Economic Sustainability of Using Light-weight Hair Reinforced Clay in Partitions and Infills of Reinforced Concrete Buildings

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ABSTRACT

The construction industry is increasingly seeking sustainable alternatives to high-consumption raw materials and environmental impact. Lightweight Hair Reinforced Clay (LHRC), a composite material incorporating human hair fibers, has emerged as a promising solution. This study compared the economic sustainability, thermal efficiency, and structural seismic mass forces effect of LHRC against conventional hollow concrete block walls in 4, 7, and 10-multi-story buildings. The research used advanced structural analysis tools like Revit and ETABS to model and evaluate the performance of the two wall types mentioned. The findings showed that LHRC model significantly reduces structural weight, enhancing seismic performance by lowering the building's seismic mass forces by approximately 12.71%. Thermally, LHRC wall demonstrated superior insulation properties with a lower U-value of 0.244 W/m²K, significantly better than conventional concrete block wall with a U-value of 1.780. In comparison between LHRC walls with conventional hollow concrete block walls, the average percentage cost reduction was approximately 63.8%. This notable decrease highlights the LHRC wall system's economic benefits over conventional building wall method. Future research should standardize production techniques, verify long-term durability and performance under diverse environmental conditions, and explore its integration with modern construction methods like 3D printing and automated manufacturing processes.

Keywords: Light-Weight Hair Reinforced Clay, Sustainability, Fiber, Labor, Multi-Story Building.

ÖZ

İnşaat sektörü, yüksek tüketimli hammaddelere ve çevresel etkilere sürdürülebilir alternatifler arayışını giderek artırmaktadır. İnsan saç liflerini içeren kompozit bir malzeme olan Hafif Saç Takviyeli Kil (LHRC), umut verici bir çözüm olarak ortaya çıkmıştır. Bu çalışma, 4, 7 ve 10 katlı binalarda LHRC'nin ekonomik sürdürülebilirliği, termal verimliliği ve yapısal sismik kütle kuvvetleri etkisini geleneksel içi boş beton blok duvarlarla karşılaştırmıştır. Araştırma, iki duvar yönteminin performansını modellemek ve değerlendirmek için Revit ve ETABS gibi ileri yapısal analiz araçlarını kullanmıştır. Bulgular, LHRC modelinin yapısal ağırlığı önemli ölçüde azalttığını, binanın sismik kütle kuvvetlerini yaklaşık %12,71 oranında düşürerek sismik performansı artırdığını göstermiştir. Termal olarak, LHRC duvarı, 0,244 W/m²K'lik daha düşük bir U-değeri ile üstün yalıtım özellikleri sergilemiş, geleneksel beton blok duvarın 1,780'lik U-değerinden önemli ölçüde daha iyi performans göstermiştir**.** Hafif Saç Takviyeli Kil duvarlar ile geleneksel içi boş beton blok duvarlar karşılaştırıldığında, ortalama maliyet düşüş yüzdesi yaklaşık %63,8 olmuştur. Bu dikkate değer düşüş, LHRC duvar sisteminin geleneksel bina duvarı yöntemine göre ekonomik faydalarını vurgulamaktadır. Gelecekteki araştırmalar üretim tekniklerini standartlaştırmalı, farklı çevresel koşullar altında uzun vadeli dayanıklılığı ve performansı doğrulamalı ve 3D baskı ve otomatik üretim süreçleri gibi modern inşaat yöntemleriyle entegrasyonunu araştırmalıdır.

Anahtar Kelimeler: Hafif Saç Takviyeli Kil, Sürdürülebilirlik, Lif, İş Gücü, Çok Katlı Bina.

DEDICATION

This thesis is dedicated to:

My parents, Alhaji Yusuf Aliyu Umar and Hindatu Sulaiman, whose constant love, support, and belief in me are my most significant sources of strength and inspiration. Your sacrifices and belief in me have made this achievement possible.

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LIST OF SYMBOLS AND ABBREVIATIONS

h_i	Internal Surface Heat Transfer Coefficient
K_{eff}	Effective Thermal Conductivity *s*
Λ_i	Layers Thermal Conductivity
R_i	Thermal Resistance
R_{se}	External Surface Resistance
R_{si}	Internal Surface Resistance
R_{tot}	Total Resistance
T_e	External Air Temperature
T_i	Indoor Air Temperature
T_{si}	Indoor Surface Temperature
U	Thermal Transmittance
ETABS	Extended Three-Dimensional Analysis of Building System
FHRC	Foam Hair Reinforced Clay
LCA	Life Cycle Assessment
LHRC	Lightweight Hair Reinforced Clay

Chapter 1

INTRODUCTION

1.1 Background of The Study

After the food processing industry, the building sector is the second largest user of raw resources [1]. Materials are elementary stuff used in building construction [2]. The materials used in constructing the building should be sustainable for today and all future generations of the structure that is to be built [3]. This has led to an urgent requirement for the development of Alternative Building Materials which can aid us in meeting our structural needs while conserving on energy and material use [2]. The term 'alternative building materials' refers to those materials developed by combining unusual, traditional, or native components with conventional industrial materials. It is highly attractive for use in housing [4]. These materials often have low embodied energy, which frequently leads to lower embodied greenhouse gas emissions, low cost, widespread availability, ease of manufacture, and other advantages over conventional materials. It is due to these qualities that alternative housing technologies are attractive for use in both residential and humanitarian engineering projects in developed and developing countries [3]. A strict necessity has consequently come up for the need to invest in the use of cheaper and environmentally friendly material, and thus, the construction industry has a golden chance to reciprocate loan wise in regard to conservation of the environment. The making of sustainable material selections remains paramount in mitigating environmental impact of the materials. It ranks top five variables influencing the attainment of sustainable building to sustainable development [7]. A detailed examination of the elements shown in Figure 1 environment (natural resources, biodiversity, environmental loads, environmental tolerance, and environmental loads) will help one gain a deeper understanding of the idea of sustainable construction. socioeconomic and human factors (social stability, built environment, transportation, health, aesthetics, and cultural features); economy (market demand, life cycle economy, futurity values, construction process and management); and practical [3].

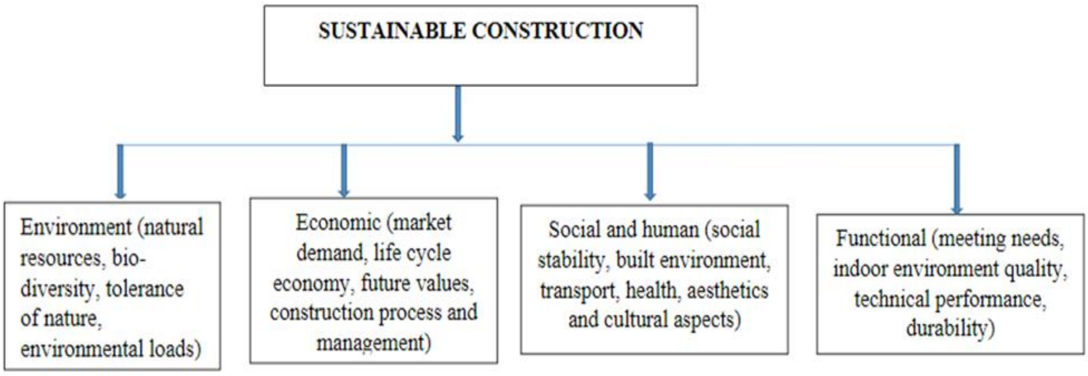


Figure 1: Sustainable construction's four primary facets [5]

One can explain, from Figure 1, the environmental elements of sustainable construction. This term means the elements of nature that need to be taken note of when building sustainably. This revolves around considerations that revolve around biodiversity conservation, use of natural resources, and the ability of the environment to withstand development and any environmental stress or artificiality that will arise from the construction. The second category includes economics in terms of environmental factors, including market demand for environment-friendly construction, life cycle economy reflecting building costs over time, whether construction, maintenance, or demolition, future values such as adaptive reuse or resale value, and dealing with the construction process and management that takes into consideration waste minimization and resource efficiency. The third one is the social and human one, and it relates to how the construction will affect the individual people as well as the community in general. This means considerations that involve the maintenance of social stability, built environment impact, transportation issues, health issues, aesthetic values, and mainly cultural components. Finally, there is the component of function. The later components deal with the aspects of sustainable building in relations to functionality and practicality. It ensures that the building has longevity, conforms to technical performance requirements, ensures quality indoor environment, and serves the purpose for which it was built. Moreover, they are domestic with fewer production and sourcing, hence saving on the expenses incurred in transportation and greenhouse gas emissions; they can be of reused products; they have a low environmental effect; they use less energy compared to the general materials due to thermal effectiveness; they use renewable resources; they emit less harmful emissions; and they are economical [3].

