Potential and challenges of advanced manufacturing for rammed earth construction: A proposal for optimal thermal performance of non-structural rammed earth in execution process for Riyadh residences.

Tamanna Jalali[1] and Lubaina Soni[2*]

[1]MS Scholar, Allama Iqbal Open University (AIOU), Islamabad, Pakistan.
[1]Assistant Professor, Department of Architecture and Planning, Dawood University of Engineering and Technology, Karachi, Pakistan.

*Corresponding Author: Lubaina Soni, https://orcid.org/0000-0003-4280-0789

Abstract. *In the current scenario of contemporary environmental and social sustainability, sustainable construction is becoming a most important topic. Investigating ways in which sustainable construction can lead to favorable results is essential as buildings are the largest contributor to depletion of environmental resources. As the world grapple with challenges posed by climate change and the requirement for more resilient cities and communities; earth construction is being explicitly rethought considering the growing awareness of the detrimental effects cement-based products have on the environment. Though mechanization of earth construction has been attempted for almost a decade, research on progressive construction from earthy material has accelerated in the past five years. The focus has primarily been on manufacturing clay-rich soil, such as in adobe and cob methods. In contrast, very little research has been done on mechanizing other methods, like rammed earth. This paper examines literature on thermal performance of rammed earth construction through the total spectrum of weather changes, in hot arid regions. A thorough investigation of recent rammed earth projects as case studies was conducted, and compared, to produce realistic feasibility assessment of thermal performance of the material, that considered both the potentials of the technique and the technical challenges. The knowledge gained from these case studies offers comprehensive and concrete road map for viability of rammed earth construction for hot arid regions like Riyadh, based on its thermal performance, which helps to increase its desirability and ability to attain passive thermal comfort in modern residential buildings in the region of Riyadh.*

Key words: *climate change, passive thermal comfort, sustainable construction, rammed earth construction, Australia, and Riyadh.*

1. INTRODUCTION

The concept of sustainability holds a significant place in the modern era, and sustainable construction plays a key role in promoting environmental and social sustainability. Sustainable construction through a building design reflects the social identity of a region by incorporating the local culture and history into the plan, creating a unique architectural identity [1, 2]. Many countries are developing their social identity by implementing sustainable modern techniques to promote sustainable development and address the impact of major environmental and social challenges [3, 4]. In the construction industry, social sustainability is an important aspect of green building design, which requires further studies to monitor and collect data over a certain period and evaluate the effectiveness of sustainability initiatives [5-8]. More recently, inclination of green building design towards using repurposed earthy materials [9-11] as a sustainable alternative to concrete material [12] is increasing that could help reduce the adverse impact of construction on the global environment [13, 14].

Earth constructions are additive manufacturing of clay-rich soil using earthy materials such as adobe, cob, and compressed earth blocks [15]. They are naturally insulated which regulates indoor temperatures, and reduces the need for heating and cooling systems, thus reducing energy consumption [16]. They have a low environmental impact due to using non-toxic chemicals, and they are also biodegradable [17]. Hence, with proper maintenance, they can last for centuries, reducing the need for replacements and construction waste, and the building returns to earth when it is no longer needed [18]. However, limited research has been done on mechanizing other earth construction methods, like rammed earth. Rammed earth is the earliest form of construction, where a mixture of earth is compacted in layers between forms to create walls. Rammed earth incorporating with recycled aggregates (clay, sand, and aggregate in balanced proportion) have durability, simplicity and elegance and results in energy efficiency in a wide range of climates [13].

Buildings are the major factor of energy consumption around the globe and residential buildings alone consume 40% of the energy globally. Reducing energy use, ensuring thermal comfort, and creating healthy interior spaces all depend on designing an energy-efficient building envelope [1, 19, 20]. In hot arid climates such as the Kingdom of Saudi Arabia (KSA), buildings consume half of all energy, and more than half of the buildings are not insulated well in the KSA [21]. Hence, the buildings rely completely on mechanical cooling and ventilation systems for attaining thermal comfort inside. The need for rammed earth walls can highly impact the cost-effective and comfortable of the interior spaces.

