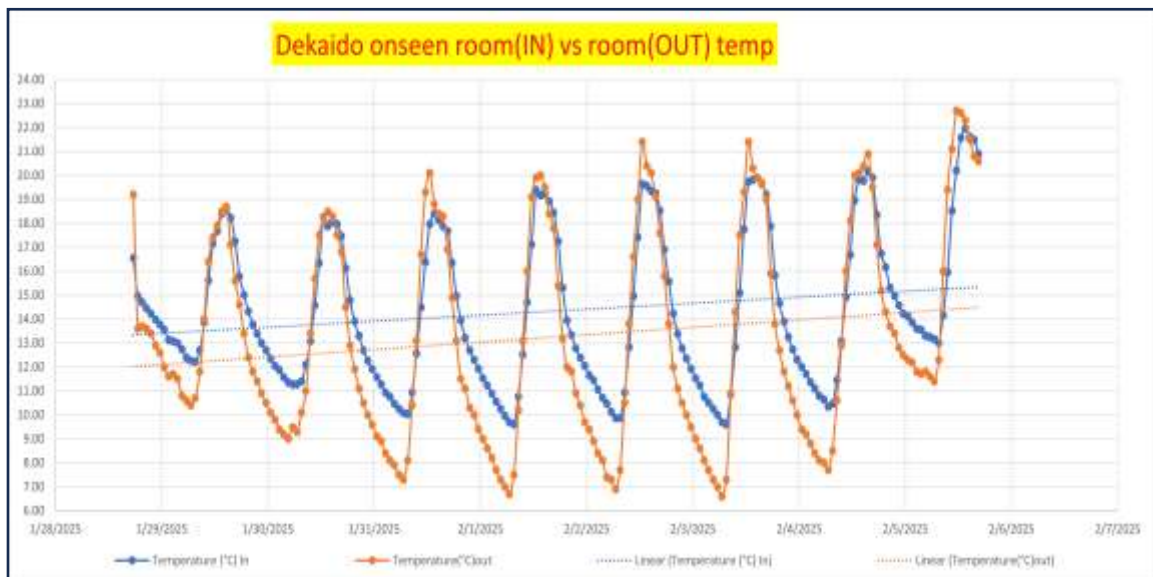


Figure 13 Variation in between indoor and outdoor temperature of stabilized rammed earth wall at Dekaido Onseen

The Fig 13 shows that the indoor temperature of stabilized rammed earth wall room is consistently warmer than the outdoor temperature, particularly during cooler evening and night periods. The dense composition provides good insulation, reducing heat gain and loss and the thermal stability minimizes the need for heating and cooling, which leads to energy savings. The indoor temperature of room was 1.09°C more warmer than that of outdoor temperature as data was compared throughout day and night at Dekaido Onseen

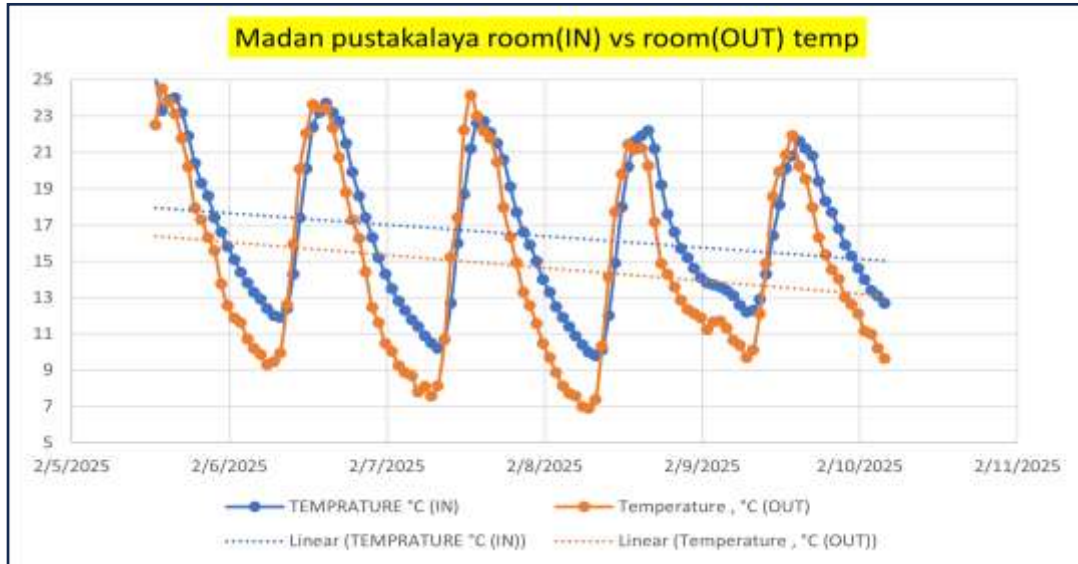


Figure 14 Variation in between indoor and outdoor temperature of stabilized rammed earth wall at Madan Pustakalaya

Fig 14 shows that the indoor temperature of stabilized rammed earth wall room is consistently warmer than the outdoor temperature that is 1.73°C more warmer than that of outdoor temperature as data was compared throughout day and night at Madan pustakalaya. This gives clear idea of better performance of stabilized rammed earth wall which effectively store heat absorbed during the day and gradually releases it when outdoor temperature drops.

From Figure 13 and 14 we can know,

The temperature analysis of two different rooms, **Dekaido Onseen** and **Madan Pustakalaya**, provides insight into how indoor and outdoor temperatures fluctuate over

time. The data was recorded over multiple days, and trends were observed for both indoor (IN) and outdoor (OUT) temperatures.

1. Temperature Trends and Variations

Both graphs illustrate a cyclic pattern in temperature variation, indicating a strong correlation with diurnal (daily) temperature fluctuations. The outdoor temperature (orange line) exhibits sharper peaks and valleys, suggesting greater exposure to environmental conditions such as solar radiation, wind, and humidity changes. Conversely, the indoor temperature (blue line) shows relatively smoother fluctuations due to insulation and controlled indoor conditions.

- In Dekaido Onseen, the indoor temperature remains more stable compared to the outdoor temperature, with less extreme variations. The trendlines indicate a slight increase in both indoor and outdoor temperatures over time, potentially due to seasonal effects or heat retention within the building.
- In Madan Pustakalaya, the trendlines suggest a gradual decline in both indoor and outdoor temperatures. This may be attributed to external climate factors, ventilation efficiency, or differences in thermal properties of the building materials.

2. Indoor vs. Outdoor Temperature Differences

The data confirms that indoor temperatures are consistently higher than outdoor temperatures during nighttime and lower during peak daytime hours. This suggests that:

- The building materials and insulation play a significant role in regulating heat exchange.
- The time delay (thermal lag) between outdoor and indoor temperatures indicates that heat takes time to penetrate or dissipate within the structure.
- The temperature gap is more prominent in some periods, suggesting that external environmental changes significantly impact the indoor climate, albeit with some buffering effect.

3. Long-Term Temperature Trends

The dotted linear trendlines suggest:

- A gradual increase in temperature for Dekaido Onseen, implying heat accumulation within the room over time.
- A gradual decline in temperature for Madan Pustakalaya, possibly due to seasonal effects or different thermal dynamics.

These findings are critical for assessing energy efficiency, HVAC (Heating, Ventilation, and Air Conditioning) system requirements, and overall thermal comfort within the respective buildings.

4. Implications for Thermal Comfort and Energy Consumption

Understanding these temperature trends helps in optimizing building design and energy usage:

- Buildings with higher thermal inertia (slow heat absorption and release) tend to provide better thermal comfort with reduced dependence on artificial heating and cooling.
- Rooms with excessive fluctuations may require improved insulation or better passive cooling strategies to maintain a stable indoor climate.
- The relationship between indoor and outdoor temperatures highlights the effectiveness of natural ventilation, which can be adjusted to minimize temperature extremes.

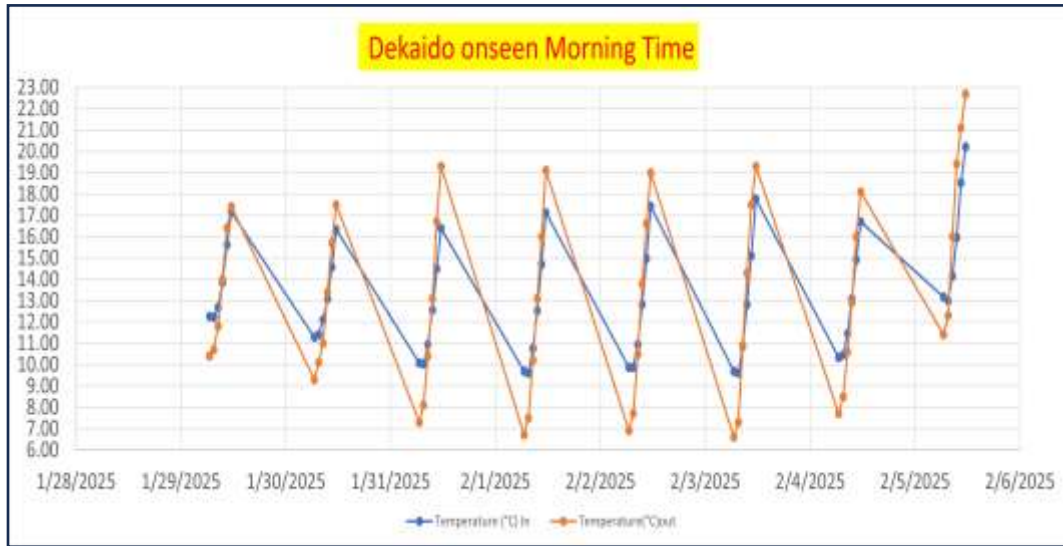


Figure 15 Variation in between indoor and outdoor temperature at Dekaido Onseen at Morning