Hence, in the case of sustainable building, these natural materials are quite useful, therefore, the use of alternative building materials should not be put in a position that compromises on these 'blessings'. Therefore, there has to be consistent consideration in the design, matters of recycling, and building material selection [8]. The sustainable building material reduces the use of resources, as well as providing solutions for environmental problems, it becomes an imperative topic in modern architecture. Constructing buildings with provides a high-performance, environment-friendly approach to sustainable materials. The reason is that the industry involves a great deal of environmental impact due to resource depletion, high levels of energy use, and waste generation. Recycling, renewable inputs, low aggregate environment impact, and energy-efficient features in production are all desired characteristics of construction materials classified as sustainable. The concept takes into account the inherent characteristics of materials and a 'from-cradle-to-grave' approach in their life cycle. Life cycle assessment (LCA) is a fundamental tool that can enable an appraisal of the environmental impact of building materials through its life cycle [10]. Green building is in line with the use of building materials that are sustainable, either locally or imported. It involves the use of materials such as bamboo, recycled plastic, and low-impact concrete due to the low environmental impact and minimal use of resources. In general, they reduce the environmental footprint of buildings and improve performance in terms of indoor environmental quality and energy efficiency. The use of sustainable building materials in their construction is also economically advantageous. Building with sustainable materials can lower the costs of building over its life cycle; thus, preventing wastes and using less throw-away conventional, often more costly, goods. Besides, the rising market demand for green buildings has also reflected an economic opportunity to the suppliers and producers of sustainable materials [12]. Given these two requirements, LHRC combines traditional construction methods with the very latest technology developments. This is an upcoming trend in green building material. The first use of LHRC came on obsolete building techniques, where organic fibers used in building materials to increase their strength and durability. Indeed, hair is a process that has developed over thousands of years and LHRC is a state-of-the-art replacement that brings the past history of clay in construction to be reinforced with the mechanical properties of hair [13]. Since, by itself, most of the hair utilized is a waste by-product that would be thrown away anyhow, use of this as reinforcing material is not only innovative but also, to some extent, environmentally friendly. This technology is in line with the current environmental objectives, as it provides a lightweight building material with lower embodied carbon compared to many of the materials commonly used in construction today. General environmental impact from construction activities reduces since LHRC consumes less energy in its manufacturing process, which generally illustrates the green benefits of this product. The variety of applications today for LHRC is such that it proves to be flexible and efficient for a vast number of construction projects. It is being studied as a potential total revolution in the building business, from residential homes to community infrastructures, based on its insulation and durability features and the cost factor [14]. The importance of lightweight materials toward improving the resilience of structures under seismic activity is underlined by the study of Zaryoun and Hosseini (2019) on a new wall and ceiling system implemented using natural and recyclable materials, including LHRC. Their study found that if lightweight materials are used, they can achieve integrity and safety overall in an earthquake of the structure, as they can reduce the seismic stresses acting on the structure [17].

Despite its many benefits, LHRC is still relatively new in mainstream construction. It is imperative to address issues such as material quality certification, standardization of production processes, and increased industry acceptance. LHRC represents the convergence of innovation and tradition in sustainable building materials. Its transformation from outmoded reinforcing techniques to a state-of-the-art sustainable building solution emphasizes the importance of historical knowledge in addressing contemporary problems. As the construction industry looks for environmentally acceptable alternatives to standard materials, LHRC makes a compelling case for the benefits of sustainable materials in building a greener future. Research suggests that human hair fibers can significantly increase the bearing capacity and the shear strength of the clayey soil, they have the potential to be a sustainable reinforcing material [15]. Furthermore, it has been shown that incorporating natural fibers, such as sheep's wool and alginate, a polymer that naturally occurs from brown algae, into clay composites improves their compression strength and supports environmental sustainability [17]. For those looking for greater seismic resistance, lightweight fiber-reinforced clay LHRC has emerged as a material of choice due to its remarkable capacity to insulate against heat, sound, and moisture [18].

Furthermore, the effects of materials like concrete on transportation have a considerable impact on the overall environmental impact of construction [17]. The embodied energy of materials such as concrete and masonry is another key consideration. Studies have indicated that structural masonry has less embodied energy than traditional building methods [20]. The environment can benefit greatly from sustainable building approaches and see a gradual increase in value. Furthermore, cost-benefit analysis of building materials and procedures becomes crucial in the construction sector due to the influence of environmental economics on its economic dynamics [21].

As a major resource consumer and waste generator, the construction industry demands a transition to sustainable building approaches that include both environmental responsibility and structural integrity. This literature review goes into great detail on the production and application of sustainable building materials, paying special attention to the materials' effects on the environment, mechanical properties, and structural resilience particularly in seismically sensitive areas. Sustainable construction places a strong emphasis on the use of materials that minimize their negative environmental effects while maintaining their economic and social viability. Notably, LHRC is created by incorporating human hair and other natural fibers into clay matrices. This greatly increases the clay's compressive and tensile strengths, which are crucial characteristics for earthquake-prone areas [22]. LHRC has exceptional mechanical qualities, including as higher shear and bending strengths, which considerably strengthen building structural integrity and seismic resistance [22]. The construction industry has experienced a dramatic movement from conventional to sustainable building materials, which can be attributed to a number of factors, including technological advancements, changing environmental consciousness, and cultural influences. This development encourages environmental sustainability while providing new possibilities in modern design. Sustainable materials often outperform traditional materials, prompting a reevaluation of materials such as steel and concrete [23]. Furthermore, by employing the natural properties of wood, stone, and soil, natural construction systems encourage environmentally friendly behaviors. These elements remain crucial to modern sustainable design, just as they did to traditional building methods [24]. The research of sustainable materials has picked up speed, with a focus on how environmentally friendly they are and how well they work with modern building techniques. The use of recycled and bio-based materials is emphasized as a way to break the cycle of resources and enhance sustainability in construction [25]. Additionally, in order to maintain social responsibility and economic viability while minimizing environmental effects, it is essential to give priority to the use of sustainable building materials [26].

It may be possible to adapt a process-integrated manufacturing technique for incorporating sensor modules into composite structures to create a self-monitoring material for LHRC that enhances building lifecycle management and raises construction project responsiveness to maintenance needs. Advanced manufacturing methods, like 3D printing and automated fabrication processes, can precisely and efficiently create LHRC in complicated shapes, optimizing material usage, cutting waste, and boosting sustainability. Miniaturized silicon sensor systems could be included into fiber-reinforced composites to build multifunctional, structurally integrated monitoring systems, according to Arnold et al. (2019) [27]. These methods could be applied to LHRC to potentially produce flexible, intelligent building materials that respond to their environment.

1.2 Problem Statement

The recent advent of growing environmental concerns, coupled with modern demand for cost-effective construction supplies, has given rise to such sustainable and affordable alternatives to conventional building materials. However, LHRC is one of them but it has not been analyzed for its applicability, cost-effectiveness, or practical use against clients' needs. The study tries to provide this very comparative analysis between LHRC and traditional building materials to appease the increasingly demanding utilization for more environmentally friendly and commercially feasible RC multistory buildings, which are very common construction worldwide.

1.3 Aim and Objectives of the Research

The study aims to compare the economic sustainability of using light-weight hair reinforced clay wall with conventional concrete hollow block wall in multi-story reinforced buildings.

- To compare the construction cost of LHRC wall used as a partition or infills with conventional hollow concrete block wall in multi-story reinforced concrete building.
- To compare the seismic mass forces between building design with LHRC wall and conventional hollow concrete block wall.
- To compare the calculated U-value for the heat loss or gain of the two different wall system.

1.4 Research Question

How do lightweight hair-reinforced clay double-skin walls provide economic sustainable alternative for multi-story buildings rather than use of conventional hollow concrete block walls?

1.5 Scope of The Study

This study will examine the economic sustainability of lightweight hair-reinforced clay wall as a sustainable building material in reinforced concrete buildings. The comparison between a conventional hollow concrete block wall and a double-skin wall made of lightweight hair-reinforced clay will be made through the insulation effect, economic viability, and structural weight effect for the seismic resilience of the building. The design of 4, 7, and 10 multi-story buildings using Revit and the ETABS program will be used for the analysis.

1.6 Research Limitations

Although this study aims to offer a comprehensive overview of LHRC, it recognizes some limitations;

1. Data Availability: The investigation of unreported material properties and behavior of LHRC may be restricted by the dependence on accessible experimental data and previously published studies.
2. Modelling Restrictions: Despite their sophistication, the ETABS simulations might not fully represent the complexity of material behavior under seismic loads in the actual world. The results could be impacted by the material modelling assumptions.
3. Geographic Applicability: Areas where seismic activity and building methods are comparable to those simulated in the scenarios may find greater use for the

study's conclusions. The wider application of the findings may be impacted by differences in local building codes and practices.

