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Towards Resilient Rammed Earth Structures in Hot-Arid Regions

[1]**Amer Al-Jokhadar,** [2]**Yasmine Soudi,** [3]**Yasser Abuhashem**

[1]PhD in Architecture, Faculty of Architecture and Design, University of Petra, Jordan

[2]Master in Sustainable Design, Faculty of Architecture and Design, University of Petra, Jordan

[3]PhD in Architecture, Faculty of Architecture and Design University of Petra, Jordan

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ABSTRACT

Background: Concrete mixtures are responsible for a substantial share of greenhouse gas emissions, atmospheric pollutants, and global warming. The transition to sustainable practices using natural resources and indigenous materials is emphasized by the United Nations. The Sustainable Development Goals (SDGs 11, 12, and 13) underscore the relevance of such activities by setting targets related to building resilient cities, fostering sustainable consumption/production practices, and moving towards climate-resilient development to achieve net-zero emissions.

Objective: This study investigates the viability of using rammed earth as a substitute for reinforced concrete mixtures, with the aim of offering durable and cost-effective alternatives suited for hot-arid climates.

Method: The research adopted three methods. First, laboratory tests were performed to ascertain the most effective composition of rammed earth mixture while minimizing maintenance expenses and reducing cost. Second, an experimental rammed earth building was designed and constructed at a university campus in Jordan. Third, assessment of indoor environmental qualities was performed across several seasons.

Result: In hot-arid climates, it is recommended to incorporate a soil mixture consisting of 20% ordinary Portland cement, 15% quicklime, and 15% of acrylic-based additive. This mixture, when combined with the optimal water content of 42%, has been found to significantly enhance the compressive strength. On-site measurements confirmed that the thermal comfort conditions and carbon emissions were found to be satisfactory and met the requirements outlined by ASHRAE-55 using 40 cm walls. This technique demonstrates a 20% reduction in construction costs when compared to the prevalent stone-based building method.

Conclusion: The research findings presented in this study offer valuable insights into the potential utilization of rammed earth as a sustainable construction material in hot-arid urban environments. Rammed earth demonstrates promise as an eco-friendly alternative that can effectively minimize the environmental impact of buildings, thereby addressing concerns related to global warming and climate change.

Keywords: SDGs, Resilient Buildings, Local Materials, Rammed Earth, Indoor Environmental Qualities.

1. INTRODUCTION

The building sector has a significant role in contributing to the phenomena of global warming and climate change. This is mostly because construction and operation activities are responsible for around 39% of energy-related CO_2 emissions (Kerr et al., 2022; Belizario-Silva et al., 2021). According to Bahrami et al. (2022), the primary contributors to greenhouse gas emissions can be attributed to the utilization of cement and steel within the construction industry. In addition, the building sector has the difficulty of escalating material costs, further compounded by the extensive utilization of reinforced concrete. In the country of Jordan, known for its rapid economic growth, the cost of cement has had two increments over the course of the last four years, resulting in a current price of $132 per metric ton. Similarly, the price of steel has undergone four successive increases, culminating in a current value of $755 per metric ton, as reported by the Jordan Chamber of Industry (2023).

The 2030 Agenda for Sustainable Development, established by the United Nations, outlines a comprehensive strategy to address the challenges of climate change, enhance public health, and foster economic advancement. The 17 Sustainable Development Goals (SDGs) prioritize the adoption of regulatory measures aimed at facilitating a shift towards more sustainable practices, including the utilization of natural resources and locally sourced materials. The significance of such initiatives is underscored by SDG-11, which sets forth objectives pertaining to the advancement of resilient urban areas and sustainable structures that make use of local materials. SDG-12 places significant emphasis on the transition towards sustainable practices and the optimal utilization of natural resources, alongside the advancement of tools that foster employment opportunities and bolster the preservation and promotion of local culture and products. SDG-13 places emphasis on the involvement of all stakeholders in promoting development that is resilient to climate change, while also providing a well-defined trajectory for attaining a state of net-zero emissions (United Nations, 2023).

Furthermore, it is imperative to maintain the healthiness of the construction sector, as it significantly impacts the well-being, particularly in countries grappling with climate change-related hazards. In Jordan, for example, the prevailing hot-arid climate intensifies the concerns due to increasing temperatures, decreasing precipitation, and escalating occurrences of drought. Gusakova et al. (2023) underscored the need of designing programs aimed at the advancement of low-rise home construction that are tailored to specific climatic conditions and utilize locally sourced building materials from natural resources. Ilyushina and colleagues (2023) emphasized the significance of formulating a methodology to effectively select affordable structural solutions for low-rise buildings that aims to conserve energy and resources and establish comfortable living conditions.

One of potentially viable strategies is utilizing natural earth, which can reduce construction expenses and mitigate carbon dioxide emissions, thereby, aligning with Sustainable Development Goals. Such a material has been employed throughout history, serving as a protective barrier against high temperatures (Dabaieh, 2014; Fathy, 1986). Moreover, the cost-effectiveness of mud stems from potentials for reuse or recycling, as well as the reliance on simple equipment and local labour (Khadka, 2020; Hadjri et al., 2007; Reddy, 2007; Minke., 2006; Walker et al, 2005; Maini., 2005). In addition, it is readily accessible in most geographical areas, and does not result in the production of hazardous wastes (Dayaratne, 2010; Dayaratne, 2007). It is worth noting that earth buildings possess several environmentally sustainable qualities. These include a notable capacity for heat storage, energy conservation, the ability to ensure thermal comfort and indoor air quality, the capacity to absorb pollutants, effective noise control, and a high level of fire resistance (Khadka, 2020; Adeguns and Adedeji, 2017; Dabaieh, 2014; Taghiloha, 2013; Morton, 2007; Hadjri et al, 2007; Minke, 2006; Walker et al, 2005, Ngowai, 2000; Smith and Austin, 1996; Norton, 1986).

