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Balancing Environmental Impact and Practicality: A Case Study on the Cement-Stabilized Rammed Earth Construction in Southeast Rural China

Shan Dai [1], Wenfeng Bai [2] and Jing Xiao [2,*]

[1] School of Architecture, The Chinese University of Hong Kong, Hong Kong, China; daishan@link.cuhk.edu.hk
[2] Faculty of Architecture and City Planning, Kunming University of Science and Technology, Kunming 650032, China; baiwenfeng@ccmccf.org.hk
* Correspondence: jing@ccmccf.org.hk; Tel.: +86-139-8710-2006

Abstract: Construction using earth materials demonstrates ecological sustainability using locally sourced natural materials and environmentally friendly demolition methods. In this study, the environmental impact of adding cement to soil materials for rammed earth farmhouse construction in rural China was investigated and comparatively simulated using the One Click LCA database, focusing on the conflict between sustainability objectives and the practical aspects of cement addition. By analyzing how the addition of cement aligns with local construction practices and addressing the debate surrounding the inclusion of cement in rammed-earth construction, our objective is to provide insights into achieving a balance between the environmental impact and the pragmatic considerations of using cement in earthen building practices. Three local structure scenarios are evaluated via simulations: cement-stabilized rammed earth wall, fired brick wall, and a localized reinforced concrete frame structure. The quantitative environmental impacts are assessed, and the qualitative differences in adaptation, economic sustainability, and other factors are examined in the context of present-day development in rural China. The results show that the use of cement-stabilized rammed earth wall-supported structures is associated with higher embodied carbon emissions compared to structures supported by reinforced concrete frames and enclosed by brick walls; however, these emissions are lower than those for brick wall-supported structures while effectively meeting the structural requirements. In addition, the use of cement-stabilized earth for perimeter walls simplifies material management and disposal throughout the building's life cycle, and the cost-effectiveness of cement has been found to be substantially greater than that of reinforced concrete frames and brick structures, improving economic viability and social acceptability, especially among low-income communities in rural areas

Keywords: cement-stabilized rammed earth; rural area; software simulation; sustainable evaluation

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1. Introduction

Along with China's rapid economic development over the past few decades, the urbanization and hollowing out of villages in rural areas have led to a massive concentration of people in towns and cities [1], with the number of natural villages in China declining by more than 12.8% between 2006 and 2021 [2]. The rapid development of information interaction and the updating of construction technology and materials have had a significant impact on traditional human construction methods, such as rammed earth, and large-scale self-demolition and self-built construction have occurred in rural areas of China [3], where rural residents have begun to emulate the standards of urban living, replacing the original earth and wood structures with energy-intensive construction materials such as reinforced concrete, masonry, and steel. People left behind are not able to uphold the maintenance of traditional buildings, and the loss of powerful and skillful labor has significantly challenged the inheritance of local construction traditions [4,5]. Building sustainable development is an urgent but inevitable goal that needs to be achieved globally. Current rural development in China is facing the following multiple challenges [6–8]:

- Simultaneously achieving twin rural revitalization and dual carbon emission reduction policy objectives.
- The loss of labor fundamentally hampers village behavior associated with human activity.
- China is going through a transition phase from poverty eradication to rural revitalization, and the level of infrastructure development in rural areas is relatively lagging, posing a risk of returning to poverty.
- Industrialized materials and technologies impact traditional construction techniques.
- Increased frequency of unpredictable weather extremes and natural disasters.
- The increased use of multiple channels to obtain information and resources without improving discernment. Although the population has decreased, resource consumption and carbon emissions have increased.

Because of the above challenges, the core objectives of housing in rural areas include the following: to improve the quality of housing, to reconfigure rural community relations through public gathering activities such as housing construction in villages while ensuring affordability, to reduce the use of energy-intensive materials and equipment, to encourage the active participation of elderly people in villages to work and be remunerated in phases while housing construction activities are carried out, and to increase the number of people in the villages who are left behind. One of the first issues to be addressed is how to solve the current housing demand problem with the lowest cost and lowest environmental impact technology to achieve comfortable housing conditions.

Rammed earth construction is the most widely used technique in the world, which could be constructed to be load-bearing structures if accompanied by the appropriate density and additions [9]. The practical project in Yunnan province has proved that the dry compressive strength of a rammed earth block in lab conditions can be improved from 1 Mpa to 3 Mpa on average by re-proportioning sand and gravel and adding about 3% cement to the soil with a clayey soil extracted from the site [10]. Shaking table experiments have also proved that a load-bearing building with appropriate proportion and binders of earth wall can satisfy the requirements of eight-degree seismic fortification [11].

Of course, the stability of rammed earth construction has always been a controversial practice, mainly in Australia [12]. The prototype was conducted based on the site where the soil is too sandy or clayey, which should be appropriate to add stabilizers to improve the durability of the earth wall and to cope with the dry compressive strength, to reduce the quality of the soil itself, which could have an either positive or negative effect on the limitations of the construction of rammed earth. On the other hand, scholars of rammed earth construction, mainly in Europe, believe that the addition of chemical stabilizers to the soil, as a natural material that can be recycled and reused, will destroy the properties of the soil itself, which will make it more difficult to be dismantled and reused, with a lower value, and will increase the load on the environment [13]; when the 'affordable' nature of rammed earth construction conflicts with its 'green' attributes, the balance of factors to be considered determines the final construction technology program.