The use of rammed earth construction is also recommended by LEED (Leadership in Energy and Environmental Design), which is a green building certification programs [22]. When KSA received its first LEED certification in 2009, the country's green building industry officially got underway and has been funding green building initiatives ever since [18]. However, not much has been done on buildings for the public, which continue to be made in the conventional way, without considering any sustainability initiatives. Hence, to rethink the building envelope for typical residential developments, is the need of the hour, to ensure better thermal comfort with minimum mechanical cooling and ventilation costs. This research paper aims to investigate the current state of building envelopes in residential buildings in Riyadh, KSA, where the climate is arid and hot. It proposes rammed earth building envelope as a sustainable alternative based on its thermal performance. By analyzing and evaluating the data gathered from literature, this research paper seeks to contribute to the development of sustainable residences in Riyadh, KSA. It also offers insights for the future implementations of rammed earth building envelopes in other regions with similar climatic conditions.

2. PROBLEM STATEMENT

The building envelope is the primary barrier of the indoor space from the outside temperature. There is a gap in research for the implementation and testing of diverse sustainable building materials, especially for the building envelop of residential complexes, in Riyadh region, as the majority of the residential apartment complexes are still relying on conventional building materials i.e., insulated, or uninsulated concrete blocks. Sustainable building envelope materials and techniques need to be explored for the Riyadh region, so that passively comfortable indoor environment can be achieved with minimal mechanical cooling and ventilation.

3. METHODOLOGY

The case study research has been utilized in various social science fields to address research questions that require context sensitivity, complexity awareness, and the utilization of multiple sources. Several times the process of comparative case studies has offered several useful instruments for comprehending practice and policy. This study employs the methodology of comparative analysis of case studies to gain analogy of how the building envelope of rammed earth and its thermal properties can be a sustainable alternative for the residential buildings for Riyadh region. It uses and compares case studies from the western cities of Australia, which share a similar weather to that of Riyadh. Western Australia has an arid and extremely hot in summer, with temperatures ranging from 35-50°C and the winters being quite cold, reaching 1-0°C. This study evaluates the comparison of the thermal properties of rammed earth buildings with those of concrete buildings in both regions, which helps identifying the comfortable indoor environment for both types of building envelopes.

4. CASE STUDIES

1. *Comparative analysis of thermal performance of rammed earth vs conventional building envelope*

To propose rammed earth as a thermal efficiency material for Riyadh, KSA, the case study here shows a comparison made between rammed earth building envelopes and concrete building envelopes in residential buildings. Bui et al., (2011) [23] found that rammed earth buildings were more energy efficient than conventional buildings while the heat transfer coefficient of the exterior building envelope was similar. Although this study was conducted in temperate climate, it is an important finding as energy efficiency is a crucial aspect of sustainable building design. Simulation studies were conducted and compared for several other hot and arid climate regions such as Morocco, India, China, and Tehran, to evaluate the thermal performance of rammed earth vs concrete walls. These simulation studies were either traditional, i.e., with rammed earth (different thicknesses of rammed earth walls with/without insulation were simulated for their thermal performances) or model-based for other conventional concrete building materials.

Table 1: Simulation Model Parameters, Gupta et al., (2020) [24].

Layer (Interior to Exterior)	Thickness (inches)	Conductivity (BTU/h·ft·°F)
Uninsulated Rammed Earth (URE 12 in)	12 in (30 cm)	0.417 (0.721 W/m-°K)
Uninsulated Rammed Earth (URE 18 in)	18 in (45 cm)	0.278 (0.481 W/m-°K)
Insulated Rammed Earth (IRE) – 12 in RE, 4 in Cavity, 4 in XPS ,4 in RE	24 in (60 cm)	0.045 (0.077 W/m-°K)
Insulated Wood Frame (IWF) – 0.75 in Stucco, 0.625 in Gypsum Board, 2.6 in R-11 Fiber Glass Batt Insulation, 4 in Wood Framing	5.375 in (13.652 cm)	0.094 (0.163 W/m-°K)
Brick Cavity Construction (BC) – 4 in Brickwork, 2 in Cavity, 4 in Brickwork, 0.5 in Plaster	8.500 in (21.590 cm)	0.275 (0.476 W/m-°K)
Insulated Concrete (IC) – 8 in Concrete, 2.6 in R-11 Fiber Board Insulation, 0.5 in Gypsum Board	11.100 in (28.194 cm)	0.076 (0.131 W/m-°K)