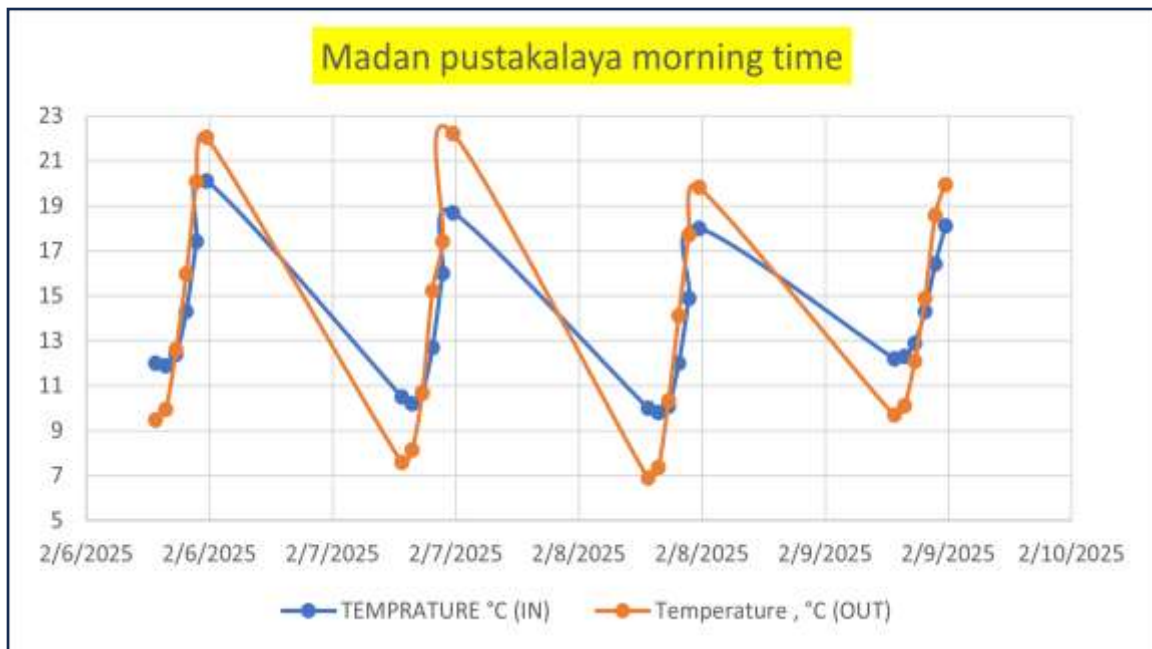


Figure 16 Variation in between indoor and outdoor temperature at Madan Pustakalaya at Morning

Fig 15 shows the comparison of indoor room temperature with that of outdoor surrounding temperature at morning time period between 6:00 am to 12:00 o'clock at Dekaido onseen and Fig 16 shows the comparison of indoor room temperature and outdoor temperature at Madan Pustakalaya and in both case gradual heat gain through the wall of stabilized

rammed earth with respect to outdoor temperature. This thermal lag and moderation provide a more comfortable indoor environment.

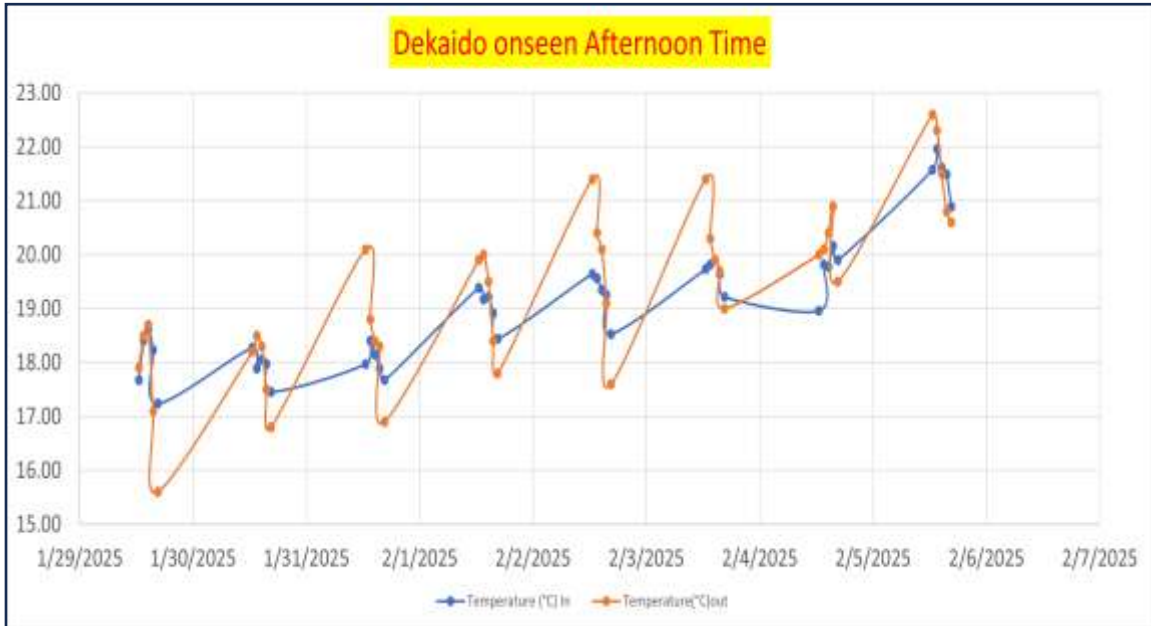


Figure 17 Variation in between indoor and outdoor temperature at Dekaido Onseen at afternoon

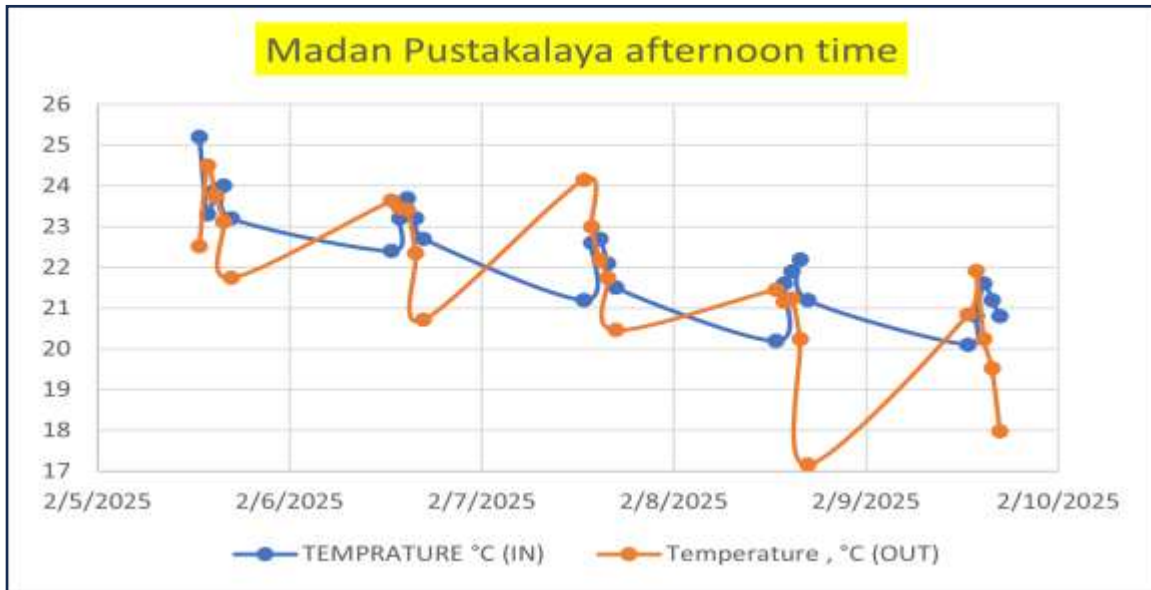


Figure 18 Variation in between indoor and outdoor temperature at Madan Pustakalaya at afternoon

Fig 17 and Fig 18 shows the comparison of indoor room temperature with that of outdoor surrounding temperature at afternoon time period between 12:00 o'clock to 18:00 pm at

Dekaido onseen and Madan Pustakalaya respectively, and it shows the heat absorption due to high thermal mass of stabilized rammed earth wall. This provides comfortable indoor environment minimizing additional heating and cooling work which contributes directly to minimizing carbon emission.

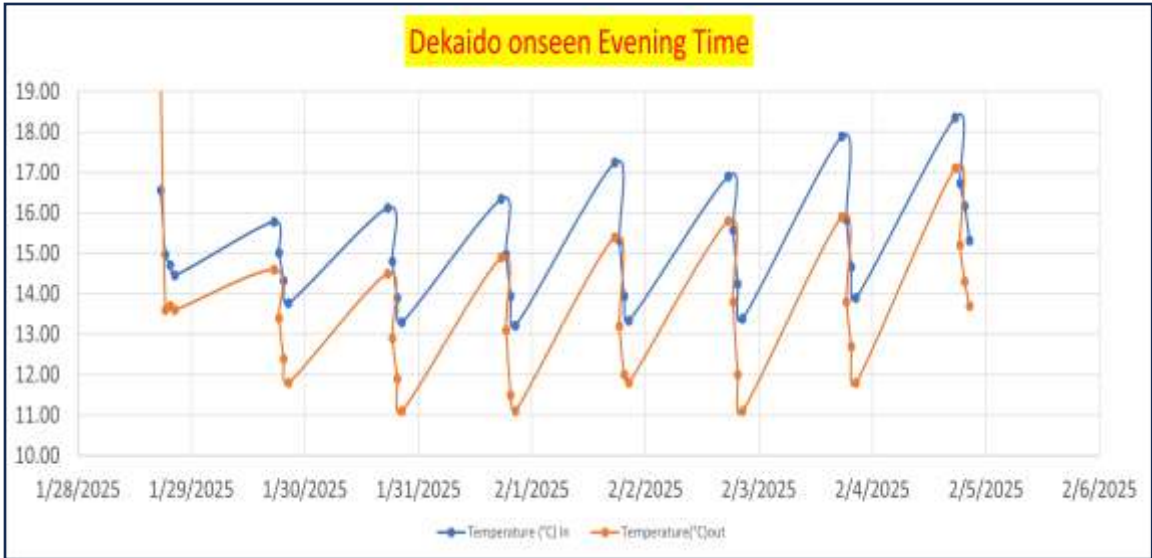


Figure 19 Variation in between indoor and outdoor temperature at Dekaido Onseen at Evening