A comprehensive analysis of the existing literature indicates a scarcity of studies pertaining to the optimal composition of stabilized rammed earth suitable for hot-arid environments. Furthermore, a dearth of scholarly inquiry exists pertaining to the indoor environmental factors associated with contemporary rammed earth constructions. Consequently, the primary objective of this study is to investigates the necessary characteristics of the mixture to improve the strength and durability of rammed earth mixtures, in addition to identify the optimal design strategies for enhancing indoor environmental conditions and achieving satisfactory thermal comfort conditions. The findings of this study provide valuable insights and suggestions for designers and builders involved in the construction of urban modern rammed earth buildings in hot-arid climates.

2. THEORETICAL FRAMEWORK

The rammed earth technique is widely recognized as a highly cost-effective method for constructing earthen buildings because of its efficient construction process, which requires a relatively short duration. The earth mixture is densely compacted in stratified layers, sandwiched between two parallel timber formworks. Once a layer has been completed and has achieved the intended level of hardness, the two planks are then raised, and the procedure of applying a further layer of compacted earth is reiterated above the initial layer. According to Avila (2022), the conventional constituents of soil mixtures consist of fundamental elements such as earth, water, and binding clay. Nevertheless, to construct modern rammed earth buildings with thinner walls, it is imperative to develop more stable mixtures and improve the mechanical properties (Narloch and Woyciechowski, 2020; Beckett and Ciancio, 2015; Windstorm and Schmidt, 2013; Hall et al, 2012; Dayaratne, 2010; Maniatidis and Walker, 2008; Hadjri et al, 2007; Walker et al, 2005, Maniatidis and Walker, 2003).

The enhancement of construction durability and the reduction of maintenance costs are imperative in hot-arid climates (Reddy, 2007; Minke, 2006; Walker et al, 2005). Various stabilizers and additives can be utilized to extend the durability of the rammed earth mixture. The utilization of lime and natural fibers has been documented in the literature as having a positive impact on the mechanical and hydraulic properties of soil (Arto et al., 2021; Koutous and Hilali, 2021; Laborel-Préneron et al., 2016; Minke, 2006; Bell, 1996). The enhancement of compressive strength and durability in structures can be achieved through the utilization of Portland cement, fly ash, and recycled concrete aggregates (Avila, 2022; Niroumand et al, 2013). To attain the desired level of strength, scholars have proposed utilizing a cement proportion exceeding 6% (Kariyawasam and Jayasinghe, 2016; Tripura and Singh, 2015; Bahar et al, 2004; Walker, 1995). According to Jayasinghe and Kamaladasa (2007, p. 1975), the maximum strength of 3.71 MPa was attained when sandy soil was stabilized with a 10% cement content. The effectiveness of cement-stabilized material, with a cement content ranging from 5% to 10%, was established by Khadka and Shakya (2016) in terms of achieving a compressive strength between 6.05 and 10.15 Mpa. This finding demonstrates the suitability of cement-stabilized material as a dependable option for the construction of load-bearing buildings.

The application of cement in soil stabilization presents several obstacles, including the development of shrinkage cracks and a reduction in tensile and shear strength (Bouhicha et al., 2005). Kesikidou and Stefanidou (2019) and Danso et al. (2015) have posited that the utilization of either natural or artificial fibers has promise in mitigating the existing constraints. The impact of moisture content on the overall strength of compacted soil has been examined in research undertaken by Reddy and Kumar (2011), as well as Walker et al. (2005). It is essential to ensure that the moisture levels are within a range of three percentage points in respect to the ideal moisture content, as specified by the New Zealand Standard (1986), before compaction takes place. The cumulative findings of research conducted by Toufigh and Kianfar (2019), Hallal et al. (2018), Khadka and Shakya (2016), Ciancio et al. (2014), and Tripura and Singh (2015) suggest that a moisture content range of 8% to 14% is considered appropriate for cement and lime rammed earth combinations.

In terms of environmental benefits, Khadka and Shakya (2016) assert that current stabilized earth construction exhibits environmental sustainability, as it emits less carbon dioxide and requires less energy compared to conventional building materials. Consequently, it is deemed suitable for urban house construction. According to Venkatarama Reddy's research conducted in 2009, the implementation of alternative low-energy building technologies leads to a significant decrease of approximately 50% in the embodied energy of a building system.

The thermal mass of an earth wall is enhanced by its increased thickness and density. According to Khadka (2019), an examination of residential rammed earth houses in hot climates revealed that earth construction offers superior heat insulation properties. Consequently, the inside of such structures tends to be cooler during summer and warmer during winter compared to conventional buildings. In addition, it is worth noting that the earth walls exhibit a rather low thermal conductivity, resulting in a significant delay of around 12 hours for heat to traverse a wall with a thickness of 300 mm (Zami and Lee, 2009). The earth construction possesses a commendable capacity for noise absorption, rendering it an advantageous attribute in the realm of architectural design for residential structures. According to the findings of the CSIRO experiments conducted by Middleton and Lawrence in 1987, it was determined that a rammed earth wall with a thickness of 250 mm possesses a sound transmission rating exceeding 50 dB. This rating indicates that the sound level is significantly quieter than that of a typical conversation.

3. METHODOLOGY

The research adopted three methods to address the objectives of the study. First, laboratory tests were performed to ascertain the most effective composition of rammed earth mixture while minimizing maintenance expenses and reducing cost of construction in hot-arid regions. Second, an experimental rammed earth building was designed and constructed at a university campus in Jordan. Third, assessment of indoor environmental qualities was performed across several seasons.

3.1. Laboratory structural tests

To determine the optimal composition for enhancing the compressive strength of rammed earth walls, the researchers utilized a selection of components based on previous research findings and the availability of local resources in the study area. These components are soil, in addition to three types of additives: quicklime, ordinary Portland cement, and acrylic-based bonding agents.

The soil samples were collected from the adjacent regions, namely at a depth of 2 meters. Prior to conducting a compressive test, which serves as an indicator of the workability of soil, a comprehensive analysis of its features is necessary. The utilization of rammed earth is not advisable in situations where there are significant levels of silt present. The utilization of topsoil is discouraged due to its potential to undermine the structural stability of the soil, mostly attributed to its excessive organic matter content, which renders it unsuitable for effective performance in compressive testing.