Simulation Results. Gupta et al., (2020) [24] obtained temperature graphs, a quantified heating and cooling needs, and thermal loss measurements of the two building variables: rammed earth and masonry.

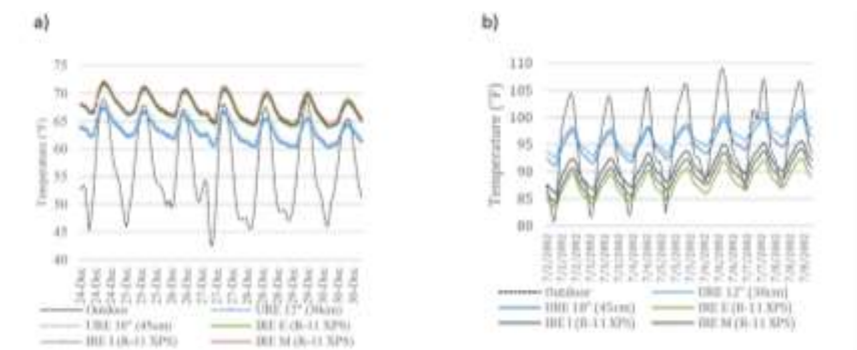

Fig. 1. Effect of insulation and thickness of rammed earth to compare indoor air temperature **a)** for winter and **b)** for summer in Jaipur – India, where URE 12" is uninsulated rammed earth of 12 in thickness; URE 18" is uninsulated Rammed Earth 18 in thickness; IRE E is semi-externally insulated rammed earth; IRE I is internally insulated rammed earth and IRE M is rammed earth with central insulation, Gupta et al., (2020) [24].

The insulated rammed earth assemblies for Jaipur (India) perform better than the uninsulated assemblies, as shown in Fig. 1. It is demonstrated that the semi-externally insulated works best at both regulating temperature fluxes and delivering the most comfortable indoor environment. More specifically, as Fig. 1a) illustrates, improved indoor comfort conditions during heating mode with insulation placed in between wall section. Additionally, as Fig. 1b) illustrates, better cooling mode performance is obtained by relocating the insulation cover to the section's exterior (designated as a "semi-externally insulated rammed earth").

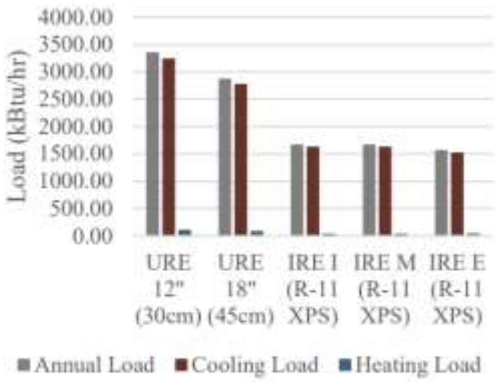

Fig. 2. Effect of insulation placement and thickness of thermal mass to compare annual loads for heating and cooling, Gupta et al., (2020) [24].

As Fig. 2 illustrates, the semi-externally insulated rammed earth performance resulting in lowest heating and cooling loads annually. This is probably because hot, dry climates have longer cooled seasons. To achieve a 45 % reduction in annual heating and cooling loads, external insulation can be added to the uninsulated 300 mm thick rammed earth wall. When compared to the insulation in the between wall section (which is currently the industry standard practice), the external insulation produced an overall 6% reduction in annual loads. Indoor air temperatures and variations in internal surface temperature are used to present comparative results. There are fluctuations in the internal surface.

