DOI: https://doi.org/10.38027/iccaua2023en0130

Potentials of Constructing Sustainable Rammed Earth Buildings in Hot-Arid Regions: Structural and Environmental Challenges

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Abstract
The continuous increasing in the price of cement is one of the major challenges facing the construction industry. Moreover, concrete mixtures are main sources of CO^2 emissions. On the other hand, rammed earth material could be a good alternative to reduce costs and amounts of emissions. In addition, it is appropriate to be used in hot-arid regions due to its thermal mass properties. Yet, such a material has limitations in terms of durability and strength. This research aims firstly to test the suitability of rammed earth as urban modern construction material, through examining characteristics and specifications of soil, sand, and other stabilizers to improve the resistance to frost attack and avoid deterioration. Secondly, to explore the efficiency in terms of indoor environmental conditions. The research was implemented by constructing an experimental building within a university campus in Jordan, to conclude the best solutions in terms of environmental and structural challenges.

Keywords: Rammed Earth; Stabilizer; Compressive Strength; Water Content; Sustainability; Thermal Comfort.

1. Introduction

The Economic Policy Council (2017) predicts that the construction industry is expected to grow at a far greater rate than the world economy over the next few years. Even so, these tendencies may have an impact on the human economy, the social fabric, and the environment. As reinforced concrete becomes the predominant building material, the rising cost of materials has become a new challenge for the construction sector. Cement and steel prices in Jordan, one of the world's fastest-growing countries, have increased twice in the past four years, to 132 and 755 U.S. dollars per ton, respectively (The Jordan Times, 2018; Jordan Chamber of Industry, 2023) due to rising demand. In terms of environmental impact, concrete mixtures are a major source of carbon dioxide emissions, which account for more than 66% of the overall emissions (Bahrami et al 2022). Fuel, energy, excavation, batching, shipping, and placement are all part of the production process that add an impact to this issue.

In addition, it is essential to keep the building industry as healthy as possible because it has direct effects on the well-being of people, particularly in nations that are confronting dangers related to climate change. For example, in Jordan, the hot-arid climate, which is characterized by rising temperatures, falling precipitation, and rising instances of drought, further exacerbates these concerns. Other countries are facing similar challenges.

One of the ecologically friendly options that could minimize construction costs and carbon dioxide emissions is the usage of natural earth. This material has been utilized throughout history in many areas, as it shields inhabitants from heat and dust (Dabaieh, 2014; Fathy, 1986). Building with earth has many potential advantages. These structures are cost-effective since they may be reused or recycled, and they require basic tools and labor with lower levels of expertise (Hadjri et al., 2007; Reddy, 2007; Minke., 2006; Walker et al, 2005; Maini., 2005). Additionally, they are widely available in most regions. Moreover, earth buildings are environmentally sustainable, as they have a high capacity for heat storage, save energy, ensure thermal comfort and indoor air quality, absorb pollutants, provide noise control, and are very good in fire resistance (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). Finally, the building process requires a little amount of energy and does not result in the production of hazardous wastes (Dayaratne, 2010; Dayaratne, 2007).

Earthen buildings could be built in a variety of techniques. The first are structures made of stacked earth (cob) by molding mud and water in the ratio of 1:3, then shaping it into a large, elongated egg. When building a wall, cobs are laid in a straight line and pressed together to seal any spaces between them. This approach excels at curved or round walls but is restricted in height (Hamard et al, 2016). Adobe is used in the second technique. The mud mixture is poured into blocks, which are then sealed with airtight polythene sheets and placed in an environment with a relative humidity of at least 100% for the first 48 hours. After that, the polythene sheets need to be removed, and the blocks are stored in shaded areas that have sufficient air circulation. It is necessary to sprinkle water over the blocks as many times needed for the next 28 days (Moquin, 1994). A third technique is rammed earth construction.

The earth mixture is packed in layers between two wooden formworks that are parallel to one another. When one piece of the rammed earth structure is finished and has reached the desired level of hardness, the two planks are then lifted, and the process of adding a second course of rammed earth is repeated over the first. One way to improve the wall's strength is to make it thicker. This will allow for a greater bearing capacity (Dabaieh, 2014).