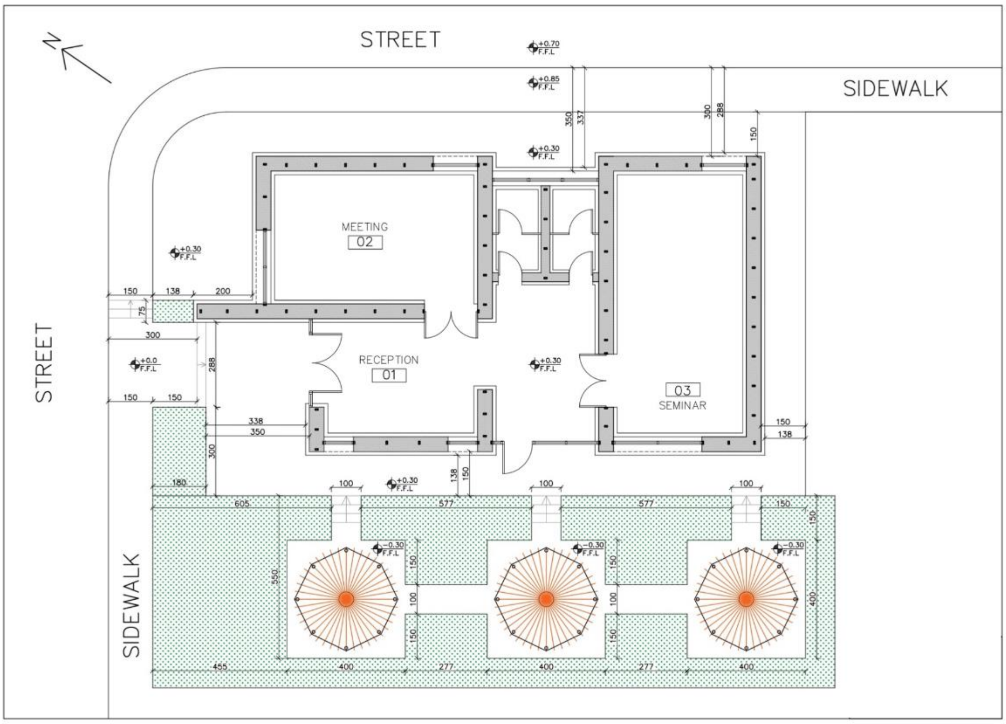
Additives include quicklime, or calcium oxide, which serves as a binder, is an alkaline chemical that exists in the form of fine particles with a diameter smaller than 0.15 millimeters. Ordinary Portland cement was employed as a binding agent to enhance the cohesive properties of the soil, resulting in an augmentation of its compressive strength. Acrylic-based additive is utilized as an agent for demonstrating exceptional bonding strength, as well as resistance to chemical reactions and moisture.

To assess the optimal components of rammed earth walls, three distinct mixtures were produced and compared to a control sample consisting exclusively of soil. The only variables that are common throughout the three combinations are a constant amount of 1000 g of soil and 150 g of an acrylic-based additive. An additional quantity of 150 grams of quicklime has been included into the first mixture. The second batch includes an additional 200 grams of standard Portland cement. The third batch includes an additional 150 grams of quicklime and 200 grams of ordinary Portland cement. The water ratio is subject to variation based on the proportions of the various constituents. The generation of different combinations entailed the application of a mechanical mixer. After a 24-hour duration, the formwork was disassembled, and the samples were thereafter stored at a temperature of 23 degrees Celsius. A total of 40 cylinders were manufactured, each with a length to diameter ratio of 2.5, encompassing three distinct mixtures and a control sample.

3.2. Design of an experimental rammed earth building

An experimental building, with a total area of 170 square meters, was designed using rammed earth. The facility is comprised of three primary areas: the reception area (designated as space #01), the conference room (designated as space #02), and the seminar room (designated as space #03), together with two restroom facilities (Figure 1). The height of the walls measures 4 meters. The composition of all walls comprises an external layer of mud plaster measuring 15 mm, a core of rammed earth measuring 40 cm, and an internal layer of mud plaster measuring 15 mm. To mitigate the risk of wall collapse, wooden studs were strategically inserted at regular intervals of one meter within the walls. The dimensions of the building's footings are 75 cm in width and 80 cm in height. The composition of the footing primarily consists of stone rubble, accompanied by a minor proportion of concrete (Figure 2). To safeguard the rammed earth walls, it is customary to maintain half of the foundation's height above ground level. A concrete ring of 20 cm in width and 20 cm in height was incorporated on the upper portion of the walls. This addition served as the foundational support for the pitched roof, which was then covered with clay tiles (Figure 3). The utilization of French windows resulted in a reduction of joints between walls (Figure 4).

Figure 1. Plan of the experimental rammed earth building.



Source: Authors

Figure 2. Foundation plan of the experimental building.