4. Material Consistency: Because LHRC uses natural components, differences in material consistency and quality may affect how easily the study's findings can be repeated using different batches or suppliers of material.

1.7 Structure of the Thesis

The structure of the thesis is presented in form of chapters as follows:

Chapter 1

This chapter presents a comprehensive review of the construction industry's environmental impact, emphasizing the crucial importance of sustainable building materials. It recognizes the main research issue: a scarcity of comprehensive studies on the cost-effectiveness and sustainability of LHRC. The chapter explicitly states the purpose of the study, which is to compare LHRC to traditional building materials, notably concrete hollow blocks. It raises essential research questions to better understand the effects of double skin walls on the cost and self-weight of multi-story buildings subjected to seismic loads. The chapter further specifies the study's parameters, emphasizing the structural and economic feasibility of LHRC in reinforced concrete structures. It also recognizes possible constraints pertaining to data accessibility, modelling constraints, regional applicability, and material consistency.

Chapter 2

The review of the literature explores into the body of knowledge regarding sustainable building materials, emphasizing natural fiber reinforced clays in particular. It highlights the advancement and use of these sustainable materials in construction by following their material composition and historical development. The novel qualities of LHRC, such as its improved mechanical qualities, thermal efficiency, and general sustainability advantages, are covered in this chapter. It also identifies important roadblocks to the broader implementation of LHRC, including obstacles to industry acceptability, legal concerns, and technical difficulties. In order to address these issues and validate the useful applications of LHRC in contemporary construction, the chapter ends with recommendations for future research.

Chapter 3

The study design and methodological strategy utilized to compare LHRC's performance with conventional materials are described in this chapter. It describes the comparative analysis method, which makes use of sophisticated modelling and structural analysis tools like Revit and ETABS in architecture and engineering. The chapter presents a detailed comparison of the LHRC double skin walls and traditional concrete hollow block walls, as well as an explanation of the materials and structural designs used in the study. It describes the analytical techniques used to evaluate a number of factors, such as cost-effectiveness, thermal transmittance (U-value), and structural performance under seismic loads. The methodological section highlights the methodical steps required to guarantee accurate and trustworthy comparisons between the various building materials.

Chapter 4

The research's main conclusions are presented in the last chapter, which also includes specifics on how LHRC was able to reduce structural weight, save cost, and increase thermal performance. It talks about the structural performance, emphasizing how buildings that use LHRC have lower seismic mass and more seismic resistance. Significant financial gains are shown by the cost analysis, including a notable drop in labor and material expenses. The reduced thermal transmittance (U-value) of LHRC, which suggests its potential for enhancing building energy efficiency, is covered in the thermal performance section.

Chapter 2

LITERATURE SURVEY AND THEORETICAL BASIS

2.1 Overview of Building Materials in Sustainable Construction

Due to the building industry's high resource consumption and waste output, it plays a significant role in promoting environmental sustainability. As a result, the requirement for environmentally friendly building materials has increased, with the aim of maintaining social responsibility and economic viability while minimizing the negative effects on the environment. Sustainable development in the construction sector aims to balance among social responsibility, ecological responsibility, and economic viability. Its main focus is on reducing energy use, greenhouse gas emissions, and natural resource depletion during the construction and operating stages. Ding (2008) discusses the importance of environmental evaluation techniques in the building industry to improve sustainability results. From the very beginning of a project's development, these instruments guide sustainable practices [26]. Research that discusses how the use of conventional building materials has a significant negative impact on environmental sustainability and how, over time, using sustainable alternatives that match or even surpass performance standards can result in financial savings [6].

"Natural construction" is now used as a blanket term over the range of building techniques: Not only wood and stone, but soil and even representative building materials that got most in vogue long after the earliest building techniques were already developed, since they were the raw material of the first constructions at the time when the dawn of construction was being completed, natural building techniques were used for a very long time. The use of natural materials like stone, wood, and dirt characterizes them. They are of an outstanding level of construction and clearly show the importance and preference that produces natural still have in construction, bearing in mind that over one-third of the world's population still lives in homes with walls of unbaked soil. This shows that a critical need arises for using natural materials in establishing sustainable and ecologically sensitive construction techniques [24]. Building materials have changed dynamically over time, accounting for changes in environmental awareness, technological advancements, and cultural influences. Traditional materials have given way to modern alternatives. Natural resources like wood and stone were often used in early building techniques because of their affordability and inherent features. However, new materials like steel and concrete emerged as construction technology advanced, revolutionizing the industry by making it possible to create larger, more complex structures [28].

Research on the use of sustainable materials or materials with special benefits for building sustainable architecture has accelerated in the current decade, and particularly in the previous few years. In 2010, Wadel Raina and companions [25] Shut down the cycle of materials, Industrialized Architecture's Sustainability. Sustainability is defined by them as the closing of the material cycle from a physical standpoint. This is achieved in predefined systems with constant resource recycling and no residual fluxes. They have stated that these systems may encounter major difficulties in the productive paradigm that the majority of contemporary enterprises adhere to, based on this definition. One of the sectors that still utilizes the greatest number of materials is construction. based on a 2012 study on sustainable building and architectural materials by Van Wyk and colleagues [29]. They claim that increased government investment in infrastructure, increased investment in the residential and commercial sectors, increased financial market liquidity, a drop in interest rates, and ongoing industrialization in developing countries will be the primary forces behind future material growth. What Fernandes et al. (2015) [30] described as vernacular Portuguese architecture was the use of traditional materials and design concepts in the environmentally friendly. All they have argued is that it is a type of formal expression cultivated as a reaction to many factors geographical, climatic, economic that define a local area or region. Additionally, they have claimed that Portuguese vernacular customs could be updated to better suit contemporary needs and that there is always space for development.

LHRC provides a wealth of research opportunities in the field of sustainable building materials, particularly considering the present economic and environmental challenges that the construction industry is experiencing. This branch of study looks into how to improve the mechanical properties and environmental impact of traditional building materials by incorporating waste and natural fibers like human hair into clay mixtures. Son, et al., (2015) [22] look at the possibility of enhancing the tensile characteristics of clay soil with the addition of hair fibers. The findings indicate that hair fibers significantly increase the compressive and tensile strengths of building materials, indicating that they may have greater structural integrity. This bolsters the viability of LHRC as a sustainable replacement, offering comparable benefits such enhanced material performance and waste minimization.

2.2 Historical Development and Material Composition

The historical development of natural fiber reinforced clays over several decades indicates a growing interest in sustainable materials across a range of industries, particularly civil engineering and construction. This interest stems from the growing need for environmentally friendly materials that reduce reliance on artificial, non-renewable resources. The first studies on natural fibers focused on traditional uses, such as adding straw and horsehair to bricks and other clay-based building materials for flooring. Future advancements in fiber reinforcing were made possible by this process. By the 20th century, natural fibers, including a range of plant-based fibers, were being integrated much more frequently into clay-based composites in an effort to enhance their mechanical properties. According to Brandt (2008) [31], the shift from simple mechanical reinforcement to an essential component of sustainable material development highlights the coexistence of traditional methods with state-of-the-art engineering breakthroughs.

While researchers focused on improving the mechanical performance of these composites in the early years of the twenty-first century, additional advances were noted. Chegenizadeh and Nikraz (2011) [23], demonstrated that variations in the length and composition of the fibers might have a significant impact on the strength and ductility of fiber-reinforced clays, providing a means for more specialized and effective applications in the building sector. One notable development in this field is the recent establishment of LHRC. Researchers have developed a composite that offers a new reuse of human waste while simultaneously satisfying the criteria for green construction materials. The renewable resource of human hair is incorporated into this composite. This innovation is a continuation of historical practices infused with modern technological advancements, according to a thorough analysis by Faruk et al. (2014) [32], which highlights the financial advantages and lower environmental impact of using natural fibers over synthetic alternatives.

LHRC is a significant advancement in building materials that attempts to increase the sustainability and resilience of structures. Its composition includes a significant number of natural fibers, especially human hair, which have been demonstrated to significantly improve the mechanical properties of clay. To increase the clay matrix's ductility and structural integrity, human hair is added. Its toughness and great tensile strength make it useful. The material can exhibit greater compressive, shear, and bending strengths as a result of this reinforcement, which makes it ideal for seismic applications [17]. The clay used in LHRC is chosen because of its lightweight properties, which help reduce the overall structural load and, consequently, the seismic forces applied to structures during earthquakes. For even fiber distribution and optimal performance in composite materials, clay types that work well with natural fibers and additives should be used. Several stabilizers and additives are used in LHRC's recipe to further enhance its efficacy. The use of natural pozzolans and recovered plastic waste not only increases the environmental longevity of the clay but also improves its thermal and acoustic insulation properties. For instance, the inventive wall system designed by Zaryoun and Hosseini [41], features a double-skin hollow core structure with reinforced clay covering the outer skins produced from waste plastic that has been recovered. This highlights not only the use of sustainable resources in its design but also the material's conformity with modern building requirements that place a high focus on the economic sustainability.