Rammed earth technique is one of the most cost-effective approaches, and it only takes a short amount of time to build. Base earth, water, and binding clay are the traditional components of soil mixtures (Avila, 2022). However, more stable mixture and enhancements to mechanical properties are necessary for contemporary rammed earth buildings with less wall thicknesses (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). In addition, increasing durability of the construction and minimizing cost of maintenance are needed in hot-arid regions (Reddy, 2007; Minke, 2006; Walker et al, 2005).

Different stabilizers and additives may be applied to lengthen the lifespan of the rammed earth mixture. Lime and natural fibers have been known to improve the soil's mechanical and hydraulic behavior (Arto et al, 2021; Koutous and Hilali, 2021; Laborel-Préneron et al, 2016; Minke, 2006; Bell, 1996). The compressive strength and durability of the structure can be improved using Portland cement, fly ash, and recycled concrete aggregates (Avila, 2022; Niroumand et al, 2013). To achieve the appropriate level of strength, researchers have suggested making use of a cement percentage that is higher than 6% (Kariyawasam and Jayasinghe, 2016; Tripura and Singh, 2015; Bahar et al, 2004; Walker, 1995). Jayasinghe and Kamaladasa (2007, p. 1975) pointed out that “the highest strength of 3.71 MPa was reached with sandy soil that was stabilized with 10% cement”. When cement is used to stabilize soil, however, several issues might arise, including shrinkage fractures, in addition to weak tensile and shear strength (Bouhicha et al, 2005). Natural or artificial fibers may help overcome these limits (Kesikidou and Stefanidou, 2019; Danso et al., 2015). According to research done by Reddy and Kumar (2011) and Walker et al. (2005), the amount of water that is present in the mixture influences the overall strength of rammed earth. Before compacting, moisture levels should be within three percentage points of the ideal moisture content, as specified by the New Zealand Standard (1986). However, research conducted by Toufigh and Kianfar (2019), Hallal et al (2018), Ciancio et al (2014), and Tripura and Singh (2015), all concluded that a moisture content range of 8%-14% is appropriate for cement and lime rammed earth mixtures.

An examination of the available research demonstrates that there are few studies concerning the perfect stabilized rammed earth mixture that should be utilized in hot-arid regions. This finding is revealed by the fact that there is currently research available. In addition, there is a dearth of study that studies the indoor environmental features of contemporary rammed earth constructions that are built with walls that are of an appropriate thickness. Consequently, the purpose of this study work is to provide responses to the following two questions: The first question is, "what are the optimal components of soil mixture that improves the durability and strength of rammed earth structures in hot-arid climates?" The second question is, "what are the indoor environmental conditions that can be achieved in buildings that are constructed using rammed earth walls?" Rammed earth is a method of constructing in which the ground is compacted and compacted earth is used to make walls.

An examination of the available research reveals that there are limited reports concerning the ideal stabilized rammed earth mixture that should be utilized in hot-arid climates. In addition, there is a lack of research that investigates the indoor environmental aspects of modern rammed earth constructions. Therefore, this research paper aims to answer two questions. Firstly, "what are the optimal components of soil mixture that improves the durability and strength of rammed earth structures in hot-arid climates?". Secondly, "what are the indoor environmental conditions that can be attained inside modern rammed earth buildings if the walls are built to the appropriate thickness?".

Laboratory structural tests were conducted to examine the best combination and optimal proportions of materials that are appropriate for the hot-arid region. Moreover, it highlights climate-friendly water content for both the rammed earth wall and the final coat of plaster. These findings are helpful in minimizing repair costs while increasing compressive strength of the mixture. In addition, an experimental building was built on a university campus in Jordan, which has a hot-arid climate, to test the mixture's practicability and to investigate the indoor environmental qualities that can be achieved using appropriate thickness of walls, as demonstrated by the results of temperature, humidity, carbon dioxide emission, and noise level measurements during different seasons. These results draw recommendations for designers and builders to be considered while constructing urban modern rammed earth buildings in hot-arid climate.

This paper is organized into four parts. The first section reviews the construction industry's problems and the need for eco-friendly materials that can cut down on expenses and pollution. Moreover, it draws attention to the benefits and drawbacks of mud buildings and the necessity to investigate the possibilities of constructing rammed earth structures in hot-arid regions. The second section presents methods and procedures of structural and environmental investigations. The third and fourth sections consider the results and discuss the main recommendations of this research.