A development strategy of rammed earth buildings that corresponds to the above challenges should be designed to deal with different local contexts, such as capable resources, the workmanship of local laborers, climate and geographical situations, cultural beliefs, etc. Pelé-Peltier and Charef [14] reviewed the multiple factors that affected the use of earth material in industrial construction. Currently, for remote mountain villages in southeast China, meeting policy requirements and economic acceptability are the primary conditions for initiating the renewal of farmhouse construction. Using rammed earth as the primary building material can result in significant cost savings [15]. In addition, social elements and environmental impacts must be prioritized before renewal. Traditionally, in rural China, there is a human or clan bond, and in the past, houses were constructed based on the village residents' mutual help [16]. With population loss and the gradual weakening of community relations in villages, public affairs in villages have gradually transformed from clan management to a market economy. However, the people's influence is still apparent. Due to limited transportation in rural China, especially in mountainous areas, and the current low level of mechanization in rural house building, the construction of most houses is still labor-intensive. By organizing labor-intensive activities such as rammed earth construction, surplus laborers in villages, including the elderly and women, are encouraged to participate in construction work actively, gradually refining the cooperative model and re-establishing rural community relations during the project. This is the primary significance of this case study.

2. Research Progress of Rammed Earth

We are seeking solutions from nature, such as the recap of the implementation of biomass materials to replace energy-intensive components [17]. Engineers have been constructing earthen buildings since the 1950s, which are not only capable of performing as building envelopes but also as load-bearing structures [13]. The characteristics that represent the sustainable definition of earth construction, such as locally obtained resources, renewable and recyclable materials, the excellent hydrothermal performance of mass earth walls, economically affordable construction [18], easy-to-learn construction techniques [19], etc., have been widely recognized; the widespread use of rammed earth construction is constrained by multiple factors no matter whether in developed or developing regions [14]. Rammed earth construction is the most widely adopted technique among the recognized 12 types of earthen techniques in the world [9]. It is constructed to compact a mixture of soil and water between temporary forms layer by layer. Areas such as the structure, material proportioning, construction organization, and thermal performance of rammed earth buildings have already been studied. The referred literature is listed in Table 1.

Table 1. Research perspectives of earthen structures.

Literature	Research Perspectives	Content
[9,15,20–30]	Material Properties and Construction Techniques	These studies examine earth materials' physical and mechanical properties, including their thermal mass, moisture absorption, and compressive strength. Research also focuses on traditional building techniques versus modern innovations in earth construction.
[23,25,31–37]	Sustainability and Environmental Impact	Many researchers have compared the sustainability of earth constructions to conventional building methods. This includes assessing the carbon footprint, energy efficiency, and potential for local material sourcing.
[11,38–47]	Seismic Performance	Since many earth structures are in seismically active regions, research often focuses on earthen buildings' structural integrity and behavior during earthquakes, including retrofitting methods and design modifications.
[48,49]	Cultural and Historical Perspectives	Earth architecture is often studied for its cultural significance, historical development, and traditional knowledge associated with earth construction, including how these practices can be preserved or revitalized.
[50–58]	Thermal Performance and Energy Efficiency	Investigations into how earth buildings perform thermally can reveal insights into energy savings and occupant comfort, often comparing these structures to those built with conventional materials.
[23–25,59–66]	Modern Applications and Innovations	Research includes integrating earth materials with modern technologies, such as prefabrication techniques, hybrid building materials, and innovative engineering solutions.
[67–72]	Regulatory and Policy Frameworks	Studies sometimes examine how building codes and regulations impact the use of earth as a building material, including barriers and opportunities for broader adoption in contemporary construction practices.

Table 1. *Cont.*

Literature	Research Perspectives	Content
[15,35,62,73,74]	Socioeconomic Factors	Research may also cover the socioeconomic implications of using earth materials, particularly in developing regions where earth construction can provide affordable and accessible housing solutions.
[62,73,75]	Resilience and Adaptation	As climate change poses challenges, ongoing research is being conducted into how earth-based structures can be adapted or designed to withstand extreme weather conditions and contribute to community resilience.

On a practical level, however, the study of rammed earth architecture has been ongoing for decades, and general acceptance remains low. Ben-Alon et al. [76] analyzed that the building permit is the strongest barrier for earthen buildings in the context of developed countries with well-established construction systems. However, the acceptance of earthen houses in less developed areas is also low, the main reason being that the locals think it is disgraceful to live in an earthen house [62,76,77]. Both types of impediments exist in rural China. Addressing the contradictions between quality living conditions and low environmental impact is a long-lasting research topic.

An analysis of the historical progression of earthen architecture revealed that each method of constructing with earth is a response to a specific social setting and the prevailing circumstances of that era [37,78–80]. However, in the past, most people in Asia and Africa, where most of the population is engaged in agriculture, strongly associated earthen buildings with poverty and backwardness, preferring industrialized materials such as cement and steel [31,79]. Since man began choosing industrialized materials over nature-based construction, there has been drastic resource depletion and a climate crisis. The transition to natural construction is an unavoidable trend; however, it is still primarily hindered by a lack of knowledge and restoration of the value of the modern system of nature-based construction. Thus, Heringer et al. summarize the years of practice and research on rammed earth construction and pose the central question, "Who profits?" [31]. The renowned American economist Jeremy Rifkin predicts an imminent end to wage labor in industrial production as intelligent technologies surpass the cost efficiency of human labor worldwide. Considering this transformative shift, Rifkin emphasized the need for innovative solutions to overcome the challenges posed by the decline in mass labor. Conversely, by reassessing its priorities, the construction industry promises to address the increasing demand for work and wage labor in the future [31]. The main advantage of expanding earthen construction lies in its ability to effectively meet these demands while maintaining a balance between labor, production costs, embodied energy, water consumption, and resource transportation, thus promoting equity. Despite these potential benefits, the widespread adoption of earth construction practices remains limited. Of this rammed earth, wattle and daub, cob, adobe, and compressed earth block (CEB), rammed earth construction requires the most teamwork.