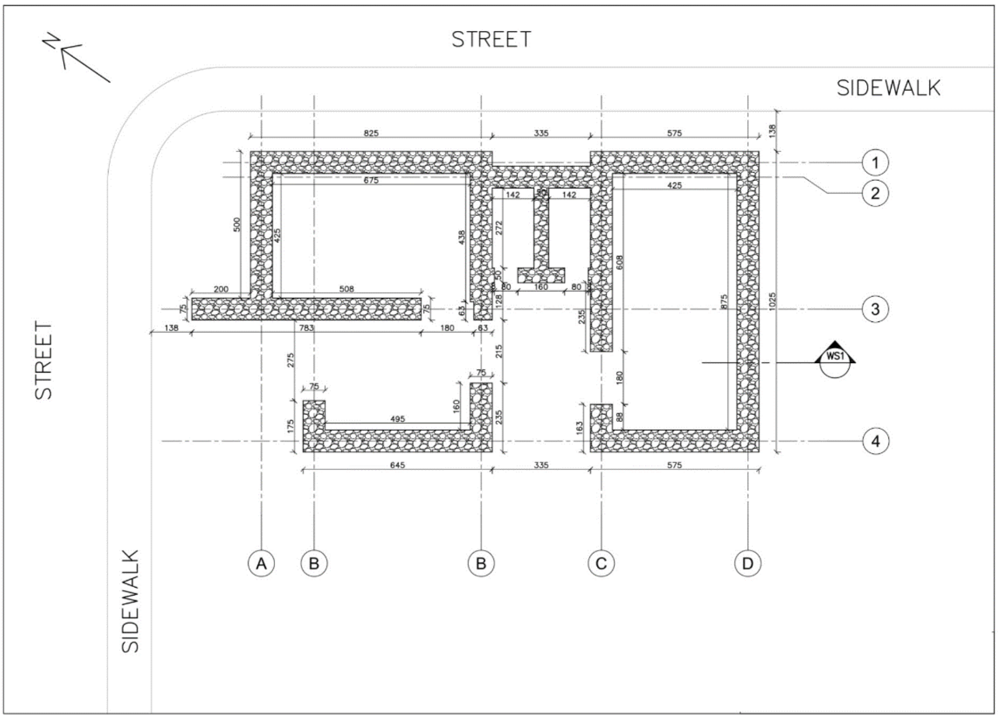


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Figure 3. Wall section of the experimental rammed earth building.

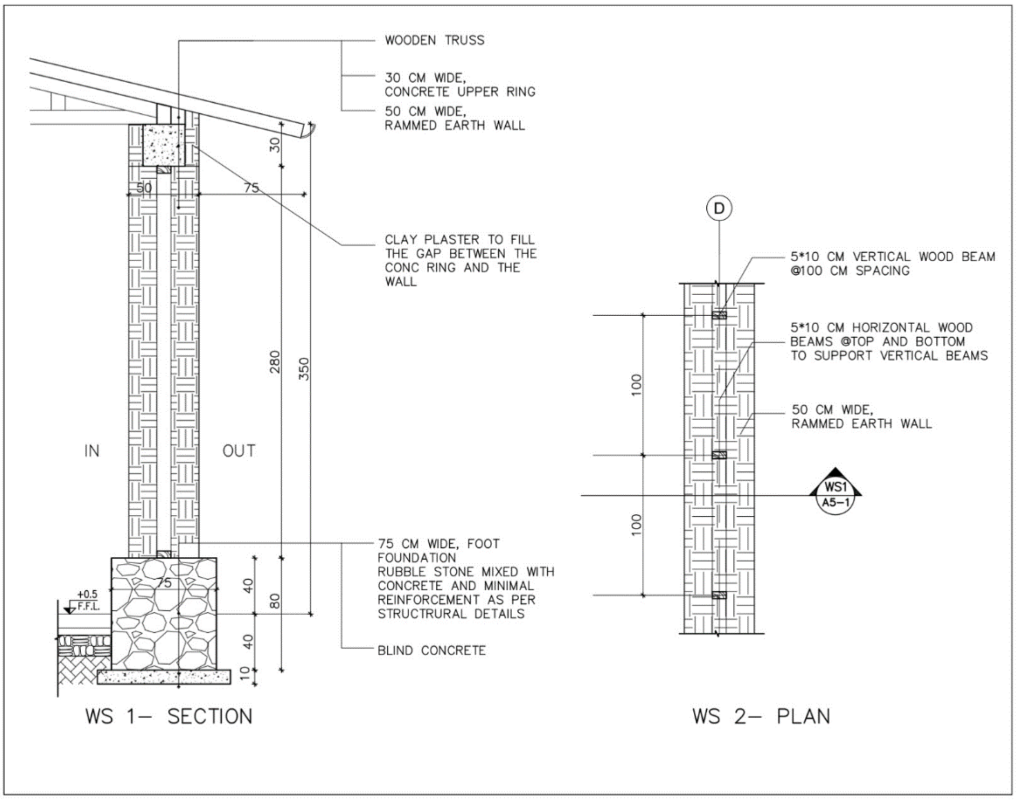

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Figure 4. Elevations of the experimental rammed earth building.