2. Material and Methods

The study adopted three experimental approaches to answering the research questions. Firstly, structural tests were conducted to determine the optimal mixture for maximizing compressive strength of the walls, as well as the ideal ratio of materials for the finishing plaster layer that would save maintenance costs while still capturing the earth's natural color. Secondly, constructing an experimental rammed earth building using the selected mixtures. Thirdly, performing tests that examine indoor environmental qualities, including air temperature, humidity, carbon dioxide emissions, and noise levels, inside the constructed building during different seasons.

2.1. Structural Tests

To identify the ideal mixture for optimizing the wall's compressive strength, the following components were employed, chosen based on prior studies and the local materials that were readily available in the area:

a. Soil: Soil was gathered from the surrounding areas, with samples obtained at a depth of 2 meters. Before a compressive test, which can indicate whether the soil is workable, a more in-depth examination of its characteristics is required. Rammed earth is not recommended for usage with high levels of silt. Topsoil is not recommended since it can compromise the soil's structural integrity because it often contains too much organic matter to perform well in compressive testing.
b. Ordinary Portland cement: It was utilized as an adhesive or cohesive agent to bind the particles together, which ultimately led to an increase in the soil's compressive strength.
c. Acrylic-based additives: It is an opacity-preserving agent that exhibits the highest possible bonding strength. Using such an additive could result in the achievement of a wide variety of desirable features. In addition to being suited for use on indoor and external surfaces, it is also resistant to chemical reactions and moisture, has a long lifespan, and may be applied to surfaces that are damp.
d. Quicklime: It is an alkaline substance in the form of fine particles smaller than 0.15 millimeters, and it is used as a binder, specifically in mortar and plaster.
e. Tap water: which is generally considered safe to drink.

To accomplish the first goal of the study and test the optimal properties of construction walls, three different mixtures were prepared and compared to a control sample consisting of soil alone. The only constants between the three mixtures are the 1000 g of soil and the 150 g of acrylic-based additive. An extra 150 grams of quicklime have been added to the original batch. The second blend has an extra 200 grams of regular Portland cement added to it. The third blend has an extra 150 grams of quicklime and 200 grams of standard Portland cement. Depending on the amounts of the various ingredients, the water's ratio can shift. A mechanical mixer was used to make the different mixtures. After 24 hours, the formwork was removed, and the samples were kept at 23 degrees Celsius. Each mixture was used to make ten cylinders with a length to diameter ratio of 2.5 (Figure 1).

Figure 1. Preparing the 40 samples for testing compressive strength (Authors).

An experiment was conducted to determine the optimal mix of materials for the finishing plaster layer of rammed earth walls, with the goal of lowering maintenance costs and achieving a more natural soil color. Six different samples were prepared using soil, sand, quicklime, cement, acrylic-water additive, and appropriate amount of water. To see if cracks could be decreased, wooden fibers were added to four mixtures and removed from two others.

- Sample (1): 350 g soil, 15% sand, 15% quicklime, 40% water, 15% additive, and 5 g wooden fibers.
- Sample (2): 350 g soil, 10% sand, 10% quicklime, 10% cement, 40% water, and 5 g wooden fibers.
- Sample (3): 350 g soil, 15% sand, 15% quicklime, 15% cement, 40% water, 15% additive, and 5 g wooden fibers.
- Sample (4): 350 g soil, 35% sand, 15% quicklime, 45% water, 15% additive, and 5 g wooden fibers.

- Sample (5): 350 g soil, 33% sand, 15% quicklime, 15% cement, 33% water, and 15% additive.
- Sample (6): 350 g soil, 33% sand, 15% quicklime, 15% cement, 15% water, and 15% additive.

2.2. Constructing an Experimental Rammed Earth Building

A 160-square-meter rammed earth building was designed for use as an experimental structure and utilized as seminar rooms. Each wall was constructed using the most compressive-strength mixture. The walls are 4 meters in height and 43 cm wide. All walls consist of outer mud plaster layer (15 mm), rammed earth (40 cm), and internal mud plaster layer (15 mm). To prevent the walls from collapsing, wooden stakes were placed inside the walls every meter. The building's footings are 75 cm in width and 80 cm in height. It is mostly stone rubble with a small amount of concrete. Half of the foundation's height is kept above ground, protecting the rammed earth walls. On the upper side of the walls, a concrete ring was added (20 cm in width and 20 cm in height) to serve as the foundation for the pitched roof, which was covered in clay tiles. Joints between walls were reduced by using French windows. The building's construction is illustrated in (Figure 3), and the completed structure is shown in (Figure 4), which displays the structure from both the interior and the exterior.