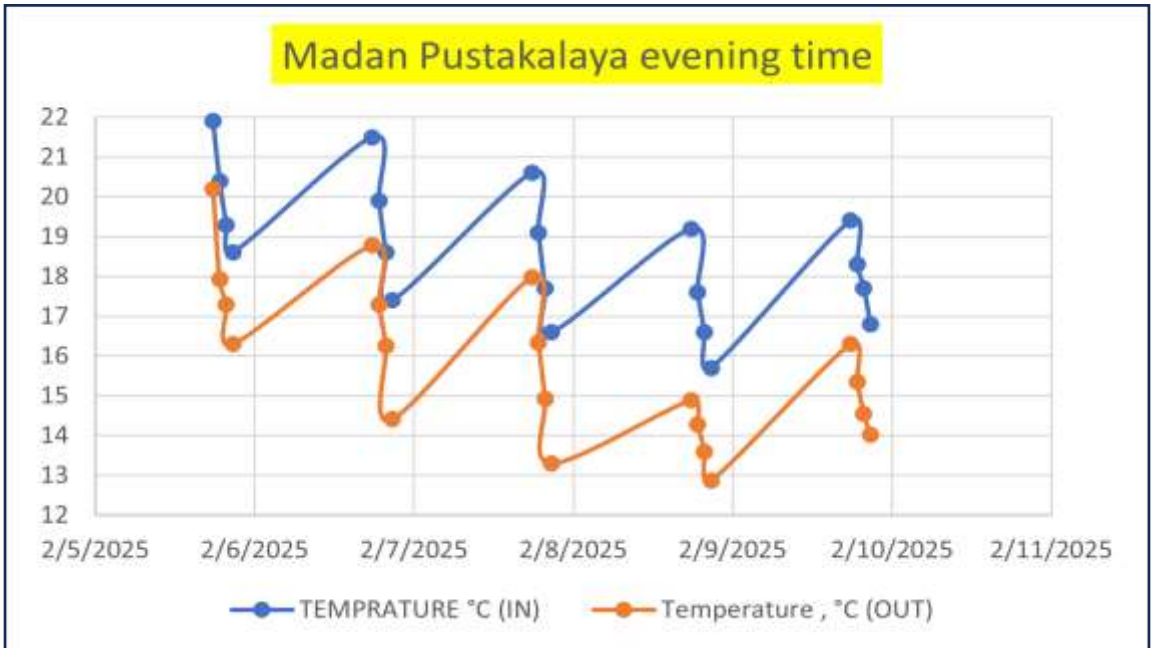


Figure 20 Variation in between indoor and outdoor temperature at Dekaido Onseen at Evening

Fig 13 and Fig 14 shows the comparison of indoor room temperature with that of outdoor surrounding temperature at evening time period between 18:00 pm to 21:00 pm at Dekaido onseen and Madan Pustakalaya respectively, and it shows the gradual heat loss of indoor room temperature as compared to outdoor surrounding temperature due to high thermal mass of stabilized rammed earth wall. This demonstrates the wall's thermal mass effect, which retains heat and provides enhanced thermal comfort. By naturally retaining heat, the need for artificial heating is minimized, *which* leads to lower energy consumption and reduced utility costs.

Fig 19 and Fig 20 shows the comparison of indoor room temperature with that of outdoor surrounding temperature at evening time period between 18:00 pm to 21:00 pm at Dekaido onseen and Madan Pustakalaya respectively, and it shows the gradual heat loss of indoor room temperature as compared to outdoor surrounding temperature due to high thermal mass of stabilized rammed earth wall. This demonstrates the wall's thermal mass effect, which retains heat and provides enhanced thermal comfort. By naturally retaining heat, the need for artificial heating is minimized, which leads to lower energy consumption and reduced utility costs.

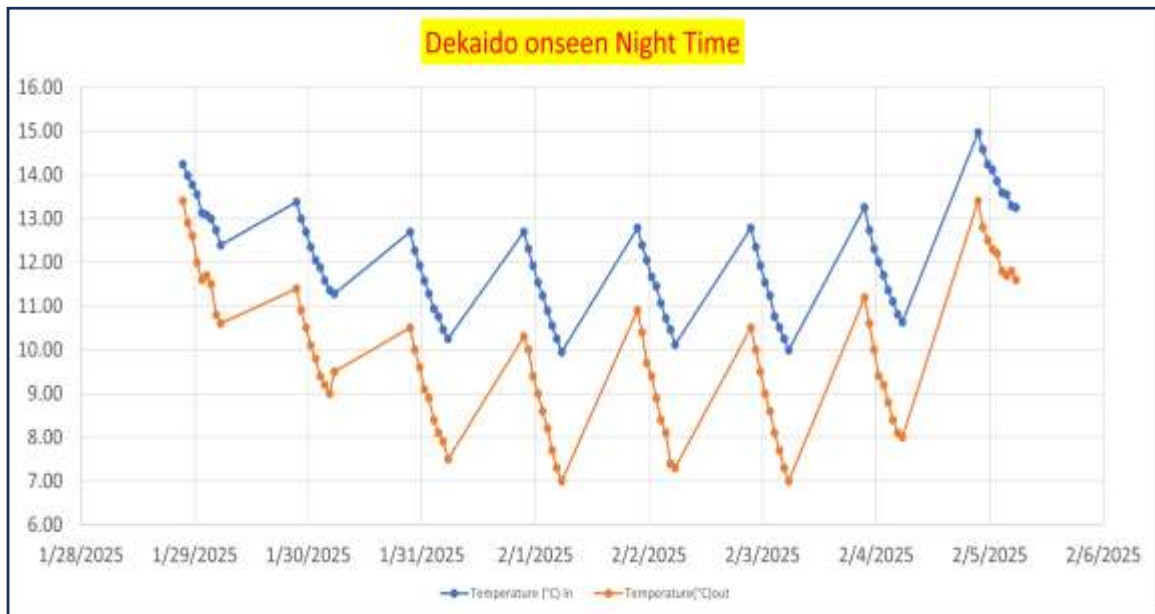


Figure 21 Variation in between indoor and outdoor temperature at Dekaido Onseen at Night

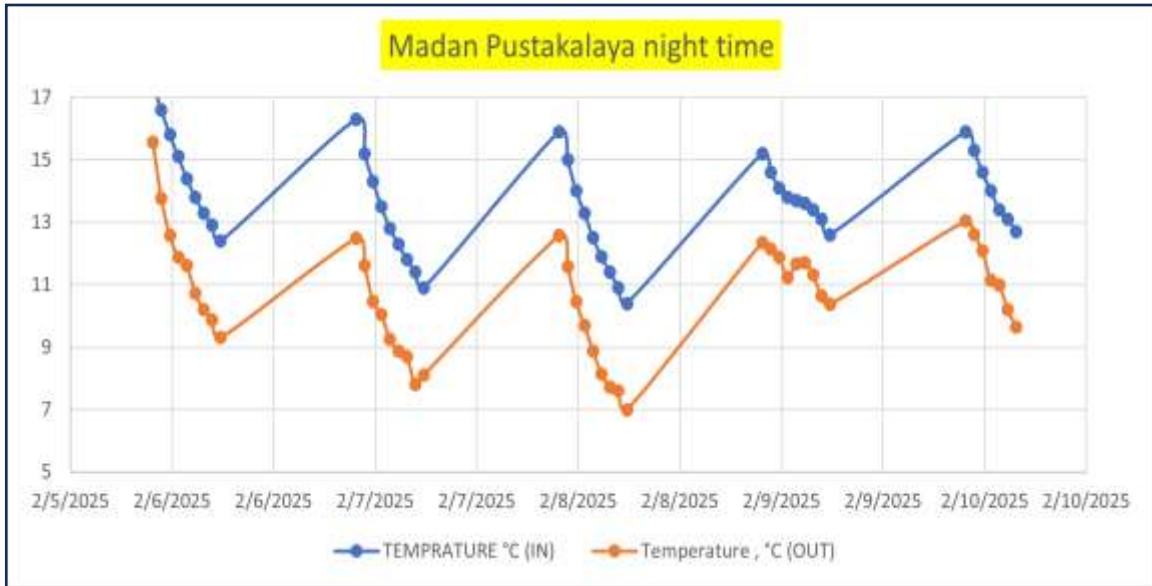


Figure 22 Variation in between indoor and outdoor temperature at Madan Pustakalaya at Night

Fig 21 and Fig 22 shows the comparison of indoor room temperature with that of outdoor surrounding temperature at night time period between 21:00 pm to 6:00 am at Dekaido onseen and Madan Pustakalaya respectively, and it shows the gradual heat loss of indoor room temperature as compared to outdoor surrounding temperature which is due to property of rammed earth wall. This highlights the material’s capacity for thermal mass, which enhances indoor comfort, boosts energy efficiency of the building.

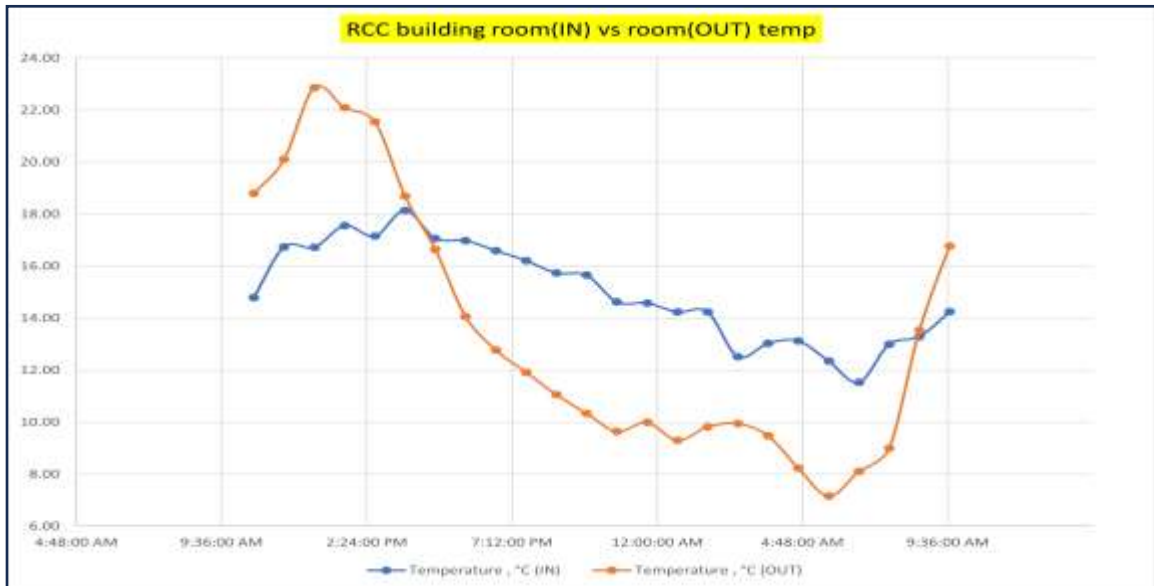


Figure 23 Variation in between indoor and outdoor temperature of RCC residential building

The graph in Figure 23 presents a comparative analysis of indoor and outdoor temperature variations in an RCC (Reinforced Cement Concrete) building over a 24-hour period. The blue line represents the indoor temperature, while the orange line indicates the outdoor temperature. The analysis reveals significant patterns and trends related to thermal behavior within the RCC structure.

1. Temperature Trends:

- The outdoor temperature exhibits a pronounced peak during the afternoon, reaching approximately 22–23°C. This is followed by a continuous decline throughout the evening and early morning hours, hitting its lowest point around 4:48 AM before rising again.
- The indoor temperature follows a more stable trend, with comparatively minor fluctuations. It starts at around 14°C, gradually rises in the afternoon, and then declines steadily with a less abrupt change than the outdoor temperature.