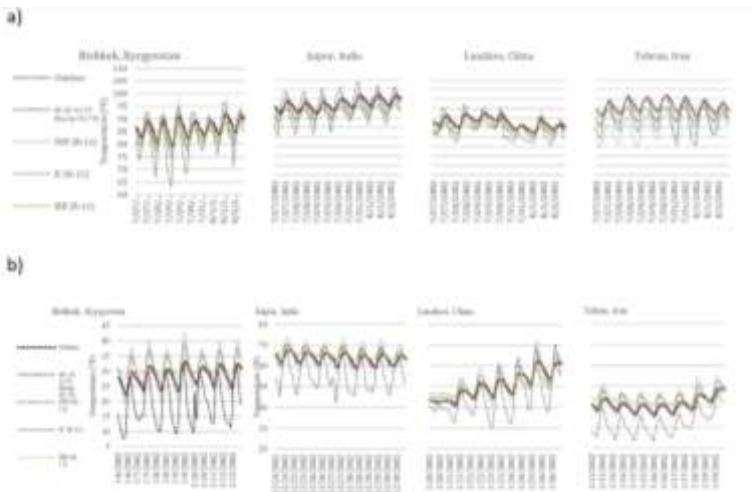

Fig. 3. Indoor air temperatures versus outdoor temperature **a)** for summer design week and **b)** winter design week, where BC is brick cavity wall; IWF is insulated wood frame; IC is insulated concrete and IRE is insulated rammed earth with semi-external insulation, Gupta et al., (2020) [24].

Fig. 3 illustrates the indoor temperature moderation of rammed earth. Insulated rammed earth resulted in similar indoor air temperature fluctuation as compared to outdoor temperature fluctuation for both summer and winter. This is significant in comparison to protected wood frames, which yield an average flux of 79% versus outdoor temperature difference of 82% during winter design week and 79% during summer design week shown in Fig. 4a and 4b.

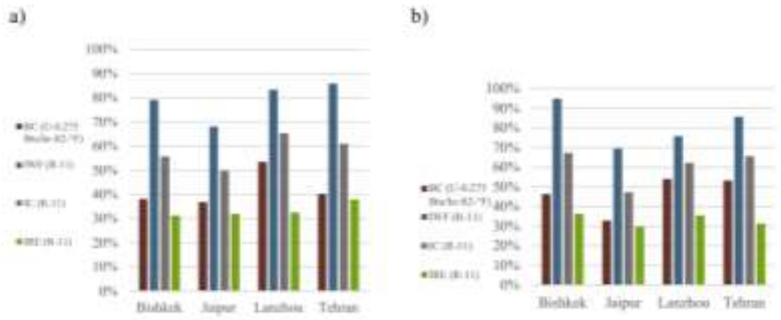

Fig. 4. Difference in indoor temperature as % of outdoor temperature variation **a)** for summer and **b)** winter design week, where BC is brick cavity wall; IWF is insulated wood frame; IC is insulated concrete and IRE is insulated rammed earth with semi-external insulation, Gupta et al., (2020) [24].

Outcomes. There is difference between the thermal performance of masonry constructions and rammed earth walls, both insulated and uninsulated, which highlights the advantages and disadvantages of each. The study concludes that rammed earth is an environmentally friendly, renewable, and energy-efficient building material. Rammed earth is a better substitute for materials like insulated timber frame and concrete. The study determined where insulation should be placed and how well rammed earth performs in comparison to conventional construction. The effects of insulation and thermal cover on heating and cooling loads were tested in hot arid climates. This study found that insulated rammed earth walls performed better in hot and dry climates than untreated rammed earth walls. It was determined that rammed earth walls with insulation facilitate heating and cooling loads reduction to nearly half. Placing insulation outside can save more energy when compared to the common practice of adding it in the center.