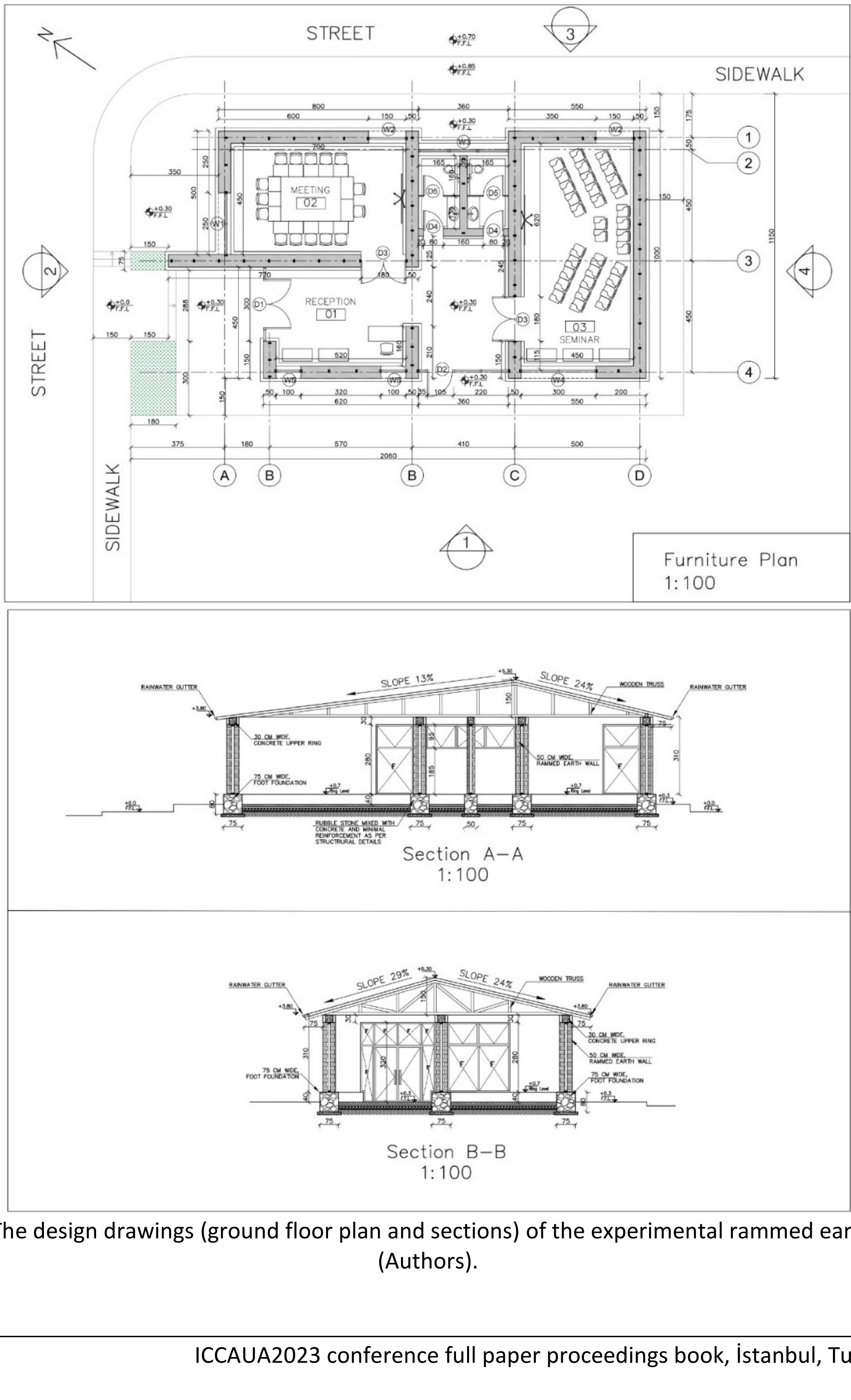

Figure 2. The design drawings (ground floor plan and sections) of the experimental rammed earth building (Authors).

Figure 3. The construction process of the experimental rammed earth building (Authors).