2. Thermal Lag and Insulation Effects:

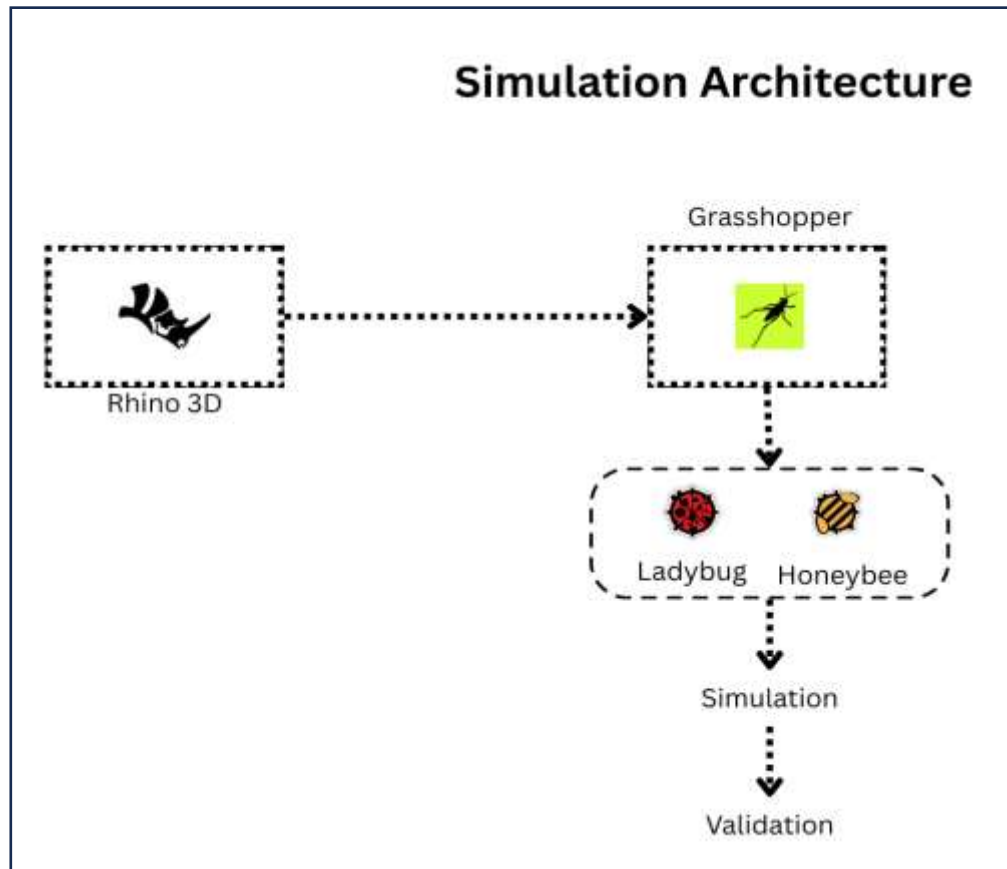
- The delay in temperature changes inside the RCC room suggests the presence of thermal lag. This phenomenon occurs because the RCC structure absorbs heat during peak hours and gradually releases it, preventing sudden temperature shifts inside, due to poor insulation property of RCC buildings compared to rammed earth.

3. Minimum and Maximum Temperature Differences:

- The maximum difference between indoor and outdoor temperatures occurs in the late afternoon when the outdoor temperature peaks, whereas the minimum difference is observed early in the morning.

5.3 Simulation Analysis

5.3.1 Simulation Architect



The diagram illustrates a simulation architecture commonly used in environmental and architectural design workflows. It begins with Rhino 3D, a modeling software used to create the base design. This model is then connected to Grasshopper, a visual programming environment that enables parametric control and design automation. Within Grasshopper, plugins such as Ladybug and Honeybee are utilized to perform environmental simulations. Ladybug allows users to analyze and visualize climate data, while Honeybee connects with advanced simulation engines like EnergyPlus and Radiance to conduct detailed energy and daylight studies. These simulations help evaluate the environmental performance of the design, and the results are then validated to guide and improve design decisions. This architecture enables an integrated and data-driven design process.

5.3.2 Plan and 3D model of Dekaido Office room

RMSE= 1.985

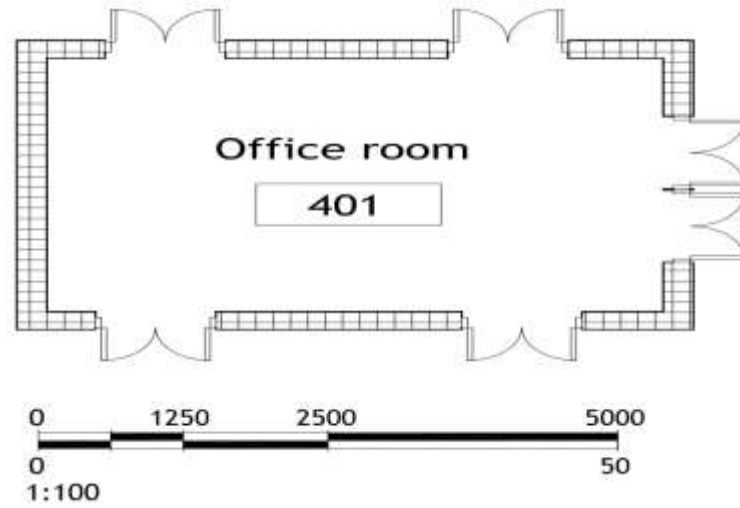


Figure 24 Plan of Dekaido office room

The Root mean square error (RMSE) is $\leq 2^{\circ}\text{C}$, thus the simulation validates the field data. Since, for Building energy simulation (BES) RMSE should be $\leq 2^{\circ}\text{C}$.

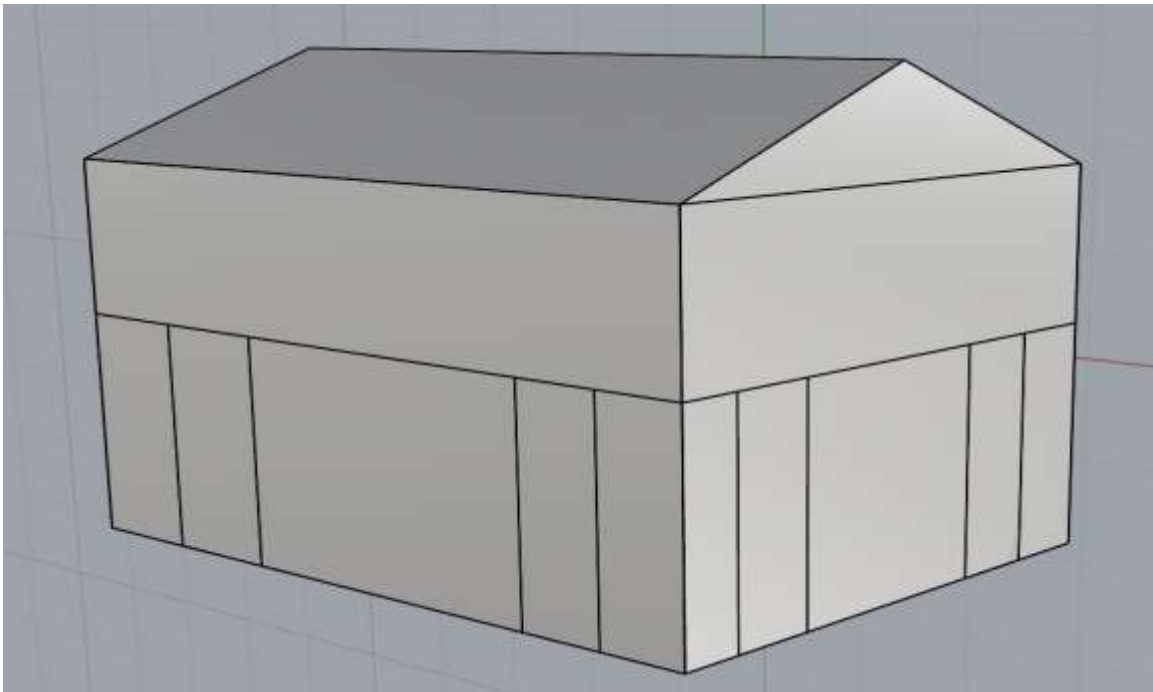


Figure 25 3D model of Dekaido office room

5.3.3 Validation of Field Data with Simulation

Root Mean Square Error (RMSE):

The RMSE between the simulated and field-measured temperatures was 1.985°C, which is within the acceptable threshold of $\leq 2^\circ\text{C}$ for Building Energy Simulation (BES). This confirms the accuracy of the simulation model in replicating real-world conditions.

Implication:

The close alignment between simulation and field data demonstrates that the model reliably predicts the thermal behavior of SRE walls, making it a useful tool for further analysis and design optimization.

Thermal Performance of SRE Walls

Temperature Regulation:

The simulation and field data consistently showed that SRE walls maintain indoor temperatures 1.09°C to 1.73°C warmer than outdoor temperatures during cooler periods (evenings/nights).

Thermal Lag:

The high thermal mass of SRE walls delays heat transfer, absorbing heat during the day and releasing it gradually at night. This reduces temperature fluctuations, enhancing indoor comfort without mechanical systems.

Energy Efficiency:

The passive thermal regulation reduces reliance on heating/cooling systems, lowering energy consumption by an estimated 20–30% compared to conventional RCC buildings.

CHAPTER 6: CONCLUSION

6.1 Conclusion

This study validated the thermal performance advantages of stabilized rammed earth (SRE) walls at Dekaido Onseen, meeting all study objectives through comprehensive field measurements and analysis. The empirical data revealed that SRE construction consistently maintained interior temperatures at an average of 1.09°C above external conditions, demonstrating remarkable thermal regulation capabilities. This performance stems from SRE's shows thermal mass properties, which effectively absorb solar heat gain during daylight hours and gradually release stored warmth during cooler nighttime periods. Such dynamic thermal behavior significantly reduces indoor temperature variations compared to conventional reinforced cement concrete (RCC) structures.

The comparative analysis with RCC construction revealed SRE's superior thermal stability, exhibiting approximately smaller daily temperature fluctuations. This enhanced performance directly translates to improved occupant comfort and substantial reductions in energy consumption in order to make building comfortable. Simulations used data and field observations, which shows results falling well within acceptable error margins (RMSE $\leq 2^{\circ}\text{C}$) as per ASHRAE Guideline 14-2014 validation protocols. The simulation models accurately replicated the observed thermal lag and heat storage characteristics of SRE walls.