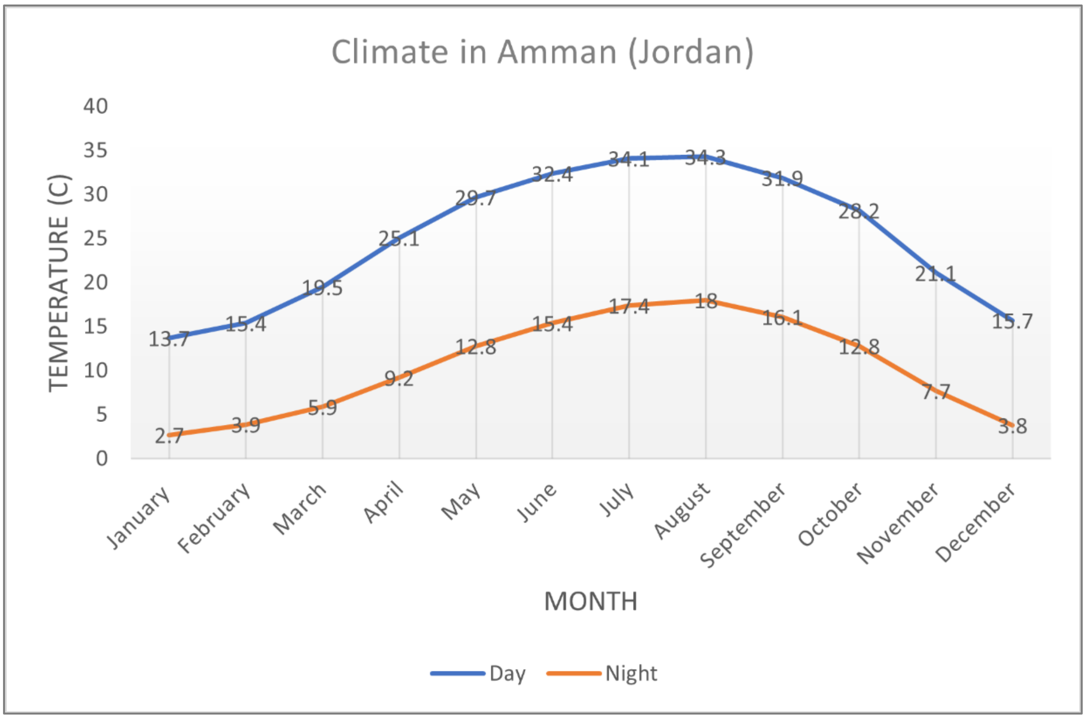
Source: Authors

3.3. Assessment of indoor environmental qualities

The experimental building was constructed in Amman, Jordan, a city characterized by a hot-arid climate. Figure 5 shows the mean maximum and minimum temperatures over the year in Amman, which are derived from data provided by the official weather station, situated at an elevation of 683 meters above sea level, and represents the mean monthly readings for a period of 20 years.

An environmental simulation was conducted as part of the design process to assess the effectiveness of various solutions related to building orientation, daylighting, and natural ventilation. Measurements of indoor environmental qualities were conducted at various times during the year, specifically on September 15, 2022, December 20, 2022, March 15, 2023, and July 15, 2023, between the hours of 9:00 am and 12:00 pm. The selection of the measurement duration is determined by the period during which the building experiences the most occupancy. The measurements were taken at regular intervals of 30 minutes from a fixed height of 1.2 meters, where the recording devices were positioned. The parameters of Indoor Environmental Quality (IEQ), including air temperature (°C), relative humidity (%), carbon dioxide content (PPM), and noise level (dBA), were measured and documented. The calibration of all instruments was conducted in strict adherence to the guidelines provided by the manufacturer. The results were assessed in accordance with the guidelines outlined by the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) 55 standards.

Figure 5. The mean maximum and minimum temperatures over the year in Amman, Jordan.



Source: Reproduced by Authors, from data available on the website: https://www.worlddata.info/asia/jordan/climate-amman.php

4. RESULTS AND DISCUSSION

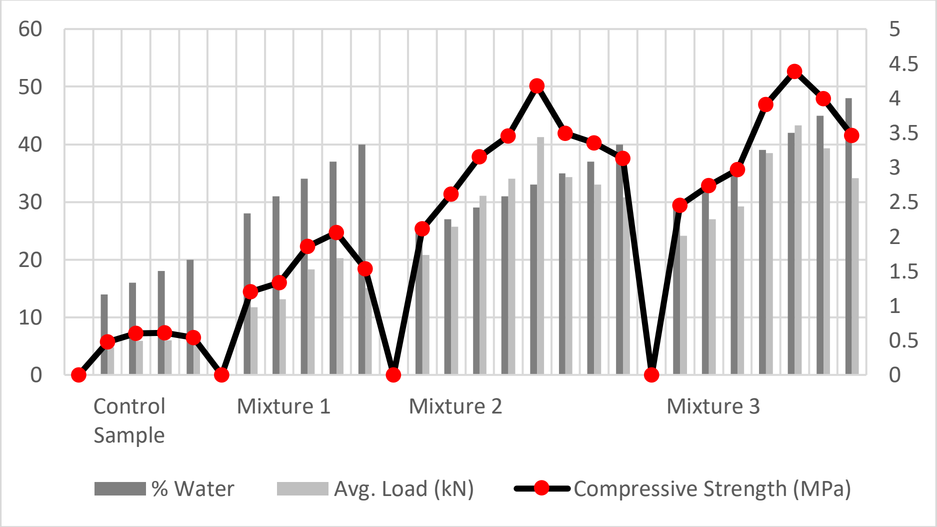
The outcomes of the three implemented approaches are depicted in this section. Initially, the laboratory test findings are provided to determine the optimal composition of the rammed earth mixture. Next, the sequential procedure for constructing the experimental rammed earth building is presented. Furthermore, readings of the assessment of indoor environmental quality are shown across different seasons.

4.1. Results of laboratory structural tests

The compressive strength of soil varies depending on its degree of change and level of compaction. The soil sample (mixture 1), which underwent modification with a composition consisting of 20% cement, 15% acrylic-based additive, and 33% water content, exhibited a compressive strength that was 6.85 times greater than that of the control specimen after a period of 28 days. The compressive strength of the soil (mixture 2), which was subjected to a treatment involving 15% acrylic-based addition, 15% quicklime, and 37% water content, was found to be approximately 3.4 times higher than that of the control material. The soil sample (mixture 3), which was enhanced with a composition consisting of 20% cement, 15% acrylic-based additive, 15% quicklime, and 42% water content, exhibited a compressive strength of 4.39 MPa. This value represents a remarkable improvement, as it is 7.2 times higher than the compressive strength observed in the control sample. The results for the compressive strength at 28 days are presented in Figure 6.

The third mixture was chosen for utilization in the construction of the experimental rammed earth building, as indicated in section 3.2 below.

Figure 6. Results of 28-day compressive strength tests.



Source: Authors

Regarding the incorporation of cement into the soil composition to enhance its strength and durability, the outcomes of the structural tests shown congruity with previous investigations conducted by Avila (2022), Khan et al. (2019), Niroumand et al. (2013), and Maniatidis and Walker (2003). In accordance with the recommendation put forth by Jayasinghe and Kamaladasa (2007), advocating for a minimum cement concentration of 10%, the resulting compressive strength exhibits an increase to 4.39 MPa. Nevertheless, it is necessary to conduct a thorough examination of the financial dimension of these proportions to reduce construction costs. The addition of water to the modified soil enhances its strength to a certain extent by reducing the inter-particle friction within the mixture, facilitating compaction, and reducing the void volume between the particles. When the moisture level of the soil exceeds the optimal threshold, the interstitial spaces between soil particles get saturated with water, resulting in a decrease in the soil's mechanical strength.