Figure 4. The completed rammed earth building from both the interior and the exterior (Authors).

2.3. Environmental Assessment

Amman, Jordan, is a hot-arid city where the experimental building was constructed (Figure 5). Environmental simulation was performed during the design process to make sure the most effective strategies in terms of orientation, day lighting and natural ventilation (Figure 6). Site measurements of indoor environmental qualities were taken during different seasons; 15 September 2022, 20 December 2022, and 15 March 2023, during the hours 9:00am – 12:00pm. The choice of measurement time is based on the most occupied time of the building. The readings were recorded every 30 minutes from a height of 1.2 meters, where the measurement devices were stationed. IEQ parameters, including air temperature (°C), relative humidity (%), carbon dioxide concentration (PPM), and noise level (dBA) were recorded. All instruments were properly calibrated in accordance with the manufacturer's instructions. The outcomes were evaluated against ASHRAE 55 standards.

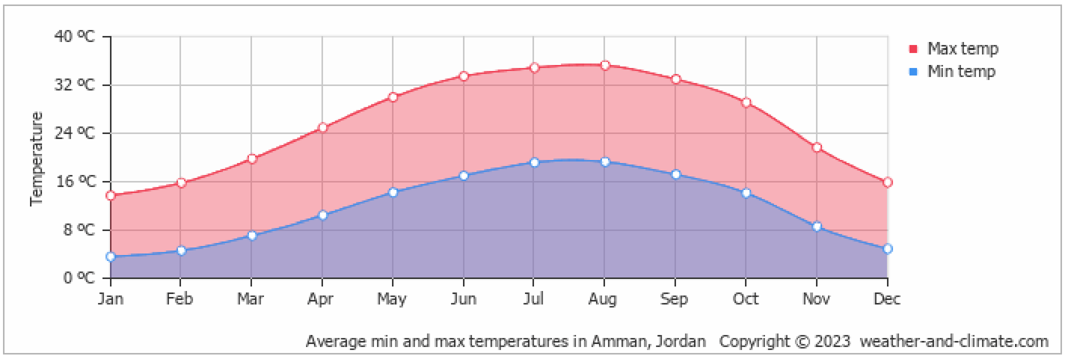

Figure 5. Average minimum and maximum temperatures in Amman, Jordan.
(Source: https://weather-and-climate.com/average-monthly-min-max-Temperature,Amman,Jordan).

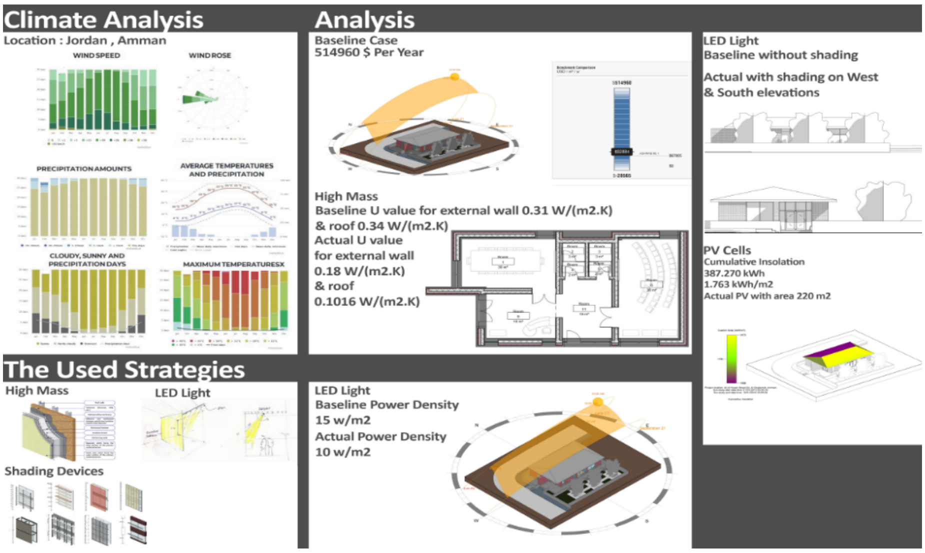

Figure 6. Environmental simulation during the design process (Authors).

3. Results

This section illustrates the results of structural tests to determine the optimal mixture that has the highest compressive strength, and an environmental assessment of the constructed building.