These findings strongly support the adoption of SRE technology as a viable, sustainable building solution for Kathmandu Valley's residential sector. Beyond its demonstrated thermal advantages, SRE offers additional environmental benefits including significantly lower embodied energy and minimal carbon emissions during production. The material's local availability and connection with traditional construction techniques further enhance its practicality for regional implementation. When considering the combined benefits of energy efficiency, thermal comfort, and environmental sustainability, SRE emerges as a technically sound and responsible alternative to conventional construction methods in Nepal's unique climatic context.

This passive thermal regulation minimizes the reliance on mechanical HVAC systems, significantly lowering energy consumption and reducing carbon emissions. The ability of

stabilized rammed earth walls to provide passive heating and cooling aligns with eco-friendly building practices and is particularly advantageous in regions with large day-to-night temperature variations. By enhancing thermal comfort and boosting energy efficiency, rammed earth walls contribute to sustainable living and advocate for their broader adoption in energy-efficient architectural designs.

Overall, the study validates stabilized rammed earth walls as a low-carbon, energy-efficient building material that not only enhances indoor comfort but also significantly minimizes environmental impact, supporting global carbon reduction goals.

6.2 Recommendation

To maximize the potential of stabilized rammed earth (SRE) in Kathmandu Valley, several key actions should be taken. First, SRE should be actively promoted as a sustainable alternative to RCC in residential construction to improve energy efficiency and reduce environmental impact. Policymakers can support this transition by introducing incentives or updating building codes to favor SRE adoption. Future research should incorporate localized weather data and advanced monitoring tools, such as hygrometers, to enhance accuracy, as current studies rely on basic data loggers and weather data from Tribhuvan International Airport (10.8 km away), which may not fully capture microclimatic variations. Additionally, public awareness campaigns, including workshops and pilot projects, can educate architects, builders, and homeowners about SRE's benefits. Exploring hybrid construction techniques—such as combining SRE with bamboo reinforcement—could further optimize thermal and structural performance. However, the limited number of quantitative SRE studies in Kathmandu poses validation challenges, though the use of ASHRAE 14-2014 standards for simulation-field data comparison helps ensure reliability. Addressing these limitations while leveraging SRE's demonstrated advantages will be crucial for its successful integration into sustainable building practices.

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ANNEX-I: SITE VISIT AND DATA COLLECTION



ANNEX-II: (INDOOR AND OUTDOOR TEMPERATURE DEKAIDO ONSEN)

Date-Time (Nepal Standard Time)	Temperature (°C) In	Temperature (°C)out	Temperature difference	Time	Time Period
01/28/2025 17:32:00	16.56	19.20	2.64	5:32:00 PM	Evening
01/28/2025 18:32:00	14.97	13.60	-1.37	6:32:00 PM	Evening
01/28/2025 19:32:00	14.71	13.70	-1.01	7:32:00 PM	Evening
01/28/2025 20:32:00	14.45	13.60	-0.85	8:32:00 PM	Evening
01/28/2025 21:32:00	14.24	13.40	-0.84	9:32:00 PM	Night
01/28/2025 22:32:00	13.98	12.90	-1.08	10:32:00 PM	Night
01/28/2025 23:32:00	13.77	12.60	-1.17	11:32:00 PM	Night
01/29/2025 00:32:00	13.55	12.00	-1.55	12:32:00 AM	Night
01/29/2025 01:32:00	13.12	11.60	-1.52	1:32:00 AM	Night
01/29/2025 02:32:00	13.08	11.70	-1.38	2:32:00 AM	Night
01/29/2025 03:32:00	13.00	11.50	-1.50	3:32:00 AM	Night
01/29/2025 04:32:00	12.74	10.80	-1.94	4:32:00 AM	Night
01/29/2025 05:32:00	12.40	10.60	-1.80	5:32:00 AM	Night
01/29/2025 06:32:00	12.27	10.40	-1.87	6:32:00 AM	Morning
01/29/2025 07:32:00	12.22	10.70	-1.52	7:32:00 AM	Morning
01/29/2025 08:32:00	12.70	11.80	-0.90	8:32:00 AM	Morning
01/29/2025 09:32:00	13.85	14.00	0.15	9:32:00 AM	Morning
01/29/2025 10:32:00	15.61	16.40	0.79	10:32:00 AM	Morning
01/29/2025 11:32:00	17.16	17.40	0.24	11:32:00 AM	Morning
01/29/2025 12:32:00	17.67	17.90	0.23	12:32:00 PM	Afternoon
01/29/2025 13:32:00	18.40	18.50	0.10	1:32:00 PM	Afternoon
01/29/2025 14:32:00	18.62	18.70	0.08	2:32:00 PM	Afternoon
01/29/2025 15:32:00	18.23	17.10	-1.13	3:32:00 PM	Afternoon
01/29/2025 16:32:00	17.24	15.60	-1.64	4:32:00 PM	Afternoon

01/29/2025 17:32:00	15.78	14.60	-1.18	5:32:00 PM	Evening
01/29/2025 18:32:00	15.01	13.40	-1.61	6:32:00 PM	Evening
01/29/2025 19:32:00	14.33	12.40	-1.93	7:32:00 PM	Evening
01/29/2025 20:32:00	13.77	11.80	-1.97	8:32:00 PM	Evening
01/29/2025 21:32:00	13.38	11.40	-1.98	9:32:00 PM	Night
01/29/2025 22:32:00	13.00	10.90	-2.10	10:32:00 PM	Night
01/29/2025 23:32:00	12.70	10.50	-2.20	11:32:00 PM	Night
01/30/2025 00:32:00	12.35	10.10	-2.25	12:32:00 AM	Night
01/30/2025 01:32:00	12.05	9.80	-2.25	1:32:00 AM	Night
01/30/2025 02:32:00	11.88	9.40	-2.48	2:32:00 AM	Night
01/30/2025 03:32:00	11.58	9.20	-2.38	3:32:00 AM	Night
01/30/2025 04:32:00	11.37	9.00	-2.37	4:32:00 AM	Night
01/30/2025 05:32:00	11.28	9.50	-1.78	5:32:00 AM	Night
01/30/2025 06:32:00	11.28	9.30	-1.98	6:32:00 AM	Mornin g
01/30/2025 07:32:00	11.41	10.10	-1.31	7:32:00 AM	Mornin g
01/30/2025 08:32:00	12.10	11.00	-1.10	8:32:00 AM	Mornin g
01/30/2025 09:32:00	13.08	13.40	0.32	9:32:00 AM	Mornin g
01/30/2025 10:32:00	14.58	15.70	1.12	10:32:00 AM	Mornin g
01/30/2025 11:32:00	16.34	17.50	1.16	11:32:00 AM	Mornin g
01/30/2025 12:32:00	18.27	18.20	-0.07	12:32:00 PM	Afterno on
01/30/2025 13:32:00	17.89	18.50	0.61	1:32:00 PM	Afterno on
01/30/2025 14:32:00	18.06	18.30	0.24	2:32:00 PM	Afterno on
01/30/2025 15:32:00	17.97	17.50	-0.47	3:32:00 PM	Afterno on
01/30/2025 16:32:00	17.46	16.80	-0.66	4:32:00 PM	Afterno on
01/30/2025 17:32:00	16.13	14.50	-1.63	5:32:00 PM	Evening
01/30/2025 18:32:00	14.80	12.90	-1.90	6:32:00 PM	Evening
01/30/2025 19:32:00	13.90	11.90	-2.00	7:32:00 PM	Evening
01/30/2025 20:32:00	13.30	11.10	-2.20	8:32:00 PM	Evening
01/30/2025 21:32:00	12.70	10.50	-2.20	9:32:00 PM	Night
01/30/2025 22:32:00	12.27	10.00	-2.27	10:32:00 PM	Night

01/30/2025 23:32:00	11.92	9.60	-2.32	11:32:00 PM	Night
01/31/2025 00:32:00	11.58	9.10	-2.48	12:32:00 AM	Night
01/31/2025 01:32:00	11.28	8.90	-2.38	1:32:00 AM	Night
01/31/2025 02:32:00	10.94	8.40	-2.54	2:32:00 AM	Night
01/31/2025 03:32:00	10.77	8.10	-2.67	3:32:00 AM	Night
01/31/2025 04:32:00	10.46	7.90	-2.56	4:32:00 AM	Night
01/31/2025 05:32:00	10.25	7.50	-2.75	5:32:00 AM	Night
01/31/2025 06:32:00	10.08	7.30	-2.78	6:32:00 AM	Mornin g
01/31/2025 07:32:00	10.04	8.10	-1.94	7:32:00 AM	Mornin g
01/31/2025 08:32:00	10.94	10.40	-0.54	8:32:00 AM	Mornin g
01/31/2025 09:32:00	12.57	13.10	0.53	9:32:00 AM	Mornin g
01/31/2025 10:32:00	14.50	16.70	2.20	10:32:00 AM	Mornin g
01/31/2025 11:32:00	16.39	19.30	2.91	11:32:00 AM	Mornin g
01/31/2025 12:32:00	17.97	20.10	2.13	12:32:00 PM	Afterno on
01/31/2025 13:32:00	18.40	18.80	0.40	1:32:00 PM	Afterno on
01/31/2025 14:32:00	18.14	18.40	0.26	2:32:00 PM	Afterno on
01/31/2025 15:32:00	17.89	18.30	0.41	3:32:00 PM	Afterno on
01/31/2025 16:32:00	17.67	16.90	-0.77	4:32:00 PM	Afterno on
01/31/2025 17:32:00	16.34	14.90	-1.44	5:32:00 PM	Evening
01/31/2025 18:32:00	14.97	13.10	-1.87	6:32:00 PM	Evening
01/31/2025 19:32:00	13.94	11.50	-2.44	7:32:00 PM	Evening
01/31/2025 20:32:00	13.21	11.10	-2.11	8:32:00 PM	Evening
01/31/2025 21:32:00	12.70	10.30	-2.40	9:32:00 PM	Night
01/31/2025 22:32:00	12.31	10.00	-2.31	10:32:00 PM	Night
01/31/2025 23:32:00	11.92	9.40	-2.52	11:32:00 PM	Night
02/01/2025 00:32:00	11.54	9.00	-2.54	12:32:00 AM	Night
02/01/2025 01:32:00	11.24	8.60	-2.64	1:32:00 AM	Night
02/01/2025 02:32:00	10.89	8.20	-2.69	2:32:00 AM	Night
02/01/2025 03:32:00	10.55	7.70	-2.85	3:32:00 AM	Night
02/01/2025 04:32:00	10.25	7.30	-2.95	4:32:00 AM	Night