2. *Behavior of rammed earth construction in hot-arid climate of Western Australia*

Numerous studies have looked at how well small scaled rammed earth structures or individual spaces perform, showing that the material can passively provide a comfortable interior environment. Two identical houses were built in the hot and arid city of Kalgoorlie-Boulder, Western Australia; one with traditional rammed earth walls and the other with insulating polystyrene core insulated rammed earth walls. Qualitative and quantitative data from sensor measurements, occupant surveys and simulated results were used to examine thermal comfort. The Chenath and SET methods were used, where the SET method is straightforward as compared to the Chenath method. SET can be applied to any space. SET uses a thermo-physiological simulation of the human body to define a range of comfortable temperatures corresponding to average monthly outdoor temperature. Both methods showed comfortable readings in summer while poor performance in winter. Likewise, model-based simulations predicted poor performance in winter.

Measured results. Every room had Chenath comfort scores exceeding 80%. For all analysis, the uninsulated room scored slightly higher than the insulated one. SET comfort scores were over 90% in both houses in summer, which was higher than Chenath scores.

Table 2: Chenath method for thermal comfort scores, Beckett et al., (2017) [25].

Season	Room	Best		Best	0.2 m/s	High		Low		Simulated	
		RE	IRE	RE	IRE	RE	IRE	RE	IRE	RE	IRE
Summer	Liv	88	89	96	95	85	84	97	97	84	83
	BE	93	84	98	97	91	87	97	97	92	94
	BS	94	91	98	97	92	88	98	97	94	94
	BW	88	87	96	95	86	84	97	97	92	92
	Kit	89	89	96	95	86	85	98	96	91	91
	Average	90	84	97	96	88	85	97	97	91	91
Winter	Liv	44	41	44	40	46	42	40	37	96	96
	BE	79	63	79	63	80	67	74	62	95	97
	BS	77	64	77	64	79	66	74	61	96	97
	BW	84	67	84	67	86	68	77	62	96	97
	Kit	43	41	43	41	45	42	39	38	97	97
	Average	65	55	65	55	67	57	61	52	96	97

Table 3: SET method for thermal comfort scores, Beckett et al., (2017) [25].

Season	Room	Best		Best	0.2 m/s	High		Low		Simulated	
		RE	IRE	RE	IRE	RE	IRE	RE	IRE	RE	IRE
Summer	Liv	94	99	91	98	94	99	89	97	63	63
	BE	94	98	89	98	94	98	90	97	65	66
	BS	93	98	87	97	94	98	89	96	60	61
	BW	95	98	91	98	95	98	90	98	66	67
	Kit	95	99	90	98	94	98	87	98	61	61
	Average	94	98	89	98	94	98	89	97	63	64
Winter	Liv	15	6	10	5	19	7	9	4	51	52
	BE	10	6	7	4	12	6	8	4	8	10
	BS	10	5	7	4	10	6	7	4	4	4
	BW	14	6	8	5	15	7	9	4	8	11
	Kit	14	6	9	5	17	7	7	4	54	54
	Average	13	6	8	4	15	7	8	4	25	26

Simulated Results. Most hours were within the comfort range, and for those that weren't, discomfort didn't change much throughout the day. Humidity effects would raise the cooling threshold slightly. Achieving 100% comfort in every room was also possible by raising the air speed to 0.6 m/s, even without taking air humidity into consideration. Since BERS Pro is based on Chenath, the Chenath comfort scores for both homes were theoretically 100%. Scores were lower than for measured values, likely due to sporadic temperature drops below the heating threshold, unlike Chenath, where no temperature was higher than the SET cooling threshold. Comfort ratings were reduced by humidity effects or faster airspeed during uncomfortable hours, which were judged to be excessively cold. Such a result was unrealistic given the (occasionally) extreme outdoor temperatures; instead, the SET method performed worse because of its high summer heating threshold, as was discovered for the measured behavior.