Rammed earth construction projects are joint in China's east, southeast, southwest, and northwest regions. Most of them involve renovating traditional earthen buildings, such as the Fujian Tulou, terraced adobe houses in Yunan, and caves in Gansu. Building with modern technology focuses on upgrading rural homes and post-disaster reconstruction. In both situations, constructing rammed earth buildings does not provide designers or builders with adequate financial resources and response times for the precise and accurate control of architectural details. A rough type of design and construction organization is more suitable for upgrading rural households and construction during a disaster context, whether due to the lifestyle habits of rural residents or the urgency of disaster relief. Considering the limited financial resources in both areas, rammed earth construction in rural China, especially for self-built houses and disaster relief, usually involves adding cement or incorporating structural elements such as steel bars or bamboo strips to ensure safe and comfortable shelters while keeping costs manageable.

Therefore, this study hypothesizes that cement-stabilized rammed earth buildings should be environmentally superior to brick masonry and reinforced concrete frame structures, which are common in rural areas of southeastern China. A life cycle analysis (LCA) using the One-Click LCA database was conducted to assess the embedded carbon emissions of the three types of structures, cement-stabilized rammed earth, brick masonry, and reinforced concrete, and to analyze the economic performance of the three technological tools in the context of actual project records. It can provide a reference value for future housing renewal and renovation in other relatively underdeveloped areas.

3. Case Study

3.1. Comparative Simulation Study

This study examines rural housing construction in China by taking a holistic approach to life cycle analysis. A comparative simulation analysis was carried out using the Design Builder software, Version 7.3.0.029, in conjunction with the One Click LCA database, which Bionova Ltd. (Helsinki, Finland) developed to comply with EN 15978 standard [81], to simulate the daylighting performance of standard building units and associated embodied carbon emissions. While the existing databases need to be expanded to be more relevant to the Chinese context, evaluating different construction methods for embodied energy consumption remains a valuable source of insight. This study extends the analysis of rammed earth construction with cement to encompass sociological and economic dimensions within the current Chinese development landscape and presents a case study involving the renovation of self-built rural houses in southeast China.

In this study, three standard building blocks commonly implemented in southeast rural China, with buildings of dimensions 3 × 5 × 3 m (width (W) × length (L) × height (H)), were simulated and constructed using four types of building materials: fired brick, cement-stabilized rammed earth (CSRE), concrete, and reinforcement steel bar. A foundation with a height of 200 mm, and a flat concrete roof thickness of 100 mm, and an extension of 300 mm on top of each block for puncture protection of the wall were proposed (Table 2).

Table 2. Parameters, quantities, and estimated material costs for the three blocks compared.

Title 1	Unit	Block 1	Block 2	Block 3
Parameter				
Load-bearing structure		380 mm thick fired brick wall	350 mm thick 5% cement-stabilized rammed earth wall	200 mm (W) × 300 mm (L) reinforced concrete frame
Footing	mm	200 (H) × 380 (W)	200 (H) × 350 (W)	200 (H) × 200 (W)
Material				
Concrete	m^3	3.60	3.49	3.62
Steel bar	kg	382	382	423
Cement	kg	720	1075	395
Fired brick	kg	23,123	0	13,224
Cost [1,2]				
Concrete	CNY/m^3	352.8	342.02	354.76
Steel bar	CNY/m	1834	1834	1905
Cement	CNY/ton	302	452	166
Fired brick	CNY/piece	3078	0	1764

[1] The unit price for each material refers to a project in southeast China. [2] The estimated cost of each material was calculated by considering 5% waste as indicated in practice.

Figure 1 shows the simulated annual daylight factor for the standard layout plan of the three blocks. This study aims to focus on the embodied carbon emissions of the different building materials to facilitate the frequent implementation of load-bearing structures in rural areas in southeast China. Figure 2 displays the study cases, which include a standard bedroom floor plan, which shows a good annual daylighting factor for the accommodation, and embodied carbon benchmarking for a single block built with an envelope.

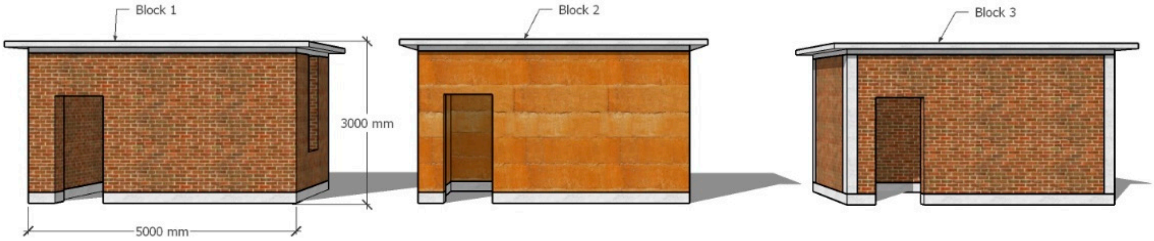


Figure 1. Model of the three blocks under comparison.