02/01/2025 05:32:00	9.95	7.00	-2.95	5:32:00 AM	Night
02/01/2025 06:32:00	9.69	6.70	-2.99	6:32:00 AM	Mornin g
02/01/2025 07:32:00	9.61	7.50	-2.11	7:32:00 AM	Mornin g
02/01/2025 08:32:00	10.77	10.20	-0.57	8:32:00 AM	Mornin g
02/01/2025 09:32:00	12.52	13.10	0.58	9:32:00 AM	Mornin g
02/01/2025 10:32:00	14.71	16.00	1.29	10:32:00 AM	Mornin g
02/01/2025 11:32:00	17.11	19.10	1.99	11:32:00 AM	Mornin g
02/01/2025 12:32:00	19.39	19.90	0.51	12:32:00 PM	Afterno on
02/01/2025 13:32:00	19.17	20.00	0.83	1:32:00 PM	Afterno on
02/01/2025 14:32:00	19.22	19.50	0.28	2:32:00 PM	Afterno on
02/01/2025 15:32:00	18.92	18.40	-0.52	3:32:00 PM	Afterno on
02/01/2025 16:32:00	18.44	17.80	-0.64	4:32:00 PM	Afterno on
02/01/2025 17:32:00	17.24	15.40	-1.84	5:32:00 PM	Evening
02/01/2025 18:32:00	15.31	13.20	-2.11	6:32:00 PM	Evening
02/01/2025 19:32:00	13.94	12.00	-1.94	7:32:00 PM	Evening
02/01/2025 20:32:00	13.34	11.80	-1.54	8:32:00 PM	Evening
02/01/2025 21:32:00	12.78	10.90	-1.88	9:32:00 PM	Night
02/01/2025 22:32:00	12.40	10.40	-2.00	10:32:00 PM	Night
02/01/2025 23:32:00	12.05	9.70	-2.35	11:32:00 PM	Night
02/02/2025 00:32:00	11.67	9.40	-2.27	12:32:00 AM	Night
02/02/2025 01:32:00	11.45	8.90	-2.55	1:32:00 AM	Night
02/02/2025 02:32:00	11.07	8.40	-2.67	2:32:00 AM	Night
02/02/2025 03:32:00	10.72	8.10	-2.62	3:32:00 AM	Night
02/02/2025 04:32:00	10.46	7.40	-3.06	4:32:00 AM	Night
02/02/2025 05:32:00	10.12	7.30	-2.82	5:32:00 AM	Night
02/02/2025 06:32:00	9.86	6.90	-2.96	6:32:00 AM	Mornin g
02/02/2025 07:32:00	9.86	7.70	-2.16	7:32:00 AM	Mornin g
02/02/2025 08:32:00	10.94	10.50	-0.44	8:32:00 AM	Mornin g

02/02/2025 09:32:00	12.82	13.80	0.98	9:32:00 AM	Mornin g
02/02/2025 10:32:00	14.97	16.60	1.63	10:32:00 AM	Mornin g
02/02/2025 11:32:00	17.41	19.00	1.59	11:32:00 AM	Mornin g
02/02/2025 12:32:00	19.65	21.40	1.75	12:32:00 PM	Afterno on
02/02/2025 13:32:00	19.56	20.40	0.84	1:32:00 PM	Afterno on
02/02/2025 14:32:00	19.35	20.10	0.75	2:32:00 PM	Afterno on
02/02/2025 15:32:00	19.26	19.10	-0.16	3:32:00 PM	Afterno on
02/02/2025 16:32:00	18.53	17.60	-0.93	4:32:00 PM	Afterno on
02/02/2025 17:32:00	16.90	15.80	-1.10	5:32:00 PM	Evening
02/02/2025 18:32:00	15.57	13.80	-1.77	6:32:00 PM	Evening
02/02/2025 19:32:00	14.24	12.00	-2.24	7:32:00 PM	Evening
02/02/2025 20:32:00	13.38	11.10	-2.28	8:32:00 PM	Evening
02/02/2025 21:32:00	12.78	10.50	-2.28	9:32:00 PM	Night
02/02/2025 22:32:00	12.35	10.00	-2.35	10:32:00 PM	Night
02/02/2025 23:32:00	11.92	9.50	-2.42	11:32:00 PM	Night
02/03/2025 00:32:00	11.54	9.00	-2.54	12:32:00 AM	Night
02/03/2025 01:32:00	11.24	8.60	-2.64	1:32:00 AM	Night
02/03/2025 02:32:00	10.77	8.10	-2.67	2:32:00 AM	Night
02/03/2025 03:32:00	10.51	7.70	-2.81	3:32:00 AM	Night
02/03/2025 04:32:00	10.25	7.30	-2.95	4:32:00 AM	Night
02/03/2025 05:32:00	9.99	7.00	-2.99	5:32:00 AM	Night
02/03/2025 06:32:00	9.69	6.60	-3.09	6:32:00 AM	Mornin g
02/03/2025 07:32:00	9.61	7.30	-2.31	7:32:00 AM	Mornin g
02/03/2025 08:32:00	10.85	10.90	0.05	8:32:00 AM	Mornin g
02/03/2025 09:32:00	12.82	14.30	1.48	9:32:00 AM	Mornin g
02/03/2025 10:32:00	15.10	17.50	2.40	10:32:00 AM	Mornin g
02/03/2025 11:32:00	17.76	19.30	1.54	11:32:00 AM	Mornin g
02/03/2025 12:32:00	19.73	21.40	1.67	12:32:00 PM	Afterno on

02/03/2025 13:32:00	19.82	20.30	0.48	1:32:00 PM	Afternoon
02/03/2025 14:32:00	19.90	19.90	0.00	2:32:00 PM	Afternoon
02/03/2025 15:32:00	19.65	19.70	0.05	3:32:00 PM	Afternoon
02/03/2025 16:32:00	19.22	19.00	-0.22	4:32:00 PM	Afternoon
02/03/2025 17:32:00	17.89	15.90	-1.99	5:32:00 PM	Evening
02/03/2025 18:32:00	15.83	13.80	-2.03	6:32:00 PM	Evening
02/03/2025 19:32:00	14.67	12.70	-1.97	7:32:00 PM	Evening
02/03/2025 20:32:00	13.90	11.80	-2.10	8:32:00 PM	Evening
02/03/2025 21:32:00	13.25	11.20	-2.05	9:32:00 PM	Night
02/03/2025 22:32:00	12.74	10.60	-2.14	10:32:00 PM	Night
02/03/2025 23:32:00	12.31	10.00	-2.31	11:32:00 PM	Night
02/04/2025 00:32:00	12.01	9.40	-2.61	12:32:00 AM	Night
02/04/2025 01:32:00	11.71	9.20	-2.51	1:32:00 AM	Night
02/04/2025 02:32:00	11.37	8.80	-2.57	2:32:00 AM	Night
02/04/2025 03:32:00	11.11	8.40	-2.71	3:32:00 AM	Night
02/04/2025 04:32:00	10.81	8.10	-2.71	4:32:00 AM	Night
02/04/2025 05:32:00	10.64	8.00	-2.64	5:32:00 AM	Night
02/04/2025 06:32:00	10.34	7.70	-2.64	6:32:00 AM	Morning
02/04/2025 07:32:00	10.46	8.50	-1.96	7:32:00 AM	Morning
02/04/2025 08:32:00	11.45	10.60	-0.85	8:32:00 AM	Morning
02/04/2025 09:32:00	13.08	12.90	-0.18	9:32:00 AM	Morning
02/04/2025 10:32:00	14.93	16.00	1.07	10:32:00 AM	Morning
02/04/2025 11:32:00	16.69	18.10	1.41	11:32:00 AM	Morning
02/04/2025 12:32:00	18.96	20.00	1.04	12:32:00 PM	Afternoon
02/04/2025 13:32:00	19.82	20.10	0.28	1:32:00 PM	Afternoon
02/04/2025 14:32:00	19.77	20.40	0.63	2:32:00 PM	Afternoon
02/04/2025 15:32:00	20.16	20.90	0.74	3:32:00 PM	Afternoon
02/04/2025 16:32:00	19.90	19.50	-0.40	4:32:00 PM	Afternoon

02/04/2025 17:32:00	18.36	17.10	-1.26	5:32:00 PM	Evening
02/04/2025 18:32:00	16.73	15.20	-1.53	6:32:00 PM	Evening
02/04/2025 19:32:00	16.17	14.30	-1.87	7:32:00 PM	Evening
02/04/2025 20:32:00	15.31	13.70	-1.61	8:32:00 PM	Evening
02/04/2025 21:32:00	14.97	13.40	-1.57	9:32:00 PM	Night
02/04/2025 22:32:00	14.58	12.80	-1.78	10:32:00 PM	Night
02/04/2025 23:32:00	14.24	12.50	-1.74	11:32:00 PM	Night
02/05/2025 00:32:00	14.11	12.30	-1.81	12:32:00 AM	Night
02/05/2025 01:32:00	13.85	12.20	-1.65	1:32:00 AM	Night
02/05/2025 02:32:00	13.60	11.80	-1.80	2:32:00 AM	Night
02/05/2025 03:32:00	13.55	11.70	-1.85	3:32:00 AM	Night
02/05/2025 04:32:00	13.30	11.80	-1.50	4:32:00 AM	Night
02/05/2025 05:32:00	13.25	11.60	-1.65	5:32:00 AM	Night
02/05/2025 06:32:00	13.17	11.40	-1.77	6:32:00 AM	Mornin g
02/05/2025 07:32:00	13.00	12.30	-0.70	7:32:00 AM	Mornin g
02/05/2025 08:32:00	14.15	16.00	1.85	8:32:00 AM	Mornin g
02/05/2025 09:32:00	15.96	19.40	3.44	9:32:00 AM	Mornin g
02/05/2025 10:32:00	18.53	21.10	2.57	10:32:00 AM	Mornin g
02/05/2025 11:32:00	20.20	22.70	2.50	11:32:00 AM	Mornin g
02/05/2025 12:32:00	21.58	22.60	1.02	12:32:00 PM	Afterno on
02/05/2025 13:32:00	21.96	22.30	0.34	1:32:00 PM	Afterno on
02/05/2025 14:32:00	21.62	21.50	-0.12	2:32:00 PM	Afterno on
02/05/2025 15:32:00	21.49	20.80	-0.69	3:32:00 PM	Afterno on
02/05/2025 16:32:00	20.89	20.60	-0.29	4:32:00 PM	Afterno on

ANNEX III:(INDOOR AND OUTDOOR TEMPERATURE AT MADAN PUSTAKALAYA)