To ascertain the most suitable combination of materials for the final plaster coating of rammed earth walls, with the objective of reducing maintenance expenses and attaining a soil colour that is more in line with natural aesthetics, a detailed experimental investigation was performed. Different samples were prepared by incorporating different percentages soil, sand, quicklime, cement, acrylic-based additive, and an adequate quantity of water. To assess the potential reduction of cracks, wooden fibers were introduced into mixtures.

The findings of the study indicated that the optimal composition for the finishing plaster layer, which led to a significant reduction in crack occurrence and the achievement of a consistently smooth surface, consisted of a mixture containing soil (350 g), sand (122.5 g = 35%), quicklime (52.5 g = 15%), water (157.5 g = 45%), acrylic-based additive (52.5 g = 15%), and natural wooden fibers (5.0 g).

The addition of sand at a proportion of 35% of the soil weight, along with appropriate adjustment of water content, has a positive effect on the final surface finish of rammed earth material. This impact is particularly evident in terms of reduced shrinkage and the achievement of the desired natural color. Numerous scholarly investigations (Avila 2022; Arto et al 2021; Koutous and Hilali 2021; Khan et al 2019; Laborel-Préneron et al 2016; Niroumand et al 2013; Minke 2006; Maniatidis and Walker 2003; Bell 1996) concur that the inclusion of fiber additives enhances the mechanical properties and long-term resilience of soil mixtures. Consequently, these findings align with the suggested composition for the ultimate finishing mixture.

4.2. The Construction of an experimental rammed earth building

A rammed earth experimental building was constructed, employing a mixture with the utmost compressive strength. The construction process commences by undertaking the necessary preparations for the building's footings, which consist primarily of stone rubble with a small admixture of concrete. The foundation's height is divided into two equal parts, with one half measuring 40 cm and positioned above the ground level. The construction process involved the deliberate placement of wooden studs at consistent one meter spacing throughout the two parallel timber formworks. Subsequently, the earth mixture underwent hand compaction, resulting in the formation of firmly packed stratified strata. After the initial layer has been constructed and has attained the desired level of hardness, the two planks are subsequently elevated, and the process of adding an additional layer of densely packed soil is repeated above the preceding one, gradually building up the overall height of the walls (Figure 7). The removal of the formwork for each wall required a time frame of 24 hours. A ring made of concrete, measuring 20 cm in width and 20 cm in height, was installed on the upper section of the walls (Figure 8). This ring was intended to provide a solid base for the pitched roof, which was afterwards covered with clay tiles.

Prior to the application of the final finishing plaster coating, the walls were enveloped with fabric fibers to minimize the occurrence of cracks and diminish the need for subsequent maintenance of the structure (Figure 9). To mitigate carbon emissions and preserve the aesthetic integrity of the structure, the decision was made to incorporate wooden doors and double-glazed windows with wooden frames (Figure 10). The interior walls of the three primary areas were utilized to serve as a platform for showcasing building materials.

Figure 7. The construction of rammed earth walls.

Source: Authors

Figure 8. Rammed earth walls after removing the formwork.

Source: Authors

Figure 9. Rammed earth walls after implementing the plaster layer.

Source: Authors

Figure 10. The completed rammed earth building

Source: Authors

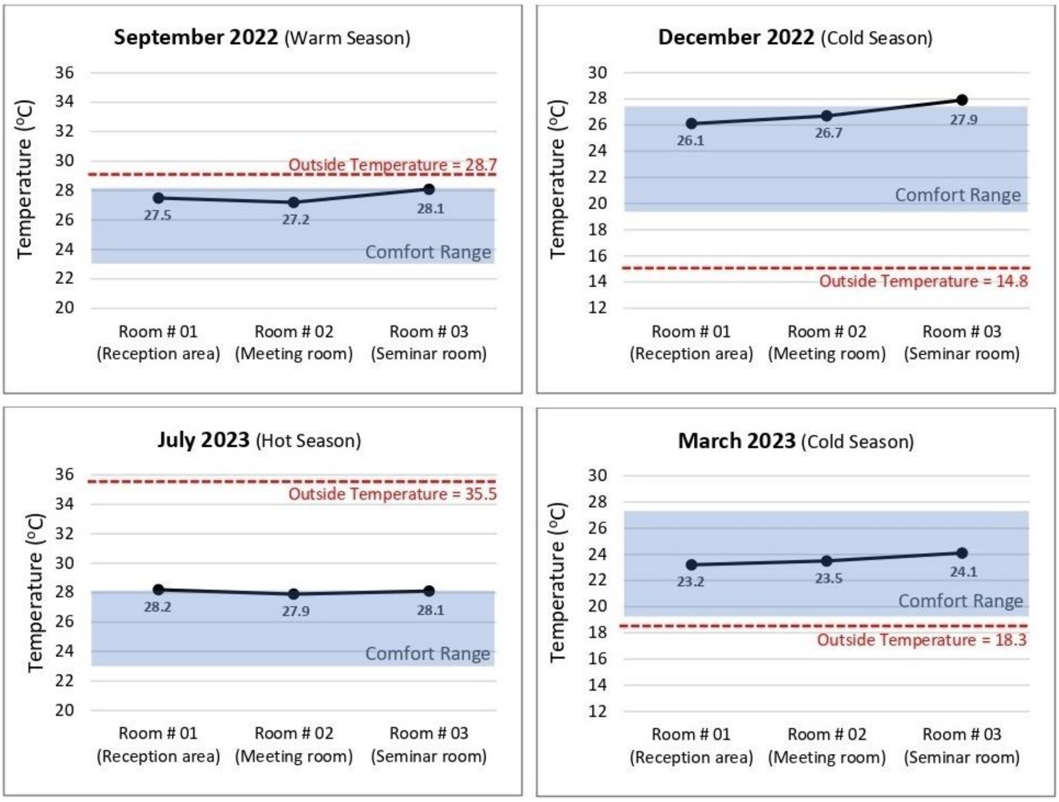
4.3. Results of the assessment of indoor environmental qualities

The comprehensive analysis of the indoor environmental quality (IEQ) in the surveyed three rooms of the rammed earth building is presented in Figures 11 and 12, 13, and 14. These figures specifically depict the variations in IEQ factors, including air temperature, relative humidity, CO_2 concentration, and noise level across different seasons. Subsequently, the conditions are juxtaposed with the globally acknowledged ASHRAE 55 criteria, as well as the prevailing outdoor conditions.