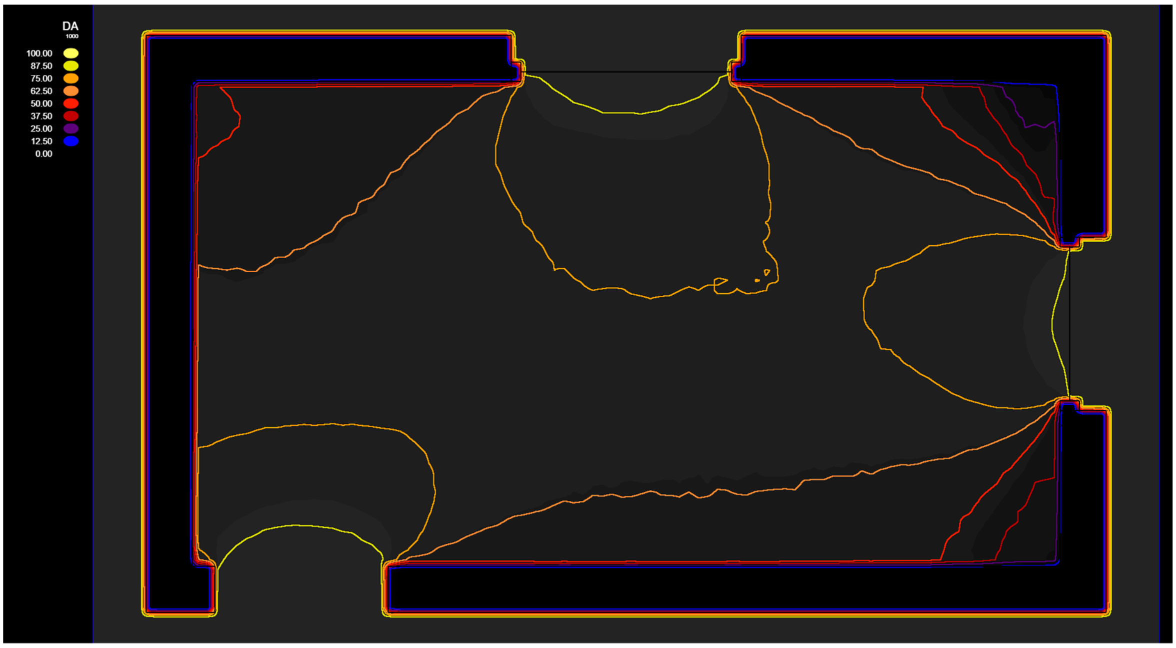
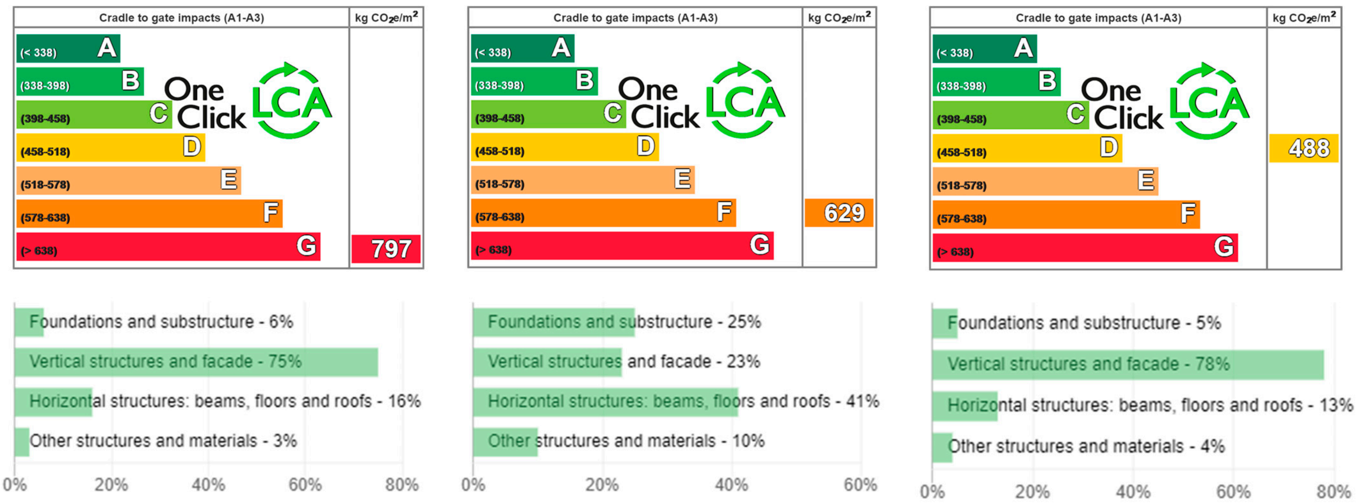


Figure 2. Simulated annual daylight factor for the standard layout plan of the three blocks.

To account for the specific conditions at the project location, the dependent variables in the three simulation results encompass variations in the quantities of the four primary materials based on typical local construction methods and discrepancies in the materials used for the vertical structures.

The modeling data analysis (Figure 3) indicates that among the existing construction methods for rural residential buildings in southeast China, using 380 mm thick brick walls as load-bearing elements shows the highest hidden energy consumption. This is followed by rammed earth walls reinforced with cement, with framed structures incorporating the load-bearing elements, which have the lowest hidden energy consumption.

The development of simulation software for preliminary decision-making analysis is a widely accepted method to help designers optimize the design at an early stage [82]. However, the simulation tool is always based on the data already collected to provide a platform for real-time data updating, and the collection of the regional characteristics of the parameters still has its limitations. Therefore, researchers and scholars often simulate the data with the measured data to compare and make a comprehensive judgment. Even though most of the databases of One Click LCA in this study are from European countries and do not match the actual data from rural China, it is still valuable to qualitatively assess the advantages of the three building systems, namely brick masonry, stabilized rammed earth, and framed structure, for reducing hidden energy consumption. To further substantiate the hypothesis put forward in this study regarding the sustainability of adding cement to rammed earth buildings, a case study on renovating a rural rammed earth dwelling located in the mountainous region of southeastern China is conducted.