Outcomes. The survey's findings indicated that both homes were cozy in the summer and winter. People didn't use any artificial cooling devices during the summer (e.g. g. ceiling fans) but did use portable air conditioning. Both homes used artificial heating in the winter, with residents using portable heaters in place of fixed heating systems. Due to the thick walls of the homes, occupants also reported reduced annual energy consumption as compared to former residences and outstanding acoustic protection. The two rammed earth houses with combinations of lightweight insulated rammed earth, and rammed earth were designed to maximize passive solar properties. Each had sensor and data loggers mounted to record both occupied and unoccupied performance. Over a two-year period, both indoor and outdoor data were collected. However, the Chenath and SET method comfort criteria did a poor job of reflecting the houses' performance in Winter. Residents stated that both homes were generally comfortable and cozy in the summer. This analysis compared the simulation and measured results, which proved that simulations often project data to be incorrect as compared to the real-life experience of thermal comfort. Both the studies found out that rammed earth and insulated rammed earth have very good thermal potential to provide adequate thermal comfort inside the buildings.

3. *Rammed earth building envelopes need exploration in Riyadh, KSA*

Rammed earth construction has been used for long in many countries around the world, including Saudi Arabia [26, 27]. In the case study of the Murabba Palace in Saudi Arabia, the use of 120 mm of rammed earth brick achieved good result [28]. These findings can significantly contribute to the use of rammed earth as a sustainable building material and can help counteract the aging of building materials. For examples of buildings in Saudi Arabia and other countries have used 1100-1200 mm thick with 10–90 mm of thermal insulation for rammed earth in their construction [29]. Despite being an ancient building material, rammed earth remains largely unexplored in Riyadh. Compressed earth blocks are a form of rammed earth that can produce better results than hollow concrete blocks [27]. The energy consumption of rammed earth was also compared to another office building, and it was found to be higher [30]. In Riyadh, the use of rammed earth as a building envelope is not explored due to the lack of awareness and knowledge about rammed earth [31]. The potential implications of not using rammed earth building envelopes in Riyadh, Saudi Arabia are considerable. As rammed earth is a highly durable material with excellent thermal insulation properties, its omission from the building envelope would lead to increased energy consumption in the building. Fahmy et al., (2022) [31] proposed an open cluster courtyard with walls built of compressed earth blocks to promote the use of rammed earth as a sustainable building material. Many examples of old historical buildings in Saudi Arabia have already proved the effectiveness and sustainability of rammed earth building envelopes.

Some small scaled experimental designs of rammed earth are seen in Riyadh region. One is the "Wadi Hanifa Cottage" aimed at establishing the concept of the cottage in Riyadh, reflecting a minimally modern design in the surroundings of the valley of Hanifa in Riyadh. It is constructed using rammed earth material and mixtures. The use of rammed earth materials in such a design efficiently promotes the idea of using regional material components, sustainable construction. A second such example of rammed earth in the building sector of Riyadh is "Al maamourah". Its aim was to design different furniture pieces, made of rammed sand and with the inclusion of other materials like mirrors, marble, and copper. The design in its first phase consisted of three main pieces, the 'Maiz', the visible mirror (Mashawafah), and the column (Al Satan). Saudi Authority of Intellectual Property (SAIP) as being the only entity to use rammed sand for the production and manufacture of furniture pieces to innovate sustainable and optimized furniture designs for extensive use in offices, residences, and other commercial purposes. Both these examples of rammed earth constructions in Riyadh, are not complete projects, one is a small experimental size chalet, and the other project has some furniture pieces made of rammed earth technique, to showcase the strengths and qualities of rammed earth constructions. As of now, there have not been any projects executed of a considerable scale, commercial or residential, which are made of rammed earth wall envelope in Riyadh.