3.1. Results of Structural Tests

Soil's compressive strength shifts in relation to its degree of alteration and level of compaction. Soil modified with 20% cement, 15% acrylic-based additive, and 33% water content at 28 days showed 6.85 times the compressive strength of the control specimen. Soil amended with 20% cement, 15% acrylic-based additive, 15% quicklime, and 42% water content achieved 4.39 MPa that equals 7.2 times the compressive strength of the control sample, which is an impressive improvement. Soil treated with 15% acrylic-based additive, 15% quicklime, and 37% water content has a compressive strength that is roughly 3.4 times that of the control specimen. The 28-day compressive strength results are shown in (Table 1).

Table 1. Results of 28-day compressive strength tests (Authors).

Properties of Samples	% Water	Avg. Load (kN)	Compressive Strength (MPa)
Control sample (Soil)	14	4.77	0.48
	16	5.89	0.60
	18	6.00	0.61
	20	5.30	0.54
Mixture (1), which consists of: • Soil • Acrylic-based additive (= 15% of soil weight) • Quicklime (= 15% of soil weight)	28	11.78	1.20
	31	13.09	1.33
	34	18.32	1.86
	37	20.28	2.06
	40	15.05	1.53
Mixture (2), which consists of: • Soil • Cement (= 15% of soil weight) • Acrylic-based additive (= 15% of soil weight)	25	20.78	2.11
	27	25.69	2.61
	29	31.08	3.15
	31	34.02	3.45
	33	41.22	4.18
	35	34.35	3.49
	37	33.04	3.35
	40	30.83	3.13
Mixture (3), which consists of: • Soil • Cement (= 20% of soil weight) • Quicklime (= 15% of soil weight) • Acrylic-based additive (= 15% of soil weight)	30	24.16	2.45
	33	27.02	2.74
	36	29.21	2.97
	39	38.50	3.91
	42	**43.27**	**4.39**
	45	39.35	3.99
	48	34.12	3.46

The optimal material proportions for the finishing plaster layer are found in sample (4), which significantly reduces the number of cracks and yields a smooth surface. Soil (350 g), sand (122.5 g; 35% by weight), quicklime (52.5 g; 15% by weight), water (157.5 g; 45% by weight), acrylic-based additive (52.5 g; 15% by weight), and natural wooden fibers (5.0 g) are all included in this mixture. It has been noticed that incorporating sand at a rate of 35% of the soil weight and adjusting the water content suitably has a good effect on the final finish of surface in terms of shrinkage and producing the most desired natural color of rammed earth material.

3.2. Results of Environmental Assessment

According to the records of IEQ of the constructed rammed earth building during different seasons, Table 3 summarises the environmental conditions of the surveyed building in terms of IEQ (air temperature, relative humidity, CO_2 concentration, and noise level) in comparison to the international ASHRAE 55 standards.

All indoor air temperatures conform to the ASHRAE 55 adaptive method for thermal comfort, which establishes acceptable limits of (19.4–27.7 °C) during the colder months and (23.1–28.2 °C) during the warmer months. However, the relative humidity (RH) levels in the rooms are below the (40%-60%) comfort ranges recommended by ASHRAE. The CO_2 levels in the rooms were within acceptable ranges, ranging from (412 to 501 PPM). Inside the building, noise level readings ranged from (40.17 to 43.02 dBA). The measurements are significantly quieter than the ASHRAE recommendations (45–50 dBA). These numbers are still lower than the measured outside noise level.

Table 2. Results of environmental assessment (Authors).

	Temperature (C^O)	**Relative Humidity (RH%)**	**CO_2 (PPM)**	**Noise Level (dBA)**
Sep. 2022 (Warm Season)				
Room 1 (Seminar room)	28.1	33.3	462	43.02
Room 2 (Meeting room)	27.2	34.9	467	41.34
Reception	27.5	32.4	453	41.19
Outside the building	28.7	27.9		47.80
Dec. 2022 (Cold Season)				
Room 1 (Seminar room)	27.9	34.7	458	41.59
Room 2 (Meeting room)	26.7	35.8	463	40.17
Reception	26.1	38.4	412	42.26
Outside the building	14.8	53.4		46.90
March 2023 (Cold Season)				
Room 1 (Seminar room)	24.1	35.2	501	40.11
Room 2 (Meeting room)	23.5	34.4	489	39.18
Reception	23.2	38.7	470	41.22
Outside the building	18.3	43.3		44.40
Comfort conditions according to ASHRAE 55 standards	Warm season: (23.1 – 28.1 °C) Cold season: (19.4 – 27.7 °C)	(40% – 60%)	(400 – 800 PPM)	(45 – 50 dBA)