Block 1 Block 2 Block 3

(**a**) (**b**) (**c**)

Figure 3. Embodied carbon benchmarking for a single block built with an envelope. (**a**) A 380 mm thick fired brick wall, (**b**) 350 mm thick rammed earth wall, and (**c**) reinforced concrete framing structure and 200 mm thick fired brick wall, which corresponds to the parameters in Table 2.

3.2. Project Case Study

Existing Situation on Site

The site selected for the pilot project is in southeast China, and it is originally an ethnic Yao settlement with a hot summer and cold winter climate. The project was launched after China had fully completed its poverty eradication mission. The projects initially aimed to preserve and restore some of the vacant traditional rammed earth dwellings. The village had lost many laborers in the past due to prevailing policies and urbanization; therefore, there were less than ten permanent residents in the village at the beginning of the project, and the average age was over 60.

There were approximately 12 traditional rammed earth buildings and 5 modern brick and masonry houses; the traditional rammed earth settlement style of the village had been destroyed, as shown in Figure 4.

Figure 4. The image on the left shows the present-day depiction of the village before the project commenced in 2021, while the image on the right showcases the village landscape circa 2008.

The pilot project was conducted with the support of non-governmental organizations, as the permanent population of the village was very sparse. Most of them were retired elderly people. Traditional rammed earth construction is an undeniable feature of the village. The project team's investigation was conducted during the hot summer months. When surveying each of the earth buildings, it was evident that the existing earth buildings were very cool inside, but the lighting could be better. The front and back of the main halls of each earth building were ventilated, but the bedrooms on the left and right sides needed better ventilation and daylighting due to poor existing situations, as Figure 5 shows. Moreover, due to the traditional building's left–right symmetrical layout, the occupants' requirements and privacy were not overly considered. As a result, most household interviews revealed a conflict between the existing rammed earth houses and the actual use of the function, including most of the unused space on the first floor.

Figure 5. Interior condition of an existing rammed earth dwelling in the village.

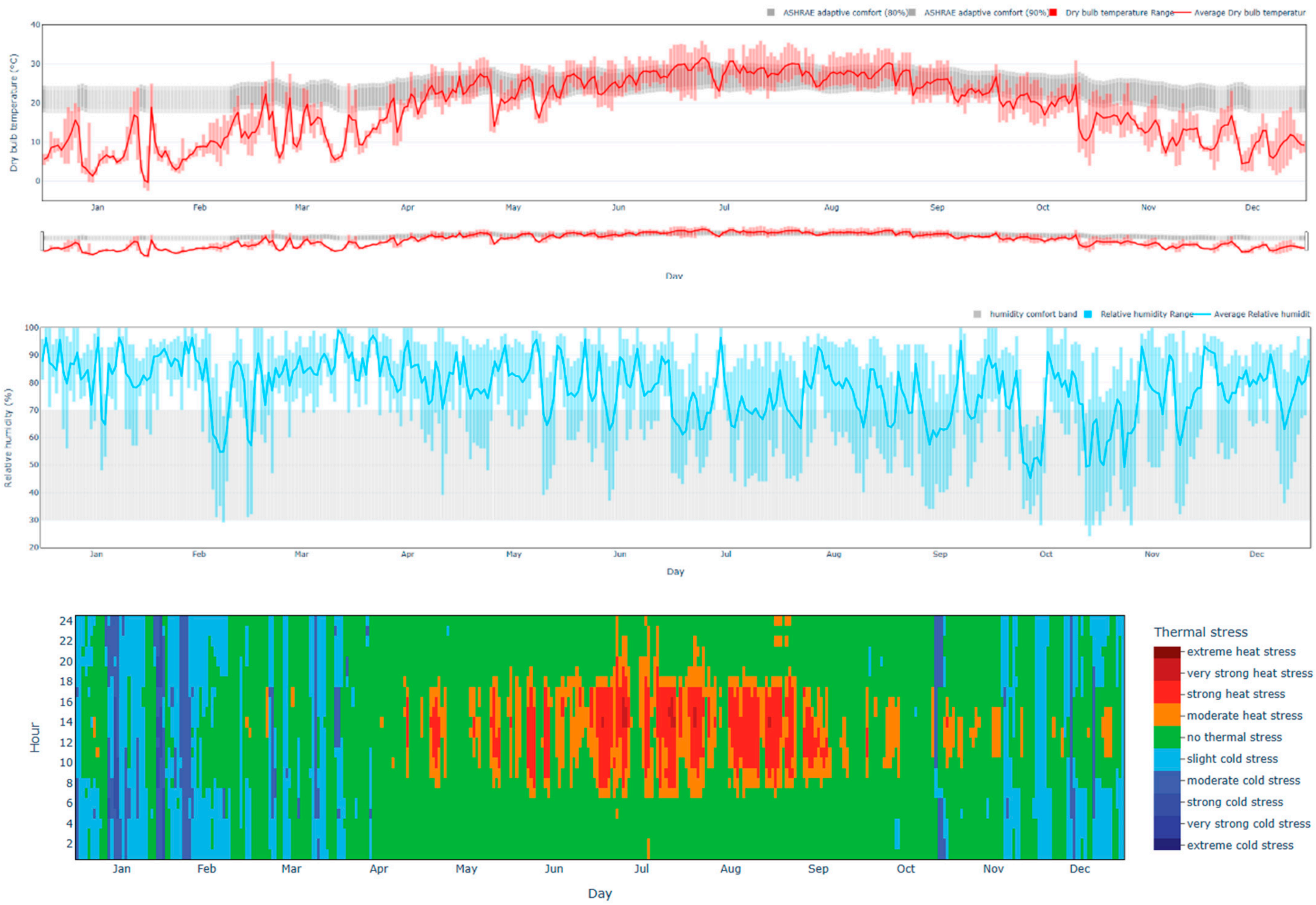
In the pilot project, some strategies were applied to investigate the feasibility and possibility in the context of the current situation, such as encouraging the elderly to participate and organize the construction of rammed earth houses in their villages to the best of their ability, using the recycled materials from existing buildings and excavated sites, proposing a cement-stabilized rammed earth technique combined with an aluminum formwork and using an electrical rammer to improve the building quality and construction efficiency.