5. DISCUSSIONS

This section emphasizes the significance of rammed earth building envelopes in the context of Riyadh's climatic conditions. The thermal properties exhibited by rammed earth walls contribute to increased energy efficiency and thermal comfort. These are aligning well with the sustainable development goals of the region, focusing on several key points:

- Rammed earth's high thermal mass is highlighted as a key factor in moderating temperature fluctuations. The walls exhibit the ability to absorb and release heat, contributing to a more stable indoor environment.
- The study underscores the potential for energy savings associated with rammed earth construction. Reduced reliance on mechanical heating and cooling systems can lead to decreased energy consumption and associated environmental benefits.
- The integration of rammed earth construction aligns with the cultural context of the region. The aesthetic appeal of earthy tones and textures can contribute to the creation of buildings that resonate with local architectural traditions.
- The durability of rammed earth structures is discussed, emphasizing their longevity and low maintenance requirements. Additionally, the environmentally friendly nature of rammed earth, as a material sourced locally and with minimal environmental impact, is highlighted.
- Rammed earth's adaptability to Riyadh's climate is discussed in terms of its ability to provide effective insulation against high temperatures. The material's inherent properties can contribute to a more sustainable and resilient built environment.

Rammed earth construction offers a holistic solution to address the thermal challenges posed by Riyadh's climate. By implementing the recommendations outlined, stakeholders can collectively contribute to the broader adoption of this sustainable building technique, fostering a more resilient and energy-efficient urban landscape.

6. CONCLUSION

The paper presented in this topic investigates rammed earth building envelopes and explores the potential of rammed earth as a building material for constructing residential buildings. The literature review highlights the scarcity of comprehensive studies on the usage of rammed earth as building envelope in Riyadh region, and the necessity of more study in this area. Rammed earth as a building material offers an environmentally friendly substitute for concrete. By varying the mix proportions, builders can modify certain properties and achieve a desired balance in the final structure's characteristics. However, they have lower thermal resistance compared to other modern solutions, often requiring additional insulation in some regions.

Rammed earth has become a popular building material for buildings that require stable temperatures, such as wineries in Western Australia. The thickness and density of rammed earth material can slow down the penetration of heat or cold, resulting in a stable internal temperature. Rammed earth buildings with 300mm thick external walls can provide excellent protection against climate extremes. Although the use of natural elements in the walls contributed to the breakdown of the facade over time, it remains a testament to the importance of thermal properties in building envelope selection.

Literature review has shown that rammed earth is one of the foremost solutions to develop structures with superior thermal mass, which makes it a favorable building material for thermal properties in building envelope selection. Architects and engineers are recognizing the benefits of using rammed earth as a building material, and there is a growing interest in its use in construction projects worldwide. In Saudi Arabia, traditional buildings made of rammed earth are rich in cultural heritage and have a high plastic and expressive value. Overall, the use of rammed earth as a building material has many benefits, including its superior thermal mass and sustainability, making it a favorable choice for building envelope selection in regions with extreme climates like Riyadh.

7. RECOMMENDATIONS

The findings of this study underscore the considerable potential of rammed earth building envelopes in enhancing the thermal performance of structures in Riyadh's arid climate. The positive outcomes revealed in this research advocate for the incorporation of rammed earth construction in building design and construction practices within the region. Based on the results, this study offers the following recommendations:

- Encourage the inclusion of rammed earth construction techniques in local building codes and regulations. This step would facilitate the widespread adoption of this sustainable building method.
- Develop architectural guidelines that promote the effective use of rammed earth in building envelopes. Providing architects and designers with specific guidance can ensure optimal performance and aesthetics.
- Conduct public awareness campaigns and educational programs to inform builders, developers, and the public about the benefits of rammed earth construction. Increasing awareness is essential for wider acceptance and implementation.
- Invest in further research and development to explore variations in rammed earth mixtures and techniques. This will contribute to refining the technology and expanding its applicability in different contexts.
- Foster collaboration between the construction industry, governmental bodies, and research institutions. Such partnerships can accelerate the integration of rammed earth construction into mainstream building practices.
- Support and encourage the creation of demonstration projects that showcase the effectiveness and aesthetics of rammed earth buildings. These projects can serve as tangible examples for stakeholders and the public.

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