The indoor air temperatures in all rooms conform to the ASHRAE 55 adaptive technique for thermal comfort. This technique establishes the acceptable temperature range as 19.4 ºC – 27.7 ºC during colder months and 23.1 ºC – 28.2 ºC during hot months. The findings indicated that during the hot season (specifically in July), the room temperature ranged from 27.9 ºC to 28.2 ºC, while the temperature outside the building reached 35.5 ºC.

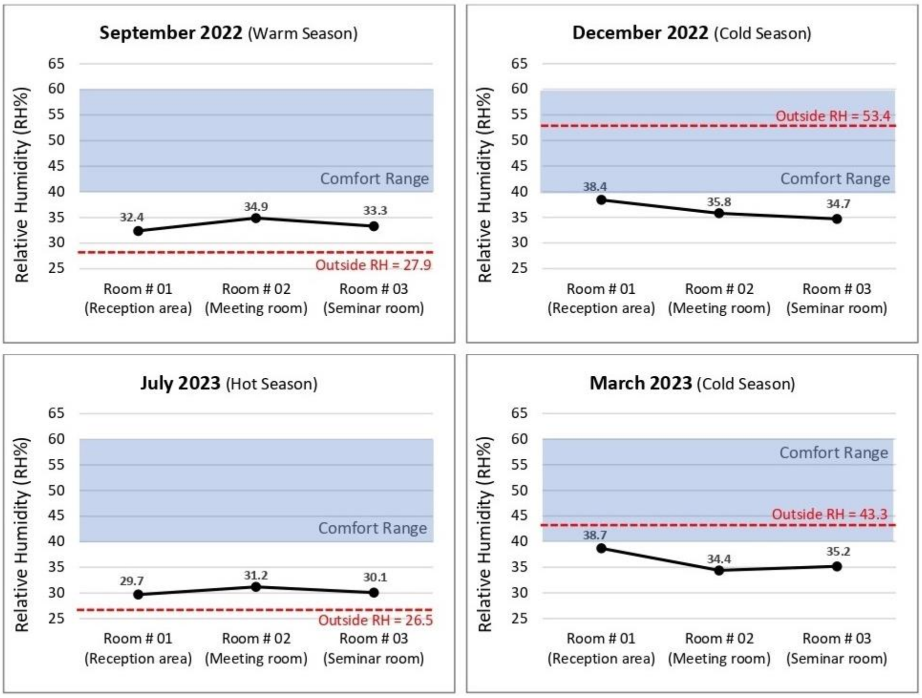
However, the levels of relative humidity (RH) in the rooms are seen to be below the recommended comfort ranges of 40% to 60% as specified by ASHRAE. Specifically, the recorded values range between 29.7% and 31.2%. The quantities of carbon dioxide (CO_2) in the enclosed enclosures were seen to remain within acceptable limits, with variations ranging from 412 to 501 parts per million (PPM). The decibel levels recorded within the specified structure ranged from 40.17 to 43.02 dBA. The data that has been recorded demonstrates a significant reduction in sound levels when compared to the suggested criteria established by ASHRAE, which normally fall within the range of 45 to 50 decibels (dBA). The recorded values consistently remain lower than the measured levels of ambient noise.

Figure 11. Indoor air temperatures in relation to the ASHRAE 55 comfort zone and the external environment.



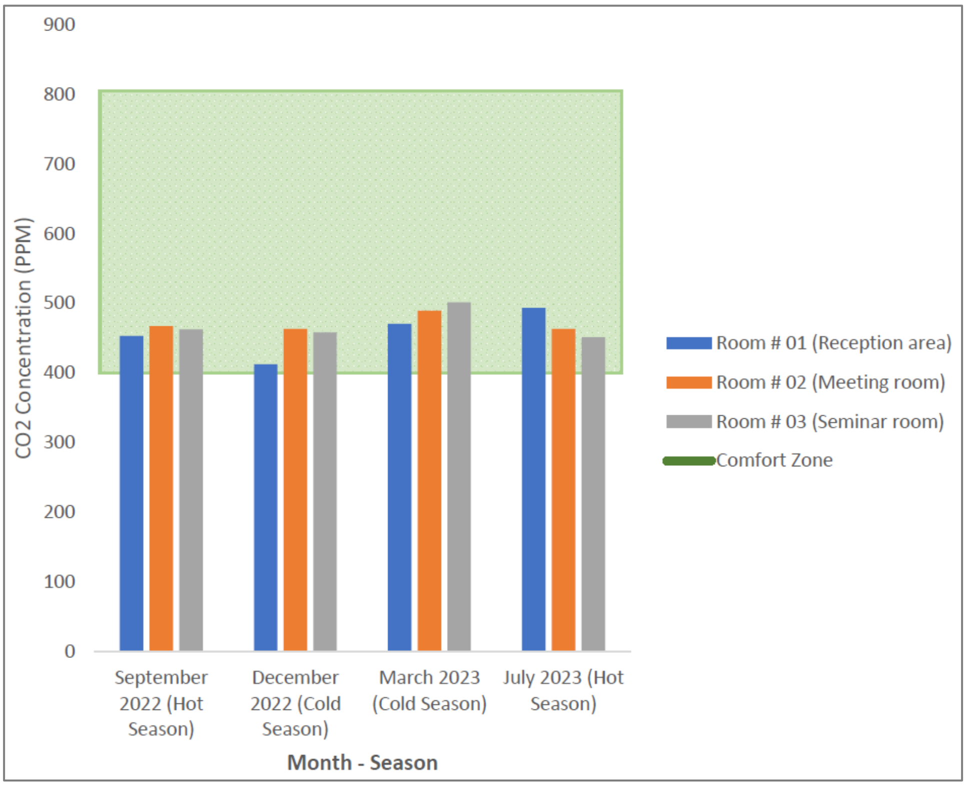
Source: Authors

Figure 12. Relative humidity inside the building in relation to the ASHRAE 55 comfort zone and the external environment.