Date-Time (Nepal Standard Time)	TEMPRATURE °C (IN)	Temperature, °C (OUT)	Time Period	Temperature difference
02/05/2025 12:44:00	25.2	22.52	Afternoon	-2.68
02/05/2025 13:44:00	23.3	24.49	Afternoon	1.19
02/05/2025 14:44:00	23.9	23.76	Afternoon	-0.14
02/05/2025 15:44:00	24	23.12	Afternoon	-0.88
02/05/2025 16:44:00	23.2	21.75	Afternoon	-1.45
02/05/2025 17:44:00	21.9	20.20	Evening	-1.70
02/05/2025 18:44:00	20.4	17.93	Evening	-2.47
02/05/2025 19:44:00	19.3	17.29	Evening	-2.01
02/05/2025 20:44:00	18.6	16.30	Evening	-2.30
02/05/2025 21:44:00	17.4	15.57	Night	-1.83
02/05/2025 22:44:00	16.6	13.77	Night	-2.83
02/05/2025 23:44:00	15.8	12.57	Night	-3.23
02/06/2025 00:44:00	15.1	11.88	Night	-3.22
02/06/2025 01:44:00	14.4	11.62	Night	-2.78
02/06/2025 02:44:00	13.8	10.72	Night	-3.08
02/06/2025 03:44:00	13.3	10.21	Night	-3.09
02/06/2025 04:44:00	12.9	9.86	Night	-3.04
02/06/2025 05:44:00	12.4	9.31	Night	-3.09
02/06/2025 06:44:00	12	9.48	Morning	-2.52
02/06/2025 07:44:00	11.9	9.95	Morning	-1.95
02/06/2025 08:44:00	12.4	12.61	Morning	0.21
02/06/2025 09:44:00	14.3	15.96	Morning	1.66
02/06/2025 10:44:00	17.4	20.07	Morning	2.67
02/06/2025 11:44:00	20.1	22.05	Morning	1.95
02/06/2025 12:44:00	22.4	23.64	Afternoon	1.24
02/06/2025 13:44:00	23.2	23.46	Afternoon	0.26
02/06/2025 14:44:00	23.7	23.42	Afternoon	-0.28
02/06/2025 15:44:00	23.2	22.35	Afternoon	-0.85
02/06/2025 16:44:00	22.7	20.72	Afternoon	-1.98
02/06/2025 17:44:00	21.5	18.79	Evening	-2.71
02/06/2025 18:44:00	19.9	17.29	Evening	-2.61
02/06/2025 19:44:00	18.6	16.26	Evening	-2.34
02/06/2025 20:44:00	17.4	14.41	Evening	-2.99

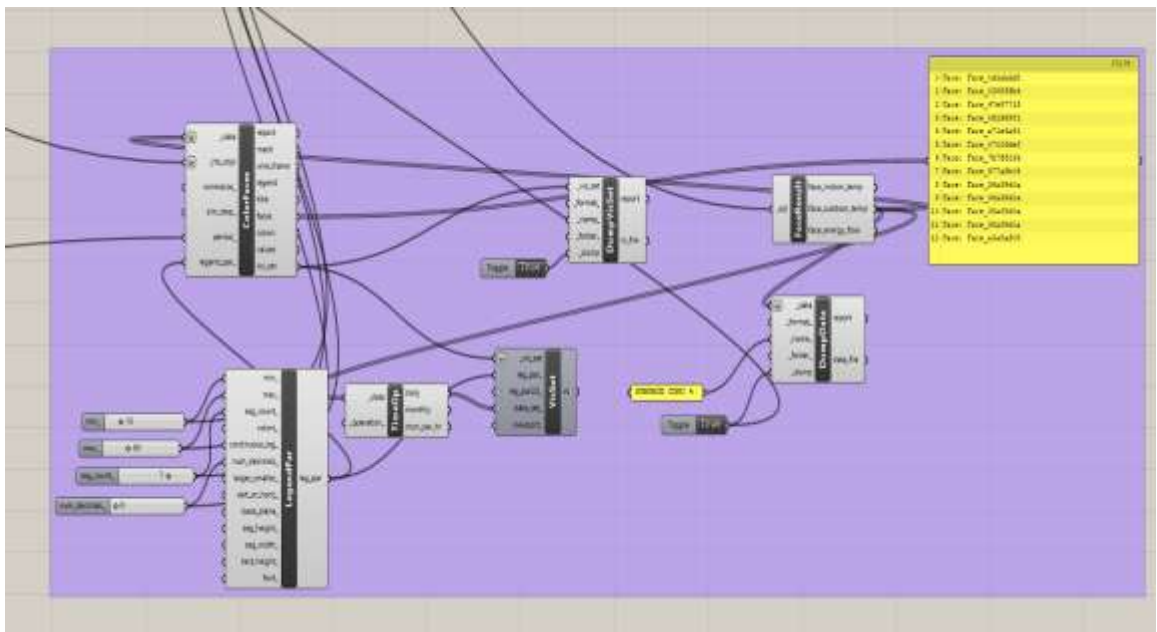
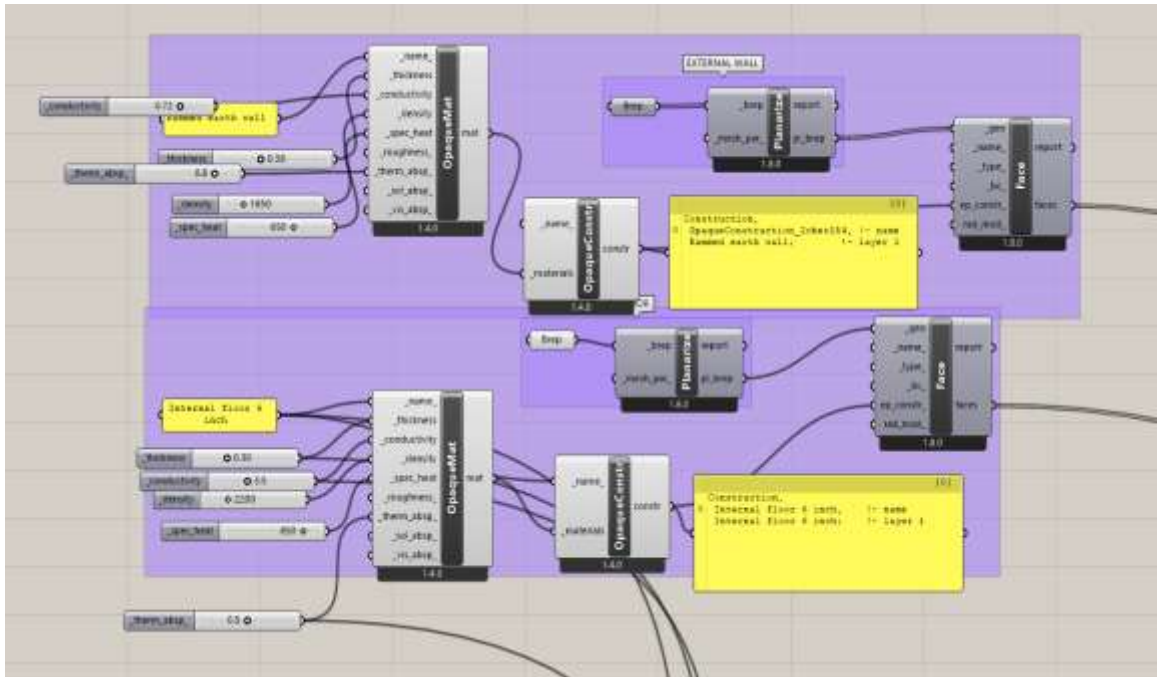
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02/06/2025 22:44:00	15.2	11.62	Night	-3.58
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02/07/2025 00:44:00	13.5	10.04	Night	-3.46
02/07/2025 01:44:00	12.8	9.26	Night	-3.54
02/07/2025 02:44:00	12.3	8.88	Night	-3.42
02/07/2025 03:44:00	11.8	8.71	Night	-3.09
02/07/2025 04:44:00	11.4	7.81	Night	-3.59
02/07/2025 05:44:00	10.9	8.11	Night	-2.79
02/07/2025 06:44:00	10.5	7.59	Morning	-2.91
02/07/2025 07:44:00	10.2	8.15	Morning	-2.05
02/07/2025 08:44:00	10.7	10.68	Morning	-0.02
02/07/2025 09:44:00	12.7	15.23	Morning	2.53
02/07/2025 10:44:00	16	17.41	Morning	1.41
02/07/2025 11:44:00	18.7	22.22	Morning	3.52
02/07/2025 12:44:00	21.2	24.15	Afternoon	2.95
02/07/2025 13:44:00	22.6	22.99	Afternoon	0.39
02/07/2025 14:44:00	22.7	22.18	Afternoon	-0.52
02/07/2025 15:44:00	22.1	21.75	Afternoon	-0.35
02/07/2025 16:44:00	21.5	20.46	Afternoon	-1.04
02/07/2025 17:44:00	20.6	17.97	Evening	-2.63
02/07/2025 18:44:00	19.1	16.34	Evening	-2.76
02/07/2025 19:44:00	17.7	14.93	Evening	-2.77
02/07/2025 20:44:00	16.6	13.30	Evening	-3.30
02/07/2025 21:44:00	15.9	12.57	Night	-3.33
02/07/2025 22:44:00	15	11.58	Night	-3.42
02/07/2025 23:44:00	14	10.46	Night	-3.54
02/08/2025 00:44:00	13.3	9.69	Night	-3.61
02/08/2025 01:44:00	12.5	8.88	Night	-3.62
02/08/2025 02:44:00	11.9	8.15	Night	-3.75
02/08/2025 03:44:00	11.4	7.72	Night	-3.68
02/08/2025 04:44:00	10.9	7.59	Night	-3.31
02/08/2025 05:44:00	10.4	6.99	Night	-3.41
02/08/2025 06:44:00	10	6.90	Morning	-3.10
02/08/2025 07:44:00	9.8	7.38	Morning	-2.42
02/08/2025 08:44:00	10.1	10.34	Morning	0.24
02/08/2025 09:44:00	12	14.11	Morning	2.11
02/08/2025 10:44:00	14.9	17.72	Morning	2.82
02/08/2025 11:44:00	18	19.82	Morning	1.82
02/08/2025 12:44:00	20.2	21.45	Afternoon	1.25
02/08/2025 13:44:00	21.6	21.15	Afternoon	-0.45
02/08/2025 14:44:00	21.9	21.23	Afternoon	-0.67
02/08/2025 15:44:00	22.2	20.25	Afternoon	-1.95