2.3 LHRC As an Innovative Material

For a very long time, hair has been utilized to strengthen soil, particularly clay. In fact, hair has long been and continues to be a part of Sarooj, a traditional reinforced mortar that has been utilized in many countries like Iran for a very long time. Lime (35%), sand (40%), ash (20%), and clay (5%), which is usually reinforced with goat hair, are the constituents of sarouj [33]. Also, this cement was utilized as a plaster covering for water cisterns and bathtubs. Prior studies have demonstrated the remarkable robustness and durability of human hair [34]. Additionally, studies have demonstrated that a modest addition of human hair to clay can significantly improve its mechanical qualities and reduce its heat conductivity [35]. In an experiment that the insertion of sporadically spaced short fibers can effectively prevent the formation of desiccation fractures in clayey soils. Additionally, as shown by the test findings, the fibers provide the clay a ductile behavior and enhanced tensile strength that the fiber-free samples lacked [36]. Mulder-Heymans (2002), who also described the Tannur, a traditional Syrian bread oven constructed of clay coupled with burlap, goat and human hair, and grit and fashioned nearly like a hollow cylinder, said that reinforced clay is also extremely fire resistant. He said that the processed clay's enormous weight prevented water from passing through it with ease. Tannurs, on the other hand, were directly exposed to fire every day in order to make bread, and their useful life ranged from 10 to 25 years, depending on their thickness [37]. The rim of this particular wheel is tied together by a mixture According to a study by Gupta (2008), the rim of this specific wheel is bound together by a combination of clay, creepers, ropes, goat, and human hair. The study claims that the oldest wheels are still in use today and are composed of clay that has been baked in the sun. The breakdown strength values of insulators constructed of human hair, coir, and sisal at room temperature are 134.5 kV/cm, 52.92

kV/cm, 22.93 kV/cm, and 20.31 kV/cm, respectively, according to Michael et al.'s 2010 study [39]. Then, the potential strength values attributed to preventing breakdown at cryogenic temperatures for bananas, glass fiber-reinforced plastics, coir, sisal, and human hair were 177.86 kV/cm, 118.99 kV/cm, 120.84 kV/cm, 127.67 kV/cm, and 102.29 kV/cm, respectively. This could also point to the fact that natural fiber composites might work well as cryogenic dielectrics. The process to enhance the soil qualities by applying HHF was developed by Pillai and Ramanathan (2012). It was discovered that the unconfined compressive strength of unreinforced soil samples increased with the addition of 2.0% HHF fibers by weight. The composites' increased ductility was demonstrated by the stress-strain curves. These findings led them to the conclusion that cohesive soils can be efficiently strengthened by HHF [52].

2.3.1 Economic Sustainability Evaluation of LHRC

It is proposed that LHRC be used as a robust and sustainable building material, especially in places that are vulnerable to disasters. This material offers economic advantages and environmental friendliness. Low-cost, easily accessible materials like recycled plastic trash and natural fibers (like animal or human hair) are used in LHRC. Since these items are frequently regarded as waste, the total cost of resources is decreased. Utilizing recycled materials reduces waste and fosters a circular economy, both of which have long-term positive economic effects. Because LHRC is lightweight, handling and transportation expenses are decreased. On building sites, labor and time costs can be decreased by using prefabricated sections manufactured of LHRC, which can be installed and transported with ease. Because LHRC is so easy to work with, building may go more quickly, thus cutting labor expenses. Due to its superior insulating qualities, buildings may be heated and cooled with much less energy, which lowers building owners' and renters' long-term energy costs. Over the course of a building's life, improved thermal performance helps to reduce operating expenses [17]. Because of LHRC's exceptional resistance to fire, moisture, and sound, it lasts longer and requires fewer replacements or repairs more frequently, which lowers maintenance expenses. Future renovation expenses can be avoided by using LHRC in moveable partitions and adaptable architectural designs, which can adjust to changing needs without requiring significant reconstruction. The cost-effectiveness, lower construction and maintenance expenses, and energy efficiency of LHRC are key components of its economic sustainability. This material is an appealing choice for upcoming construction projects because it not only promotes sustainable building practices but also has substantial financial advantages [41].

2.3.2 Energy Efficiency and Thermal Performance

Traditional building materials like clay and concrete bricks have long been the cornerstone of construction because of their durability and strength. Their U-values, or thermal transmittance, often do not meet the current energy efficiency standards in the absence of additional insulation. For example, the U-values of concrete blocks typically vary significantly depending on the composition and if insulating materials are present. Geem (1985) noted that the kind of insulation material, such as expanded polystyrene or perlite, had a significant impact on the U-values for concrete block walls with core insulation, which varied greatly. According to the experiments, empty core concrete block walls with lower U-values benefit more from core insulation than do walls with higher U-values. The heat transmittance was reduced to 49% or more when core insulation was added to a concrete block wall that measured 12 inches (300 mm) in length. This reduction also occurred while testing walls with block densities smaller than 100 pcf (1600 kg/m3) [42].

The paper by Evangelisti et al. applies to subjects dealing with rather critical issues between modeled and actual thermal behavior of building walls: "In situ Thermal Transmittance Measurements for Investigating Differences between Wall Models and Actual Building Performance" (2015). The study uses an electro-thermal analogy, which is likened to one-dimensional heat flow across a series of resistors to represent the layers of a wall. This comparison works well for walls composed of homogeneous materials and is compensated for inhomogeneity using an effective conductance technique, especially for materials like hollow bricks. The authors measure in situ across various wall stratigraphy's using a heat flow meter, and then they compare the results with the theoretical thermal transmittance values calculated in compliance with UNI EN ISO 6946 [44]. The results emphasize the limitations of relying solely on theoretical models lacking empirical evidence by demonstrating significant disparities between the calculated and observed values. This discrepancy emphasizes the necessity of updating standard computation techniques to more accurately represent the performance of buildings in real environments and more accurately predict energy consumption [43]. UNI EN ISO 6946 prescribes a method for checking the thermal transmittance and thermal resistance of a building component by considering the electrical analogy. The calculated value of the thermal resistance of the wall was a sum of resistances, resulting from a series of resistances due to each single layer [44]:

Equation 1. Thermal Resistances.

$$R_i = \frac{d_i}{\boldsymbol{\lambda}_i}$$

Equation 2. Total resistance

$$R_{tot} = R_{si} + \sum R_i + R_{se}$$

Equation 3. Thermal transmittance

$$U = \frac{1}{R_{tot}}$$

where U is the thermal transmittance, R_{tot} is the total wall thermal resistance, which comprises the resistances of the internal and external surfaces, R_{si} and R_{se}, and di is the thickness of the i-th layer. λ_i is the layer's thermal conductivity [44].

For comparable energy efficiency levels, conventional materials with higher thermal conductivities, such as concrete and clay bricks, generally require more insulation. For instance, studies on concrete blocks have shown that, while insulating components can improve the blocks' thermal performance, these modifications are necessary to achieve energy efficiency standards. Geem (1985) [42], noted that the type of core insulation a concrete block wall had might have a significant impact on its U-value, indicating a range of potential for energy conservation. On the other hand, adding natural fiber, such as hair, can alter the thermal behavior of ordinary clay bricks. Goodhew and Griffiths (2005) investigated the thermal performance of unfired clay bricks supplemented with natural fibers, such as straw, and discovered that the bricks' U-values were significantly lower than those of regular bricks. These outcomes complied with UK building regulations. These findings show that stringent energy requirements can be met with natural and repurposed materials without compromising environmental sustainability. slender hair Reinforced clay, which is identified by the addition of natural fibers like hair to the clay, has better thermal properties. This modification to the traditional clay composition significantly improves insulation, which is necessary to reduce the amount of energy used in construction. To reduce thermal conductivity and increase thermal resistance while lowering density, natural fibers are mixed into the clay matrix. Goodhew and Griffiths (2005) found that walls constructed with unfired clay bricks and natural fibers such as hair and straw can attain thermal transmittance values much lower than those required by UK Building

Regulations. This suggests that the walls could increase insulation, which would reduce the need for heating and cooling in buildings. Conversely, recently developed materials with improved thermal performance, such as broken brick and polystyrene blocks with recycled content [45]. Krstić et al. (2021) looked into the thermal transmittance of lightweight concrete blocks with recycled materials. The results showed decreased U-values ranging from 1.363 to 1.782 W/m²·K, indicating their potential to improve building energy efficiency. By reducing waste, these materials improve building thermal insulation and advance sustainability. In their investigation, the following techniques were employed to determine the wall's thermal properties: The Heat Flow Method was used to calculate the wall's thermal transmittance (U-Value); c) The relatively new and simple non-standardized Temperature Based Method was also used to calculate the observed wall's U-value. a) Infrared thermography (IRT) was used to search for possible thermal bridges in the wall. Figure 2 depicts blocks that include ground expanded polystyrene (RBC-EP) with recycled crushed brick aggregate (RCC). The dimensions of each block are detailed. The U-value was obtained from the equation [46].