The selected case projects have two main objectives: to help improve the housing quality and provide safe and comfortable accommodation for the village residents. Secondly, to explore step-by-step a sustainable development model that encompasses the village architecture's environmental, economic, and social dimensions. For the case selected for this study, a multi-stakeholder partnership model is proposed that involves examining the living and production habits of rural residents in the area, the types of resources available in the area, and the artisans experienced in construction. In addition, an analysis of the climatic conditions in the region revealed that it was rainy and humid throughout the year and that frequent rainfall in the region's mountainous areas is not conducive to rammed earth construction.

An analysis of meteorological data for Dao Xian County, the closest county to the site, was conducted using Berkeley's CBE tool [83,84], as illustrated in Figure 6a. In addition to the recorded outdoor temperature and humidity data for the site, the geographical location of the village was found to be consistent with the climatic patterns of cold winters and hot summers [85]. During the winter season when there is little rainfall, the average external relative humidity can exceed 85%. According to the on-site monitoring of microclimate date, as Figure 6b presents, these environmental conditions, characterized by high humidity levels and frequent rainfall [86], can pose a challenge to rammed earth construction.

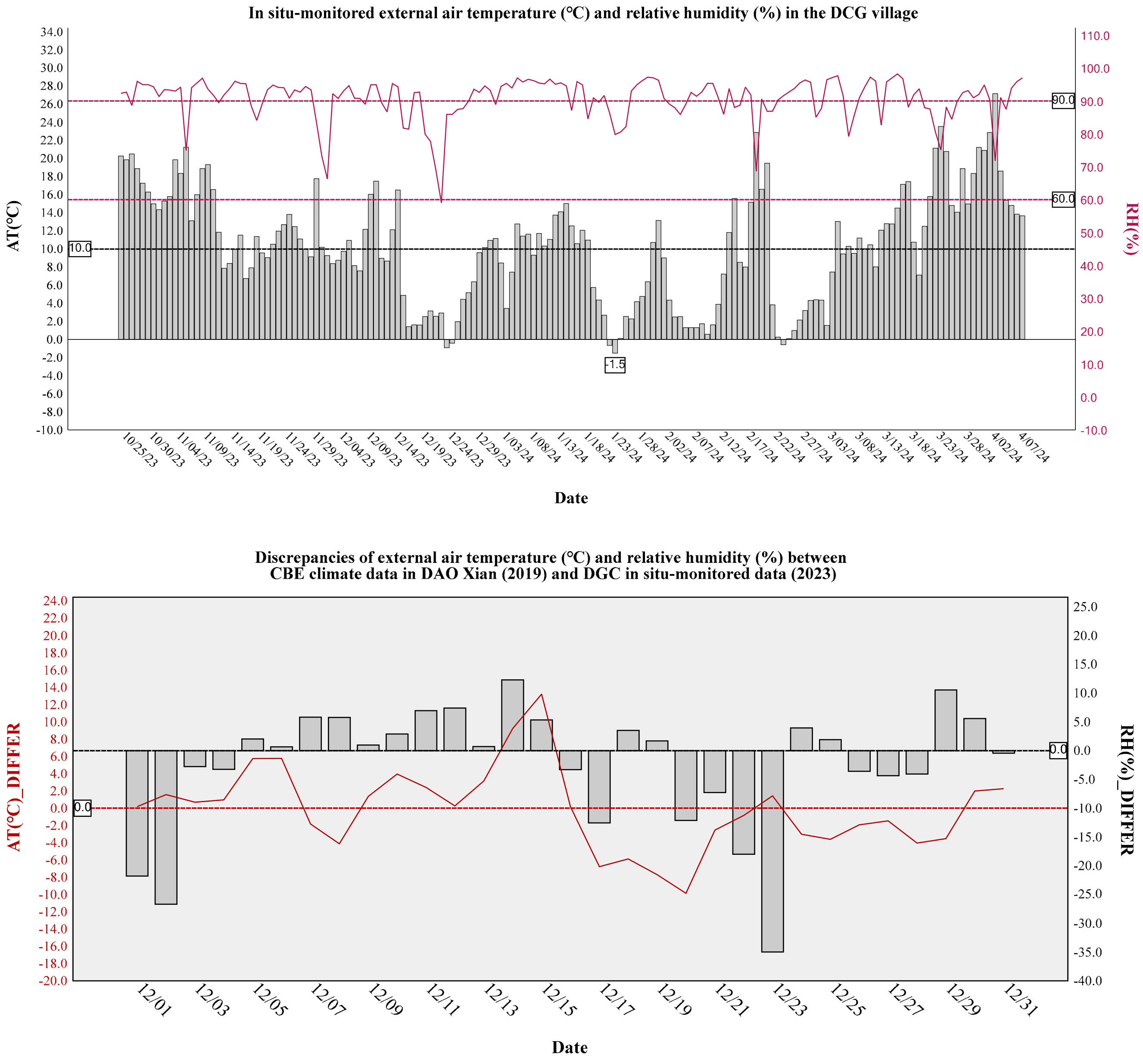
Traditional rammed earth structures are susceptible to erosion by rainwater; therefore, construction work must be carried out in dry weather with minimal interruptions due to rainfall. This requirement is usually met with two approaches: improving the inherent resistance of the walls to erosion by rainwater and constructing temporary shelters on site. As the village is classified as economically underprivileged and has limited technical resources, the cost-effectiveness of constructing rammed earth houses compared to conventional local brick and concrete buildings is paramount to increasing community interest. As the integration of temporary shelters would significantly raise construction costs by at least 50%, this solution poses an economic challenge. Therefore, in the context of the current socioeconomic situation in rural areas, prioritizing measures to improve the resistance of walls to rainwater erosion proves to be a more viable strategy for advancing construction successfully.