4. Discussion

In terms of adding cement to the soil mixture to improve its strength and durability, the structural test results were consistent with those of prior research (Avila 2022; Khan et al 2019; Niroumand et al 2013; Maniatidis and Walker 2003). Following the advice of (Jayasinghe and Kamaladasa 2007), which recommends a cement content of at least 10%, the compressive strength increases to 4.39 MPa. However, the financial aspect of such proportions needs to be examined to cut down on building expenses. Water increases the strength of the modified soil up to a point by decreasing the friction between the mixture's particles, making compaction easier, and decreasing the void volume between the particles. If the soil's moisture level is higher than ideal, water will fill the spaces between the soil particles, reducing the soil's strength.

Furthermore, it has been noticed that incorporating sand at a rate of 35% of the soil weight and adjusting the water content suitably has a good impact on the final finish of surface in terms of shrinkage and the most desired natural color of rammed earth material. Most studies (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) agree that fiber additives improve the mechanical behavior and durability of the soil mixture, so these findings are consistent with the recommended final finish mixture.

The acquired readings of environmental assessment can be regarded as the consequence of multiple factors. Due to the large thermal mass of walls, the building's interior is kept at a comfortable temperature and humidity level (Liu et al., 2015). The mixture's components, which include quicklime and an acrylic-based additive, undoubtedly enhance the wall's insulating characteristics, contributing to the comparatively low value of wall heat transmission. Plaster is applied to both sides of the wall, and it consists of natural timber fibers, sand, quicklime, an acrylic-based additive. By combining these elements, interior climate control in terms of cooling and heating is unnecessary. The daytime heat is conveyed into the room at night, while the nighttime coolness is used to spruce up the interior during the day. Additionally, due to the mass and density of the wall, rammed earth walls are notably good at insulating against noise (Ivan et al, 2017).

5. Conclusions

The results of this study will shed new light on how rammed earth might be applied to the building of contemporary cities. The information provided in this study will be useful to architects, engineers, and builders as they consider rammed earth for their projects. It will help promote the need to use eco-friendly materials in construction. Rammed-earth building has the potential to lessen both financial and environmental burdens. Designers and builders can improve the mud's mechanical properties, such as reducing shrinkage cracks, and stabilize the mixture to increase its durability against water erosion and compressive strength. Lime, fibers, artificial stabilizers, and cement are just some of the potential additives. The following conclusions were drawn from the experimental study due to the scarcity of studies that examine the optimal stabilized rammed earth combination for use in hot-arid climates:

- Adding 20% of ordinary Portland cement, 15% quicklime, and acrylic-based additive to the soil mixture, with the optimum percentage of water (42%) is a suitable mixture to be applied in hot-arid climates, and this is the key to increase the compressive strength of 7.2 times than of the control sample that include soil only.
- Increasing the sand content to 35% of the soil weight, adding 15% quicklime, 15% acrylic-based additive, natural wooden fibers, and appropriately increasing the water content to 45% of the soil weight yielded a smooth surface with the desired natural color when applied to rammed earth walls in the finishing plaster layer.
- During construction, it is crucial that the prescribed percentages of the mixture be applied accurately, hence converting percentages of components into weights (grams) is essential.
- Indoor environment qualities and thermal comfort are achieved in hot-arid regions using a thickness of 40 cm of rammed earth walls.

The overall heat transfer coefficient (U-value) for various wall sections should be researched through additional studies. This has the potential to improve humidity-related levels of convenience. Another study that needs to be done to guarantee a healthy environment is the measurement of TVOCs inside the structure. Mold growth on the exterior of rammed earth buildings is another issue that needs more research.

Acknowledgements

The authors would like to acknowledge the University of Petra, Jordan for supporting the study by a fully financed grant (Project Number 1/6/2020). The authors would also like to thank Engineer Ahmad Masoud from the University of Petra's Civil Engineering Department for his assistance with the structural tests.

Conflict of Interests

The authors declare no conflict of interest.

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