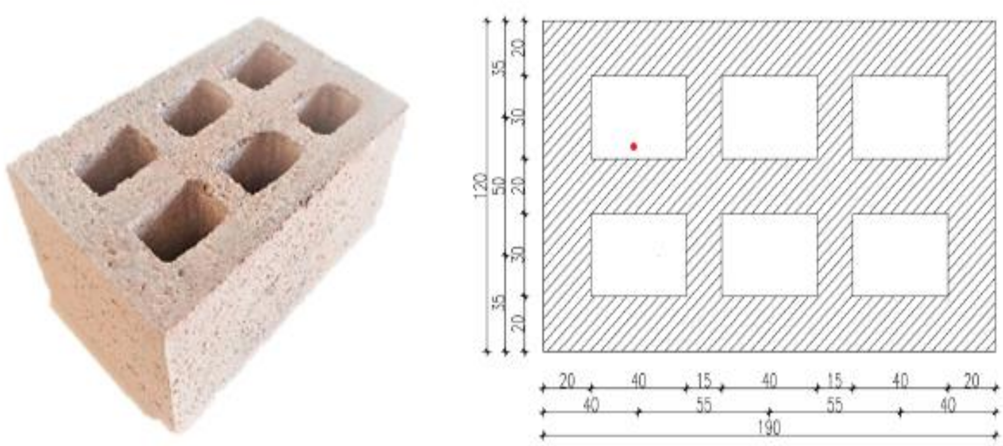


Figure 2: Block image (a) concrete masonry block, (b) Dimensions in millimeters [46].

Equation 4. Temperature base method (U-value)

$$U = h_i \frac{T_i - T_{si}}{T_i - T_e}$$

where T_i is the indoor air temperature, T_{si} is the indoor surface temperature, T_e is the external air temperature, and h_i is the internal surface heat transfer coefficient.

Table 1. shows the comparison between new masonry blocks made from recycled clay brick and regularly used blocks on the market with respect to the thermal conductivity values and material qualities used in the research.

Table 1: Properties of New Masonry Blocks Made from Recycled Clay Brick Are Compared with Those of Regularly Used Blocks Found in The Market [46].

Type of Block	**Hollow Clay Blocks (HCB)**	**Lightweight Concrete (LWC)**	**Concrete Blocks (CB)**	**Recycled concrete Brick/ Ground Polystyrene (RBC-EP)**
Dimensions (mm)	250 × 190 × 190	625 × 200 × 100	200 × 200 × 400	190 × 120 × 90
Normalized Compressive Strength (MPa)	6.51	2.60	6.50	2.99
Thermal Conductivity (W/mK)	0.4800	0.3700	1.4000	0.3789
Weight (kg/unit)	14.00	10.00	17.00	2.50
Overall Mass of 1 m³ of Wall (kg)	1554.00	800.00	1071.00	1220.00

In addition, lightweight concrete blocks created from recycled components exhibit a discernible reduction in heat transmission. Krstić et al. (2021) discovered that the utilization of recycled crushed brick and ground polystyrene in concrete blocks not only enhanced the blocks' thermal efficiency, leading to lower U-values and better energy-saving capabilities, but also made use of waste products [46].

2.3.3 Cost-effectiveness Analysis

This highlights the role that LHRC plays in passive design strategies intended to reduce operating energy consumption, hence highlighting the importance of LHRC in green building practices. The utilization of fly ash waste and human hair fibers to reinforce soil in advance of land reclamation and embankment construction projects is examined in Rekha, et al (2016) study. Their study indicates that incorporating human hair fibers into soil-fly ash mixtures significantly boosts strength and is a useful technique to improve soil properties and potentially lower construction costs [47]. Further research on soil reinforcement with human hair fibers and chloride compounds by Sharmila, et al. (2019) supports these findings. According to their research, these additives enhance the engineering properties of clayey soil, which makes it a cheap and readily available material for construction projects requiring soil stabilization [48]. Additionally, their research indicates that human hair fiber significantly enhances soil properties, opening the door to affordable and ecologically friendly construction methods, especially in regions with poor soil quality [15].

An important study by Butt, et al (2016) investigate the strength nature of clayey soil reinforced with human hair, an essential component of long-hair reinforcing cement. Their findings indicate a significant improvement in the carrying capacity and shear strength of the soil, which are critical for the structural integrity of foundations and other construction components. Human hair is a waste product that can be reasonably priced utilized to create building materials instead of being thrown away. In addition to improving environmental sustainability, this would save money on raw materials [15].

2.3.4 Structural Performance and Seismic Resilience

The mechanical properties and durability of lightweight concrete made from Tunisian expanded clay were described by Nawel et al. in a 2017 study. After analyzing the impacts of various clay types and processing temperatures, they discovered that using lightweight expanded clay aggregates maximizes the mechanical properties and durability of concrete. These results might benefit LHRC in a similar way [49]. Further details are given by Mohseni et al. (2019), who assessed the mechanical and long-term properties of fiber-reinforced lightweight geopolymer composites based on rice husk ash and nano-alumina. The investigation's findings demonstrated that while polypropylene fibers enhanced flexural strength, the addition of lightweight aggregates somewhat reduced compressive strength. The balance between the fiber and aggregate content is crucial for composite materials such as LHRC to have the best mechanical characteristics [50]. The seismic performance of LHRC buildings, particularly when compared to traditional materials, should be taken into account when determining whether or not they are appropriate for construction in earthquake-prone areas. Numerous studies have examined this component, shedding light on the materials' durability to earthquakes and mechanical stress.

Imran and Aryanto (2009) evaluated the performance of reinforced concrete (R/C) frames filled with lightweight materials, such as autoclaved aerated concrete (AAC), to frames filled with conventional clay bricks under seismic loads. Their findings indicated that frames containing AAC exhibited better in-plane behavior, stronger, better deformation properties, and enhanced energy dissipation capacity. Since the properties of lightweight hair clay are comparable to those of AAC, LHRC offers a number of benefits [52].

Vandanapu and Krishnamurthy (2018) examined the seismic response of a six-story reinforced concrete frame using lightweight concrete. The lightweight concrete's lower density compared to the other one resulted in decreases of 15% and 20%, respectively, in bending moments and shear forces. Their analysis showed that because the reduced density significantly decreased the seismic pressures acting on the structure, its overall seismic performance was improved [53]. Khandare and Jaiswal (2019) investigated the seismic performance of conventional and lightweight concrete structures. They analyzed the benefits and drawbacks of using Autoclaved Aerated Concrete (AAC) blocks instead of traditional clay brick masonry. They found that buildings containing AAC blocks sustained less damage during seismic events, suggesting that LHRC might be equally beneficial in seismic zones [54].

For the first time, Mandal and Gupta (1994) looked at the carrying capacity and stability of buildings composed of clay reinforced with hair. Their investigation of geocell-reinforced soft soil buildings showed significant gains in load-settlement characteristics and higher bearing capacity as a result of the reinforcement, similar to hair-reinforced clay setups. This suggests that hair fibers might provide similar benefits, enhancing the clay constructions' structural stability [55]. In 2002, Unnikrishnan, et al., examined these materials' dynamic reactions under load in more detail. Improved strength and deformation behaviors under both static and cyclic loading conditions were demonstrated by their research on reinforced clay [56]. In 2019, Basson and Ayothiraman conducted a study to investigate the behavior of clay soils reinforced with human hair fibers during shrinkage. Their trials' results demonstrated that, except from a significant modification and decrease in fracture propagation, hair fibers perform similarly to synthetic fibers like polypropylene. This characteristic is crucial for prolonging the lifespan and practical application of hair-reinforced clay in construction, as it mitigates structural breakdowns caused by drying and additional environmental factors [57].