Figure 6 shows a comparable climate condition between the microclimate of the village and the climate data of the neighboring county concerning the CBE climate tool. Considering the frequency of climate changes in recent years, natural disasters and challenges are frequent in Chinese rural areas. Therefore, referencing the monitored microclimate data is more significant in analyzing the hydrothermal performance of renovated rammed earth houses in this case study.



(a)

Figure 6. *Cont.*



(**b**)

Figure 6. Microclimate data included external air temperature (°C) and relative humidity (%) from CBE climate tool and on−site. (**a**) is the climate data analysis derived from the CBE climate tool [84]. (**b**) Top is the outdoor temperature and relative humidity derived from in−situ monitoring by HOBO sensors in winter. Bottom is the discrepancies of external dry bulb air temperature and relative humidity between adjacent county's climate data from CBE climate tool, Daoxian, CHN, and the climate data monitored on−site in the village.

4. Results

This section may be divided into subheadings. It should provide a concise and precise description of the experimental results, their interpretation, and the experimental conclusions that can be drawn.

The internal structure of traditional rammed earth walls in the village, with many wood and bamboo strips embedded to ensure the strength and stability of the rammed earth walls, is analyzed. Based on the on-site observations, approximately 50% of the wall volume is estimated to be filled with bamboo strips, wood strips, and pebbles. Despite clear traces of ramming and scaffold installation, the construction technique resembles a fill-based wattle and daub method. The density and compressive strength of the existing rammed earth wall are relatively low. A step-by-step repair of the wall is not feasible due to the interlaced network of embedded strips throughout its structure, as Figure 7 shows.

Figure 7. The internal structure of the earthen walls in the village's traditional rammed earth buildings shows remnants of the traditional formwork and scaffolding used in construction.

Concurrently, the recently constructed cement-stabilized rammed earth wall was structured as a load-bearing entity using a mixture of soil, sand, gravel, and cement. This homogenously blended composition resulted in increased compressive strength of the earth wall of over 2 MPa as tested in the Kunming University of Science and Technology lab and in situ and adequately met the structural load requirements. No additional horizontal or vertical banding structural components were incorporated within the wall to maintain the material's compacted density. Owing to its point-by-point repairability, the wall can be repaired or reconstructed incrementally depending on where the damage is located, whether in the original construction or future maintenance work.

By analyzing the renovation process of existing houses and the construction process of new houses, it has been found that traditional earth-built walls are prone to collapse under high humidity and light rainfall. Figure 8a–c show the actual occurrence of the study case, where the existing preserved rammed earth wall collapsed unpredictably during the construction process due to the constraints of the construction conditions under the influence of natural rainfall. The construction site personnel adjusted the design of the collapsed earth material in light of the actual situation, remixed it, and completed the masonry. Figure 8d shows that the new rammed earth wall, with the addition of cement, can continue to be built so that it does not collapse even in high humidity, light rain, and a wet environment.

Mustafa and Al-Amoudi [13] provided a comprehensive analysis of the various factors affecting the use of earth as a building material, including adding stabilizers. Cement-stabilized rammed earth construction can, to some extent, enhance the strength of the soil. However, Mustafa and Al-Amoudi [13] also pointed out that the hydration of the cement destroys the original properties of the soil and can result in bigger environmental problems. This case study is based on a rural area with low resource allocation and low technology, where upgrading the quality of housing is the primary goal to be accomplished at this time. Although there is room for further optimization in the use of cement-stabilized rammed earth construction, compared to the practice of residents of randomly demolishing brick and reinforced concrete, the low cost of cement-stabilized rammed earth construction and the indoor thermal performance of cement-stabilized rammed earth construction, compared to that of brick and reinforced concrete, make them relatively optimal choices for the villagers in this area.

(**a**) (**b**) (**c**)

(**d**)

Figure 8. Water resistance performance of rammed earth walls with and without the addition of cement in a harsh construction environment and in high humidity and light rain. (**a**) shows the preserved existing rammed earth wall at the beginning of construction; (**b**) shows the collapse of an area of retained traditional rammed earth wall due to sudden rainfall during construction; (**c**) shows the re-mixing of collapsed earth wall materials and re-laying of masonry in the form of adobe bricks in the collapsed position, connecting the new rammed earth wall with the retained rammed earth wall; (**d**) shows the relatively high resistance performance of the new rammed earth wall in the face of a wet and watery construction environment.

This empirical observation presents qualitative evidence supporting the better water resistance of cement-stabilized rammed earth walls than unmodified raw rammed earth walls. From a construction organization perspective, this performance suggests a beneficial influence on rural construction behavior at the minimum management level through adopting more resilient practices, such as integrating cement into rammed earth.