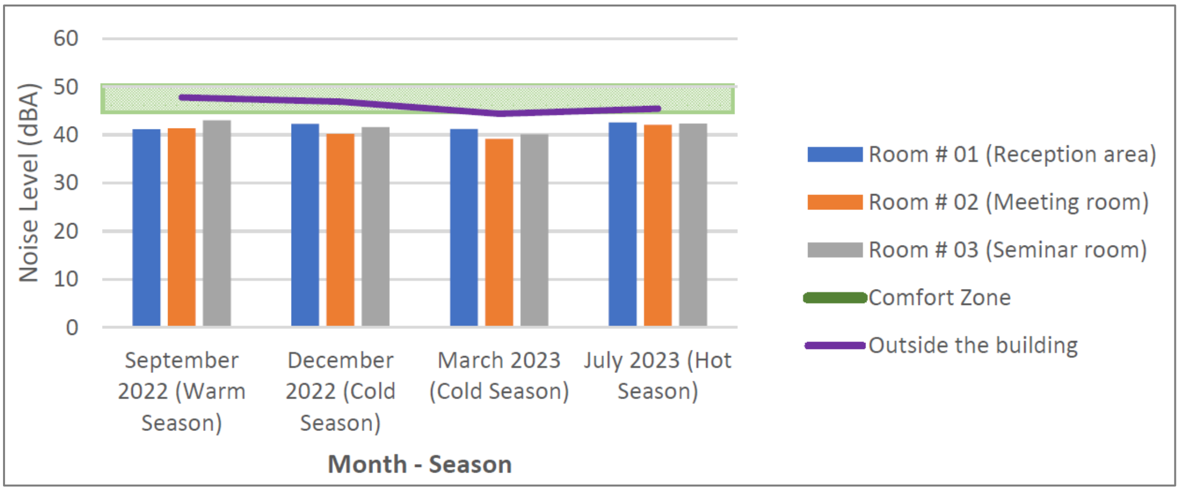
Source: Authors

Figure 13. Results of CO_2 concentrations inside the building in relation to the ASHRAE 55 comfort zone.



Source: Authors

Figure 13. Results of noise levels inside the building in relation to the ASHRAE 55 comfort zone and the external environment.



Source: Authors

The readings obtained in the field of environmental assessment might be seen as the result of several contributing variables. The interior of the structure is maintained at a pleasant temperature and humidity level because of the substantial thermal mass of its walls (Liu et al., 2015). The addition of quicklime and an acrylic-based additive to the mixture surely improves the insulating properties of the wall, hence contributing to its relatively low heat transmission value. Moreover, the application of plaster on both surfaces of the wall, with the addition of natural timber fibers, sand, quicklime, and an acrylic-based additive, has a positive impact on the indoor environmental conditions. The incorporation of these elements obviates the necessity for indoor climate control with regards to cooling and heating. During the nighttime period, the thermal energy accumulated during the daytime is transferred into the indoor environment, whereas the lower temperatures experienced at night are harnessed to enhance the interior ambiance throughout the diurnal phase. Moreover, the acoustic insulation properties of rammed earth walls are enhanced by their substantial mass and density (Khadka, 2020; Ivan et al., 2017).

5. CONCLUSIONS

The findings of this research provided novel insights into the potential applications of rammed earth in the construction of modern urban areas in hot-arid climates. The data presented in this study proved valuable to professionals in the fields of architecture, engineering, and construction, as they deliberate the incorporation of rammed earth techniques into their respective projects. The utilization of rammed-earth construction techniques possesses the capacity to alleviate both economic and ecological pressures. Designers and builders have the capacity to enhance the mechanical qualities of mud, including the mitigation of shrinkage cracks, as well as the stabilization of the mixture to augment its resistance to water erosion and boost its compressive strength. Lime, fibers, artificial stabilizers, and cement are among the various potential additives that might be utilized.

In hot-arid climates, it is recommended to incorporate a soil mixture consisting of 20% ordinary Portland cement, 15% quicklime, and an acrylic-based additive. This mixture, when combined with the optimal water content of 42%, has been found to significantly enhance the compressive strength. Specifically, the compressive strength of this modified mixture is approximately 7.2 times greater than that of the control sample, which solely consists of soil. Moreover, the achievement of a smooth surface with the desired natural color on rammed earth walls in the finishing plaster layer was observed by incorporating specific proportions of sand, quicklime, acrylic-based additive, natural wooden fibers, and water. This involved increasing the sand content to 35% of the soil weight, adding 15% quicklime and 15% acrylic-based additive, incorporating natural wooden fibers, and appropriately increasing the water content to 45% of the soil weight. It is of utmost importance in the process of construction to ensure precise application of the designated proportions of the mixture. Therefore, it becomes imperative to convert the component percentages into their corresponding weights, measured in grams.

In hot-arid climate, the attainment of indoor environmental attributes and thermal comfort is accomplished by the utilization of rammed earth walls with a thickness of 40 cm. The inside of such structures tends to be cooler during summer and warmer during winter compared to conventional buildings. The earth walls exhibit a relatively low level of thermal conductivity, as evidenced by the considerable amount of time it takes for heat to traverse a 40 cm thick barrier. This phenomenon may be quantified by the R value, a measure of thermal resistance, which typically ranges between 0.35 and 0.70 m2 K/W. The building possesses a commendable capacity for noise absorption, rendering it an advantageous attribute in the realm of architectural design for residential structures.

Further investigations are warranted to ascertain the comprehensive heat transfer coefficient (U-value) for different wall configurations. This can enhance the degrees of convenience associated with humidity-related factors. Another research endeavor that is necessary to provide a sustainable environment involves the assessment and quantification of Total Volatile Organic Compounds (TVOCs) inside the built environment. Further investigation is warranted about the occurrence of mold growth on the outer surfaces of rammed earth structures.

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CONFLICT OF INTERESTS

The authors declare no conflict of interest.

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