2.4 Barriers to Wider Adoption and Operational Challenges

Despite all of LHRC benefits for sustainable building, there are still technical difficulties that may keep it from being extensively used in the construction industry. These include issues with compatibility with other building materials, consistency, and resilience in various climates. In their 2015 study, Neramitkornburi et al. examined the durability of lightweight materials, such as cellular cemented materials, under wetting-drying cycles. The study states that the material's strength and long-term endurance may be compromised as a result of structural degradation over time [58]. This degradation highlights the need for greater research to strengthen the resilience of LHRC, which raises serious concerns about using it in environments with frequent or severe moisture changes. Another important consideration is the variety in mechanical properties of LHRC that may arise from the intrinsic heterogeneity of the hair fibers used for reinforcement. In another investigation, they noted that issues with compaction behaviour could lead to higher compressibility and variability in structural performance, which may explain the observed disparities. This version highlights the need for strict quality control measures to be used at every stage of the production process in order to ensure consistent quality in the final product [58].

Before employing innovative materials like LHRC in conventional construction, a number of concerns and considerations must be made after analyzing the regulatory framework surrounding them. Following building requirements, environmental regulations, and integrating innovative materials into traditional construction techniques are important topics. Environmental limitations are significant because they affect the utilization of cutting-edge building materials like LHRC. Sustainability in building materials is being scrutinized more thoroughly, and LHRC must demonstrate that it has no environmental impact at all during its life. Neramitkornburi et al. (2015) stress the significance of doing in-depth study on emissions and resource utilization in their discussion of the environmental evaluations required for materials like LHRC. They also look at the technological aspects of lightweight cellular cemented materials, which are similar to LHRC and provide information on potential compatibility issues. Building codes usually lag behind in adopting novel materials like LHRC since they are primarily based on conventional materials with established properties and long-term performance data [58]. Heiza, et al. (2017) point out that new standards must be developed or existing ones must be adjusted in order to ensure safety and efficacy when incorporating new materials like LHRC [59].

Later, Heiza, et al. (2017) talked on the financial factors impacting the adoption of innovative materials like LHRC. They argue that in order for LHRC to become more widely accepted, it needs to be both financially feasible and meet or exceed the performance and sustainability requirements set by previously utilized building materials [59]. Zaryoun and Hosseini (2018) also examined the advantages of LHRC, including its resilience to earthquakes and other natural disasters. They note that despite its benefits, the adoption of LHRC is often hampered by inexperience and the upfront costs associated with switching to new materials. According to their research, increasing awareness and supplying proof in the form of successful case studies might increase the acceptance rates among building experts [41].

2.5 Future Research and Technological Advancements

With the potential to significantly advance sustainability within the global building sector, Lightweight Hair Reinforced Clay is a significant step toward more environmentally friendly building practices. Lightweight and insulating materials are crucial for reducing building energy consumption, as heating and cooling systems contribute significantly to a building's lifecycle carbon footprint. Moreover, LHRC contributes to the construction of more earthquake-resistant buildings, which is essential for sustainable urban development. In keeping with global sustainability targets intended to reduce the risk of catastrophes and promote urban environment safety, Zaryoun and Hosseini (2018) discuss how structures made of LHRC provide higher resilience to disasters [41].

Building environmental and structural health monitoring could be completely changed by integrating smart sensors into LHRC constructions. Piezoelectric sensor integration, for instance, might make it easier to collect stress and vibration data in real time, which is crucial for maintenance and safety assessments. A publication by Geller and Gude (2015) describes a process-integrated manufacturing method for incorporating sensor modules into composite constructions; this technology could be adapted for use in LHRC. Because of this relationship, LHRC has the potential to function as a self-monitoring material that enhances building lifecycle management and makes construction projects more responsive to maintenance needs [60]. Furthermore, because to advanced production techniques including automated fabrication processes and 3D printing, LHRC may be created in complex configurations with remarkable precision and efficiency. This capability allows for customized architectural applications while optimizing material use, reducing waste, and boosting sustainability. Arnold et al. (2019) claim that miniaturized silicon sensor systems can be included into fiber-reinforced composites to produce multifunctional, structurally integrated monitoring systems. It might be able to develop more flexible, intelligent building materials that respond to their environment by applying these strategies to LHRC [27].

2.6 Summary and Research Gap

The literature study delves further into the application of lightweight hair-reinforced clay as a sustainable building material, emphasizing how it can revolutionize the building construction industry by harnessing its benefits in the financial and environmental domains. This innovative material, which combines natural fibers like human hair with clay, may be able to replace conventional building materials like gypsum and bricks due to its lower environmental effect and usage of recycled materials [6]. Even though LHRC has several advantages, like the capacity to reduce construction waste and enhance building insulation, there are still a number of research gaps that need to be filled. First and foremost, it is obvious that LHRC needs to be standardized and approved in order to promote its integration into mainstream construction. This would need the creation of certificates for standardized production processes and material quality, both of which are lacking at the moment [15]. Furthermore, although early studies on the mechanical properties and environmental impact of LHRC produced promising findings, there are few long-term performance data under varying climate conditions. These statistics are necessary to determine the dependability and durability of LHRC relative to more traditional materials [16]. Moreover, there has not been a comprehensive study done on LHRC's seismic resilience. More extensive research is required to validate its effectiveness in enhancing its integrity and safety in earthquake-prone areas [17]. Lastly, the integration of LHRC with modern construction methods such as 3D printing and automated manufacturing processes is an important area for additional research. This integration may maximize the material's sustainability and efficiency in contemporary building techniques, per Arnold et al. (2019) [27].

This in-depth understanding is required to position LHRC as a competitive alternative in the hunt for more sustainable and environmentally friendly building solutions. Base on the above facts, this study is focused on comparing the economic sustainability of using light-weight hair reinforced clay wall with conventional concrete hollow block wall in multi-story reinforced buildings. The comparison will include the construction cost, seismic mass forces and the insulation capacity for the two wall types.

Chapter 3

MATERIAL SPECIFICATION AND THE USED SOFTWARE

3.1 Lightweight Hair Reinforced Clay (LHRC)

The LRC material presented in this section is primarily composed of clay, with a small quantity of concrete foam added to increase its porosity and reduce density, as well as a small amount of gypsum, plant fibers, wood fibers, and natural hair strands, among other reinforcing materials. The foam may have a natural or synthetic foundation. Horn, nail, and other abdominal leftovers from cattle that can be obtained from slaughterhouses can be used to make natural foam. Hair can come from hair salon trash or from farms where goats and other animals have their yearly haircuts. It can come from human hair or any other kind of animal hair.

The mechanical characteristics of LHRC, as determined by a series of laboratory bending experiments, are initially reported in chapter two. The "light-weight hair-reinforced clay," which has superior advantages over other types of LRC, is then introduced. The results of its shear and compression tests were also shown in chapter two, and finally, it is discussed how to use this material as a building material to create resilient and sustainable architecture for buildings.

3.2 Preparing the Clay Samples and The Conducted Tests

A series of bending, compression, and shear experiments were planned and carried out on dried clay samples in order to determine the mechanical properties of the LHRC.

The clay samples were all made of clay that had passed through sieve number 25 (maximum particle size 0.707 mm) in combination with another necessary element. The International Institute of Earthquake Engineering and Seismology (IIEES), located in Tehran, Iran, hosted the testing at its structural laboratory.

For gypsum, the weight percentage of the reinforcement was 10%; for plant, wood, and hair fibers, it was 0.5%. In every instance, the mixture had a 25% water content, while the foam had a 2% water concentration. In both plant and wood fiber examples, the aspect ratio averaged 100, which is comparable to the scenario examined by Abou Diab., et al (2016) [15]. The average length of the fibers in human hair fiber (HHF) was 15 mm. A mixer was used to create a somewhat homogeneous and uniform combination of clay with the specified amounts of water, foam, and reinforcing material in order to create the samples. The HHF that was employed as the clay sample's reinforcing material has the following specifications: a diameter of 50 microns, a modulus of elasticity of 20,000 kgf/cm2, ultimate elongation of 30%, and tensile strength of 2200 kgf/cm2 [17].

As mentioned in a study by Zaryoun & Hosseini (2019), which conducted an experimental study by measuring the material's compressive, shear, and bending strengths using a battery of tests. The results of the tests indicate that LFRC is significantly stronger than both regular clay and clay reinforced with various other types of fibers that were previously employed Less than 75% of dried plain clay has a density of 1.37, which is the approximate density of the LFRC substance. Additionally, based on test results, medium clays had a UCS of 200–250 kN/m2, while the FHRC had a UCS of 300 kN/m2 [17]. It is significant to note that the FHRC samples in the inquiry had a density of 1370 kg/m3, but the clay samples in the Quagliarini and colleagues’ study had a density of 1860 kg/m3. The sample exhibited good integrity under bending force, as demonstrated in Figure 3, even in the face of considerable deformation brought on by compressive force and severe distortion [51].

Figure 3: A sample of LHRC from (left) compression test, at the (middle) unloading, and from the (right) bending effect.