In addition, in conjunction with the perspective of local people's living demand, a survey revealed that local villagers still adhere to a relatively traditional way of life, characterized by practices such as using rammed earth as indoor flooring, maintaining fire pits for cooking and preserving food, storing firewood both indoors and outdoors, and constructing dry toilets and bathhouses made of tree bark outside the main rammed earth structures, as shown in Figure 9. All activities associated with water supply, such as laundry, food preparation, and dishwashing, are carried out in outdoor areas adjacent to the main rammed earth buildings. These practices are necessary because the villagers are exposed to harsh environmental conditions that span extreme winters and summers, which are very uncomfortable for them. Most importantly, the villagers have foregone the conventional practice of indoor toilets because of concerns regarding the poor waterproofing performance of rammed earth structures. They have had to adjust their living habits and movement patterns to safeguard the integrity of the building walls. Therefore, adding cement to the earth wall and combining modern mechanized ramming methods greatly improve the strength and compacting density of the wall. The durability and tolerance of the interior space and wall structure are higher, to a certain extent, for the compatibility of traditional living habits as well as modern living habits between the old, middle-aged, and young generations of local residents.

Figure 9. Living habitats in the village studied.

The greater strength and water resistance achieved by incorporating cement into rammed earth walls represent a remarkable advance over conventional raw earth construction. However, despite these improvements, such walls are still poorly suited for shower rooms exposed to high humidity and water from washing activities over long periods. Therefore, it is imperative to undertake additional waterproofing measures for bathrooms.

Construction cost is another critical factor in evaluating the sustainability of adding cement to earth walls for housing improvements in rural areas. A comparative analysis was conducted on the rammed earth buildings of the collective properties and the brick houses constructed simultaneously in the same village. This study revealed differences between the new rammed earth buildings and the brick houses built by the villagers, apart from the influence of climatic factors on the construction efficiency of both types of buildings, as detailed in Table 3.

Table 3. The differences in time, cost, and labor input between cement-stabilized rammed earth (CSRE) construction and fired brick building in the same village.

Items	Cement-Stabilized Rammed Earth Building	Fired Brick Building
The launch date of construction	1 October 2021	1 March 2021
Date of handover	6 July 2022	31 December 2022
Story	2	3
Material cost/m^2 (CNY)	500	1000
Wall thickness (mm)	350	180
Daily average labor input	5	3

5. Discussion

This study analyzed the effects of using cement-stabilized rammed earth construction in rural areas of southeast China by using software simulations and case studies in parallel.

In rural areas of China, limited economic resources and underdeveloped infrastructure have hindered the adoption of modern technologies and construction materials to improve the overall standard of buildings. Despite these challenges, the long-standing cultural practice of using rammed earth dwellings and local beliefs have driven and welcomed technological advances in renovating rammed earth construction.

This study investigated the effects of implementing cement-stabilized rammed earth construction in rural southeastern China through a combination of software simulations and case studies. Challenges such as limited economic resources and lack of infrastructure have hindered the adoption of modern building technology in this region. Using rammed earth construction was critical to the project's progress, considering economic, social, cultural, and environmental factors.

With the clash between traditional practices and modern lifestyle preferences becoming more apparent across generations, the adoption of cement-stabilized rammed earth construction has emerged as a practical solution that addresses cost-effectiveness, convenience, comfort, and the preservation of local building customs. Analysis of simulation data and on-site construction evidence showed that using cement-stabilized rammed earth walls led to higher carbon emissions than traditional earthen construction, almost half that of a reinforced concrete frame system commonly used in the region. Moreover, despite the higher emissions, incorporating cement into the rammed earth walls resulted in a 50% cost reduction compared to building a house with 180 mm thick brickwork. In addition, this method improved the structure's resistance to sudden weather changes during the construction phase, surpassing the durability of traditional earth, brick, and reinforced concrete buildings.

This study relies more on integrating software simulations and site-specific studies to evaluate the cement-stabilized rammed earth construction holistically. This study shows that rammed earth construction with cement added is superior to traditional raw earth construction in terms of construction quality and technical durability and superior to reinforced concrete frame and brick masonry structures in terms of economic efficiency and environmental friendliness. However, looking at it from a broader perspective, adding cement is only suitable for regions with limited resources and technology, with an urgent need for safe housing and improving the overall environment. However, it is not the best solution for promoting the low-carbon development of buildings worldwide. As the economic level of rural areas rises, further investigation will inevitably be conducted into how to incorporate rural rammed earth construction into the raw earth construction and semi-fabricated assembly construction system. At the same time, how to collect and improve the database for software simulation through the continuous practice of rural rammed earth construction is worthy of more in-depth study.

6. Conclusions

Cement stabilizers are somehow workable for low-resource areas in particular economic and socio-cultural conditions. The environmental impact of adding cement to raw earth is inevitable. However, construction organizations' economic benefits and convenience formed a preliminary preference for those living locally to verify the urgency of living demand and ecological friendliness, which can be related to the conflicts between human-centered and nature-centered perspectives in a specific development context. This case study analyzed the necessity of cement stabilization in the context of low rural resources and rough living habits. The results proved to be adverse in terms of environmental performance but beneficial in their economic and socio-cultural aspects. Instead, exploring an eco-binder for future practice is necessary to decrease the dependence on cement further. At the same time, this can be achieved by simultaneously guiding and updating the living habits of local human beings and forming an intergenerational integration of habits to strengthen local people's awareness of the construction of low-carbon green buildings and to reduce waste and the demand for resources in their living habits, thus reducing the redundancy of the functional design of the building as well as the pursuit of decorative components that "have a face".

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