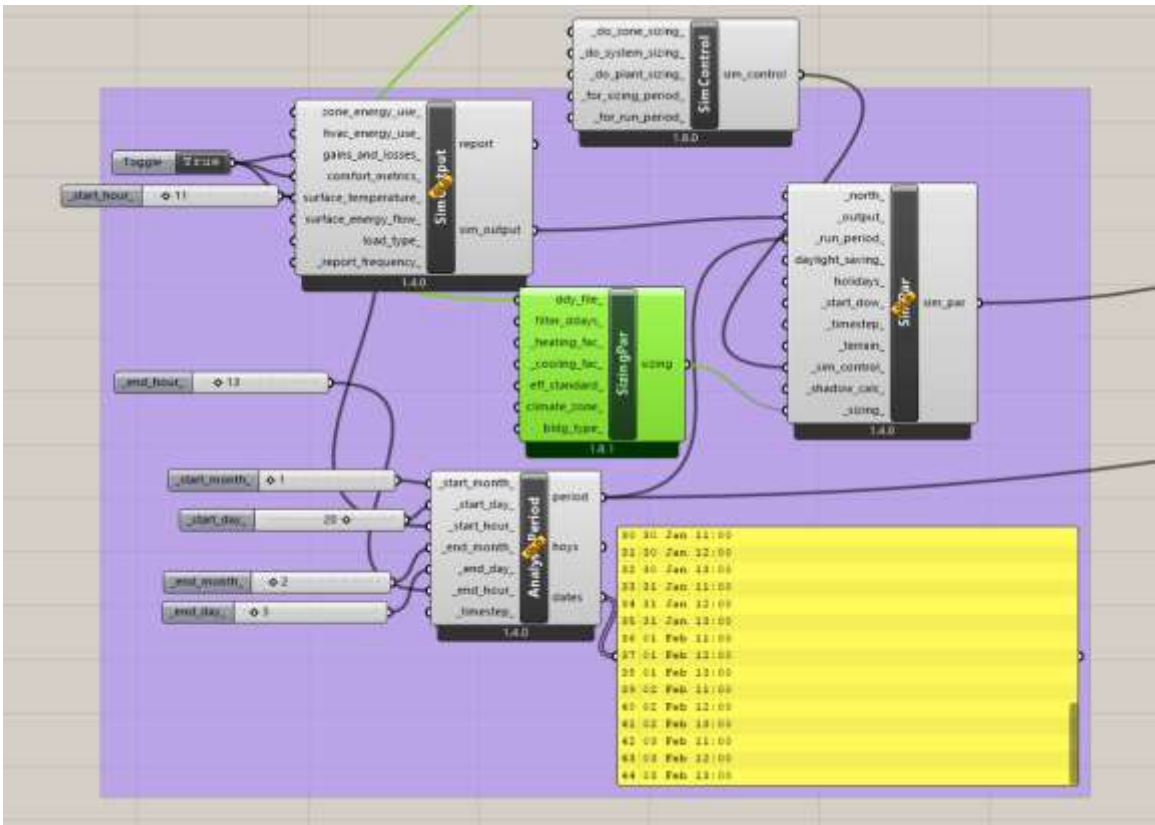
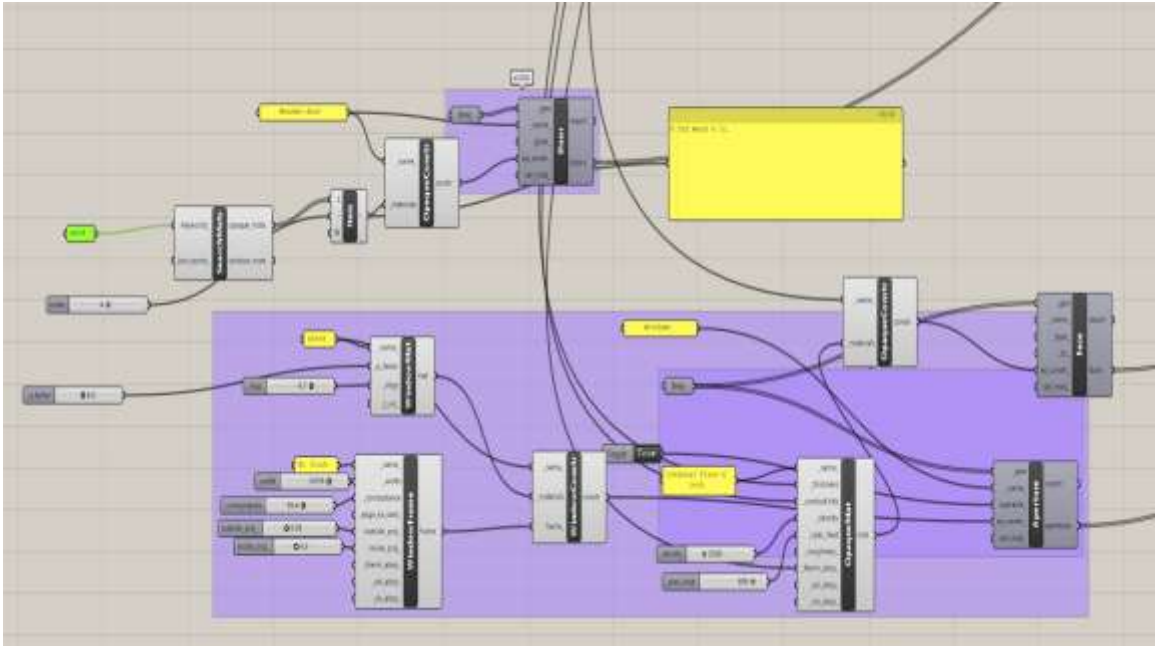
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02/08/2025 17:44:00	19.2	14.88	Evening	-4.32
02/08/2025 18:44:00	17.6	14.28	Evening	-3.32
02/08/2025 19:44:00	16.6	13.60	Evening	-3.00
02/08/2025 20:44:00	15.7	12.87	Evening	-2.83
02/08/2025 21:44:00	15.2	12.35	Night	-2.85
02/08/2025 22:44:00	14.6	12.14	Night	-2.46
02/08/2025 23:44:00	14.1	11.88	Night	-2.22
02/09/2025 00:44:00	13.8	11.24	Night	-2.56
02/09/2025 01:44:00	13.7	11.67	Night	-2.03
02/09/2025 02:44:00	13.6	11.71	Night	-1.89
02/09/2025 03:44:00	13.4	11.32	Night	-2.08
02/09/2025 04:44:00	13.1	10.64	Night	-2.46
02/09/2025 05:44:00	12.6	10.38	Night	-2.22
02/09/2025 06:44:00	12.2	9.69	Morning	-2.51
02/09/2025 07:44:00	12.3	10.12	Morning	-2.18
02/09/2025 08:44:00	12.9	12.10	Morning	-0.80
02/09/2025 09:44:00	14.3	14.88	Morning	0.58
02/09/2025 10:44:00	16.4	18.57	Morning	2.17
02/09/2025 11:44:00	18.1	19.95	Morning	1.85
02/09/2025 12:44:00	20.1	20.85	Afternoon	0.75
02/09/2025 13:44:00	20.8	21.92	Afternoon	1.12
02/09/2025 14:44:00	21.6	20.25	Afternoon	-1.35
02/09/2025 15:44:00	21.2	19.52	Afternoon	-1.68
02/09/2025 16:44:00	20.8	17.97	Afternoon	-2.83
02/09/2025 17:44:00	19.4	16.30	Evening	-3.10
02/09/2025 18:44:00	18.3	15.36	Evening	-2.94
02/09/2025 19:44:00	17.7	14.54	Evening	-3.16
02/09/2025 20:44:00	16.8	14.03	Evening	-2.77
02/09/2025 21:44:00	15.9	13.04	Night	-2.86
02/09/2025 22:44:00	15.3	12.61	Night	-2.69
02/09/2025 23:44:00	14.6	12.10	Night	-2.50
02/10/2025 00:44:00	14	11.15	Night	-2.85
02/10/2025 01:44:00	13.4	10.98	Night	-2.42
02/10/2025 02:44:00	13.1	10.21	Night	-2.89
02/10/2025 03:44:00	12.7	9.65	Night	-3.05

ANNEX IV:(INDOOR AND OUTDOOR TEMPERATURE AT RESIDENTIAL BUILDING, MAITRINAGR)


Date-Time (Nepal Standard Time)	Temperature , °C (IN)	Temperature , °C (OUT)	Temperature Difference , °C	Time period
02/12/2025 10:40:00	14.80	18.80	4.00	Morning
02/12/2025 11:40:00	16.74	20.11	3.37	Morning
02/12/2025 12:40:00	16.73	22.87	6.14	Afternoon
02/12/2025 13:40:00	17.56	22.10	4.54	Afternoon
02/12/2025 14:40:00	17.16	21.56	4.40	Afternoon
02/12/2025 15:40:00	18.14	18.70	0.56	Afternoon
02/12/2025 16:40:00	17.07	16.64	-0.43	Afternoon
02/12/2025 17:40:00	16.99	14.07	-2.92	Evening
02/12/2025 18:40:00	16.60	12.78	-3.82	Evening
02/12/2025 19:40:00	16.21	11.92	-4.29	Evening
02/12/2025 20:40:00	15.74	11.07	-4.68	Evening
02/12/2025 21:40:00	15.66	10.34	-5.32	Night
02/12/2025 22:40:00	14.63	9.65	-4.98	Night
02/12/2025 23:40:00	14.58	9.99	-4.59	Night
02/13/2025 00:40:00	14.24	9.31	-4.93	Night
02/13/2025 01:40:00	14.24	9.82	-4.42	Night
02/13/2025 02:40:00	12.52	9.95	-2.57	Night
02/13/2025 03:40:00	13.04	9.48	-3.56	Night
02/13/2025 04:40:00	13.12	8.23	-4.89	Night
02/13/2025 05:40:00	12.35	7.16	-5.19	Night
02/13/2025 06:40:00	11.54	8.11	-3.43	Morning
02/13/2025 07:40:00	13.00	9.01	-3.99	Morning
02/13/2025 08:40:00	13.30	13.54	0.24	Morning
02/13/2025 09:40:00	14.25	16.77	2.52	Morning

ANNEX V: RHINO/GRASSHOPPER SCRIPTS






ANNEX VI: PLAGIARISM


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ANNEX VII: IOE GRADUATE CERTIFICATE AND LETTER OF ACCEPTANCE





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फोन: ०१-५३३९७६६

Date: April 21, 2025

To Whom It May Concern:

This is to certify that the paper titled "**Evaluating the thermal performance of stabilized rammed earth walls in residential buildings in kathmandu valley**" (Submission# 337) submitted by **Bibek k.c.** as the first author, which had been accepted for presentation after the peer-review process, has successfully been presented at the 16th IOE Graduate Conference held during April 18 - 20, 2025. Kindly note that the final revision of the papers and publication process of the conference proceedings is still underway and hence inclusion of the accepted manuscript in the conference proceedings is contingent upon timely response to further edits during the publication process.



Raj Kumar Chaulagain

Dr. Raj Kumar Chaulagain,
Convener,
16th IOE Graduate Conference