Regarding FHRC samples' shear test, Figure 4 illustrates that the sample has not split into two distinct portions after shear failure and that the cut edge is not very sharp.

Figure 4: The FHRC sample during the direct shear test's final stage (left) and its integrity's preservation following shear failure (right).

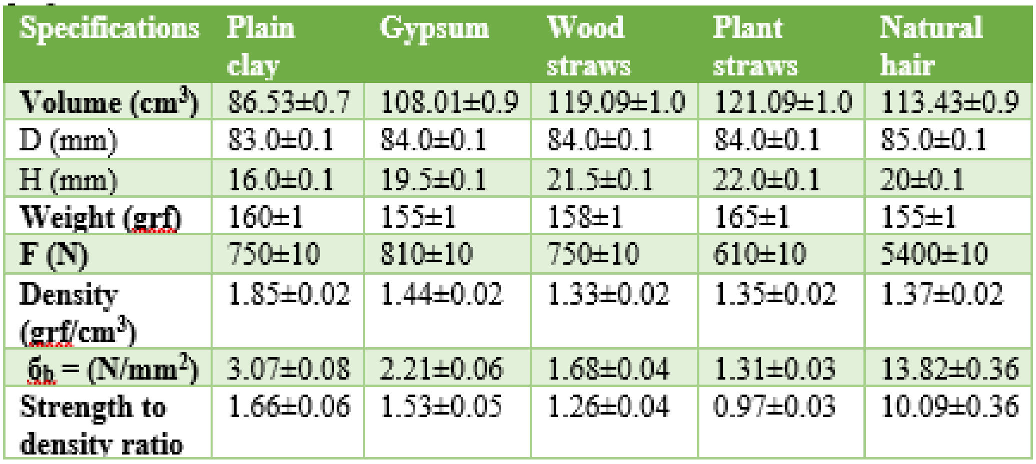
Table 2 displays the mechanical specifications of the FHRC material, which the authors recently proposed be utilized as the cover for the proposed system (Zaryoun and Hosseini 2018) [17].

Table 2: Mechanical Specifications of The LHRC Material [17].

Density kg/m^3	**Shear strength kgf/cm^2**	**Tensile strength kgf/cm^2**	**Unconfined compressive strength kgf/cm^2**
1370	3.60	13.80	2.94

The tensile and shear strengths of the material sample, as well as the unconfined compressive strength following the study, are provided by the mechanical specification of the FHRC material, which is displayed in Table 2. Furthermore, there is a larger disparity in the compressive strength of natural hair reinforcement when compared to the bending test result summary displayed in Table 3.

Table 3: The Five Materials' Specifications That Were Obtain from The Bending Test [17].



Specifications	**Plain clay**	**Gypsum**	**Wood straws**	**Plant straws**	**Natural hair**
Volume (cm^3)	86.53±0.7	108.01±0.9	119.09±1.0	121.09±1.0	113.43±0.9
D (mm)	83.0±0.1	84.0±0.1	84.0±0.1	84.0±0.1	85.0±0.1
H (mm)	16.0±0.1	19.5±0.1	21.5±0.1	22.0±0.1	20±0.1
Weight (grf)	160±1	155±1	158±1	165±1	155±1
F (N)	750±10	810±10	750±10	610±10	5400±10
Density (grf/cm^3)	1.85±0.02	1.44±0.02	1.33±0.02	1.35±0.02	1.37±0.02
σ_b = (N/mm^2)	3.07±0.08	2.21±0.06	1.68±0.04	1.31±0.03	13.82±0.36
Strength to density ratio	1.66±0.06	1.53±0.05	1.26±0.04	0.97±0.03	10.09±0.36

Figure 5 shows the 5-clay sample after bending test, which clearly shows how this material ability to retain it structural integrity after bending test.

Figure 5: Bending Test of The Crushed Clay Samples [17].

The five clay samples are as follows: plain clay, LRC reinforced with gypsum, LRC reinforced with wood fiber, LRC reinforced with plant fiber, and LRC reinforced with natural hair. It is evident that even after the bending test, the naturally hair-reinforced clay keeps its structural integrity. It increased its advantage over the test subjects [17].

3.3 Soft Ware Used

ETABS stands for Extended Three-Dimensional Analysis of Building System. ETABS is an engineering software tool used for multi-story building analysis and design. Together with the structure's unique grid-like design, code-based load prescriptions, modeling tools and templates, analysis techniques, and solution methodologies all function. Systems of any complexity can be evaluated in either static or dynamic environment using ETABS. For a more intricate assessment of seismic performance, modal and direct-integration time-history analysis can be combined with P-Delta and large displacement effects.

Nonlinear connections, focused PMM, or fiber hinges can all capture material nonlinearity under monotonic or hysteretic behavior. Because of its integrated and intuitive features, applications of any complexity can be developed. Because of its connectivity with other design and documentation platforms, ETABS is a coordinated and successful tool for designs ranging from simple 2D frames to complex modern high-rises.

3.3.1 Modeling of Structural Systems

An essential component of ETABS modeling is the generalization that multi-story buildings typically consist of similar or identical floor designs that repeat vertically. Some modeling features that make it easier to create analytical models and simulate complex seismic systems are as follows:

- Modeling templates for both local elements and global systems
- Particularized section shape and constitutive action
- assemblage of shell and frame objects
- Assigning links for simulating dampers, isolators, and other sophisticated seismic systems
- Nonlinear hinge definition
- meshing automatically and manually
- Features for editing and assigning plans, elevations, and three-dimensional views

3.3.2 Loading, Analysis, and Design

When the modeling is finished, ETABS automatically generates and assigns code-based loading conditions for thermal, seismic, wind, and gravity forces. The user can accept an infinite number of load scenarios and combinations. Subsequently, analysis capabilities offer advanced nonlinear methods for characterizing static-pushover and dynamic response.

Dynamic concerns include things like modalities analysis, response spectrum analysis, and temporal history analysis. Geometric nonlinearity can be explained by the P-delta effect. Provide features that will create systems and elements that scale automatically, create schemes for reinforcement, and otherwise optimize the structure according to the encompassing specification's desired performance criteria.

Chapter 4

SAMPLE BUILDINGS

4.1 Introduction

This work is a creative step in the quest for sustainable building materials that provide improved performance and economic advantages of using LHRC wall as an infill/partition wall in comparison to conventional hollow concrete block wall. This section describes the detailed method utilized to compare the performance of LHRC wall with traditional hollow concrete block wall in multi-story building. The most advanced architectural and engineering software packages, Revit and ETABS, were utilized to meticulously create and examine models for buildings with four, seven, and ten stories. These models served as the basis for assessing a variety of aspects, such as economic viability, and structural weight effect in the face of seismic activity. As required by contemporary building standards, the following sections provide a detailed explanation of the comparative analysis procedure, highlighting the analytical methods and the techniques method used to assess the structural and economic sustainability implications of the recommended material under typical loading conditions.

4.2 Method

For the comparative analysis in this study, two distinct alternative materials for the building walls were chosen. The double skin wall composed of lightweight clay reinforced with hair and the conventional wall system composed of concrete hollow blocks are examples of alternative wall materials. The design models included both of the substitute materials (LHRC wall and concrete hollow block wall), where 4, 7, and

10-story buildings were design for both wall method. The result was then compared in regards to the structural seismic mass force, the drift and period. The blocks utilized for the two options are depicted in figures 6 and 7, which present a schematic representation of the novel double skin wall system composed of lightweight clay reinforced with hair.

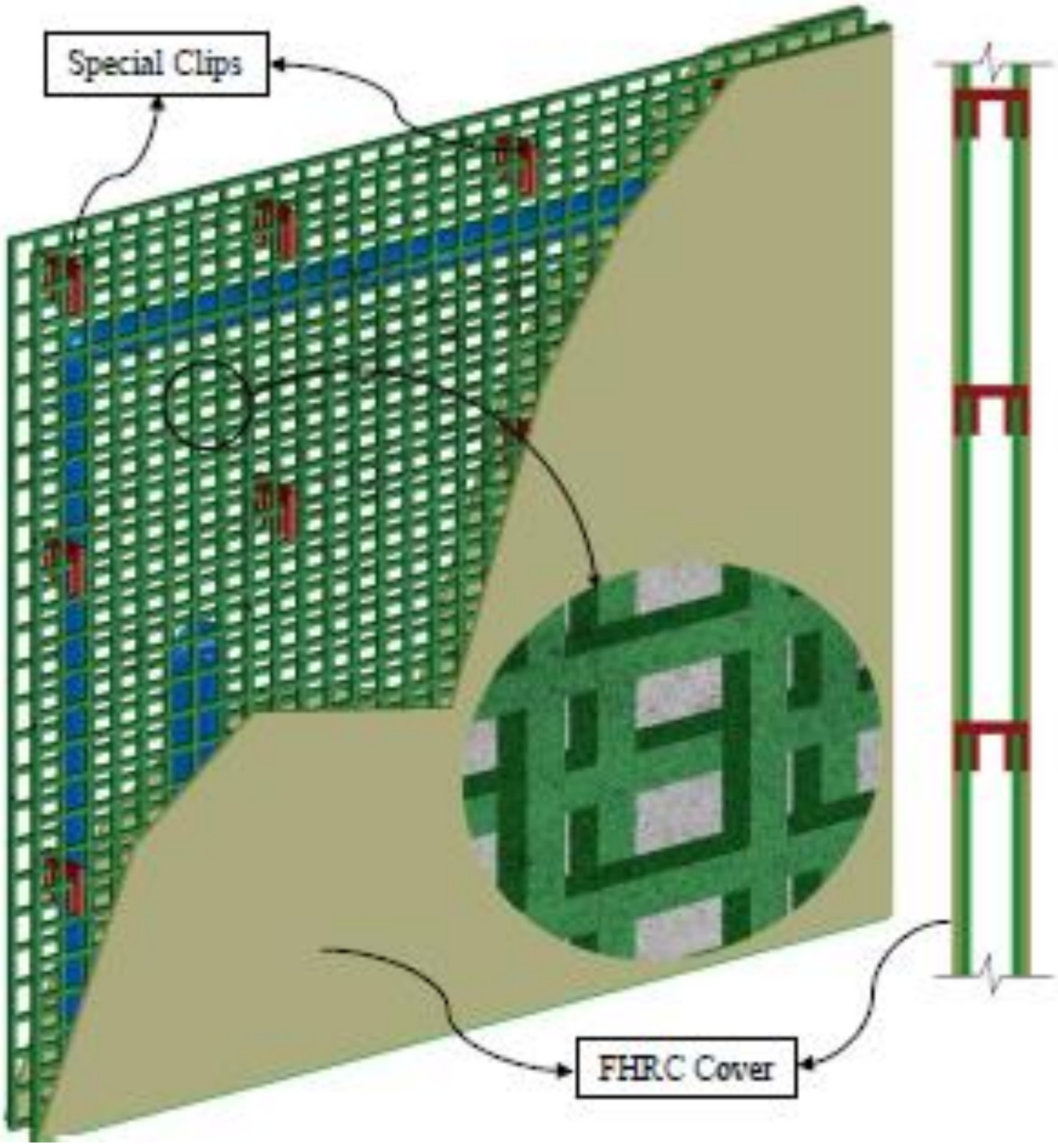


Figure 6: A Schematic View of The Proposed Double Skin Wall System (3D View) [41].

The lightweight hair-reinforced clay used in the double-skin wall system is a composite material that was painstakingly created to balance sustainability and performance. The majority of the recycled plastic debris used to create the wall system's structural grid, or "skins," is what gives the system support. Clay acts as a bulking and binding agent, giving the other ingredients a structural matrix to be embedded in. The incorporation of hair fibers into the clay matrix enhances its mechanical qualities, such as its tensile and compressive strengths, significantly. This strengthening increases the material's lifetime and seismic resistance. The method also includes foamed hair-reinforced clay (FHRC), a special sort of clay that uses foam to improve insulating properties and decrease density. This foamed clay covers the outside edges of the plastic grid and forms the apparent surface of the wall structure. These components work together to create a building material that is lightweight, robust, and has the least negative effect on the environment. It also maximizes insulation. Block wall, which served as the second option for the comparative studies of the wall systems, made up the traditional wall system. A sample of the block utilized in the wall design is shown in Figure 7.

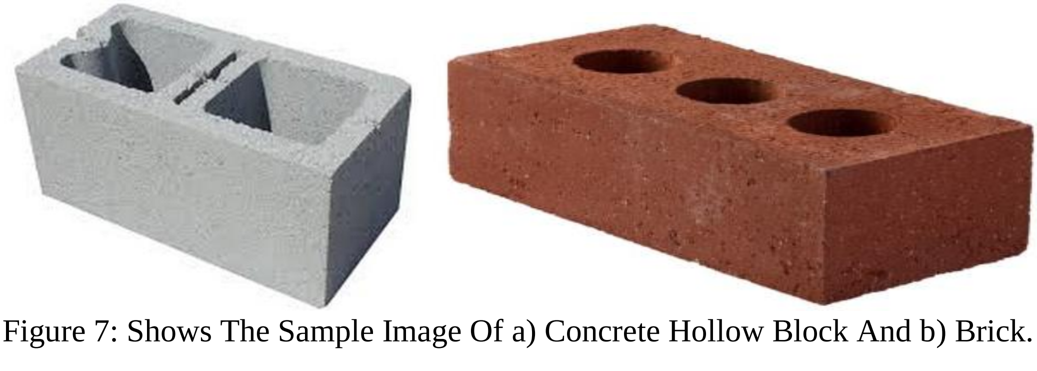


Figure 7: Shows The Sample Image Of a) Concrete Hollow Block And b) Brick.

The image shown in figure seven were used as a conventionally wall material. The architectural 3D models, ground floor, first floor, and section are shown in figure 8-11.

With two flats on each floor and a garage on the bottom floor, the architectural model depicted in Figure 8(a, b, and c) was designed using Revit design software for the analyses in this research project.

Figure 8: Architectural 3D Models.

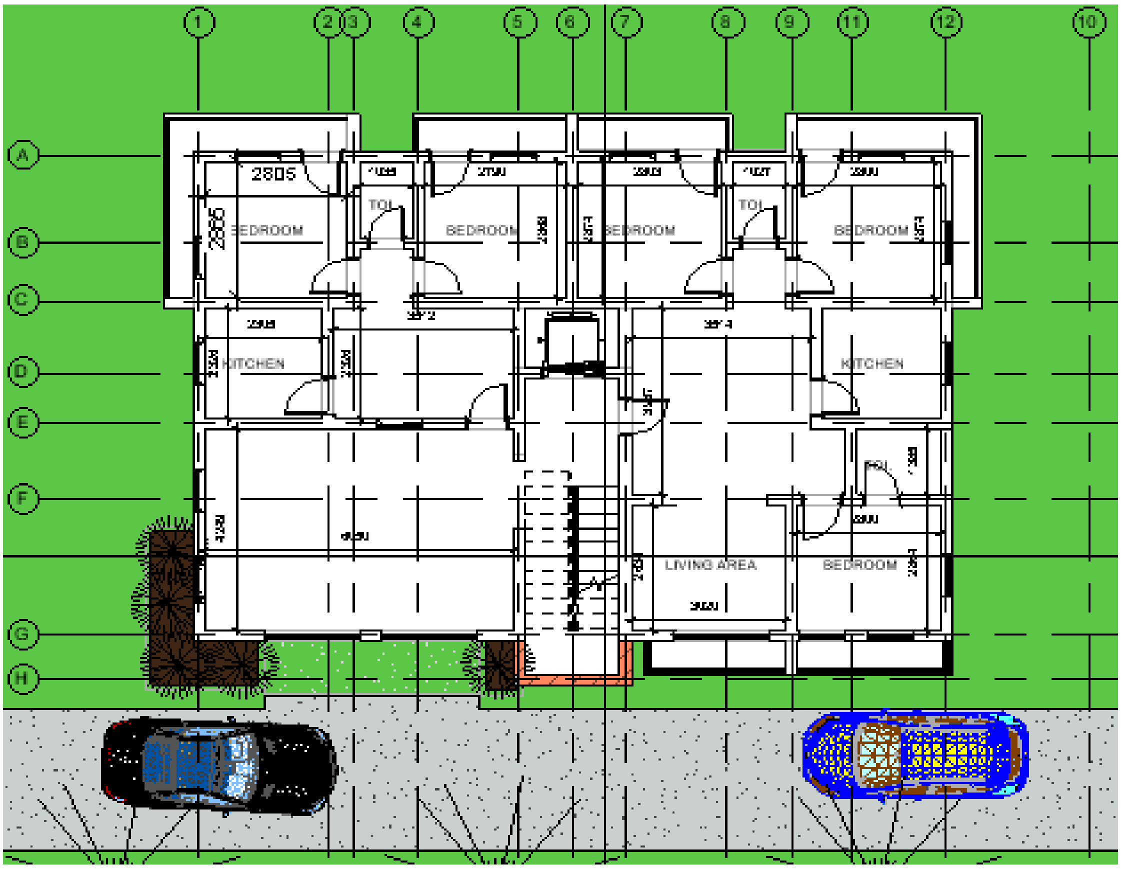


Figure 9: Ground Floor Plan of the Model.

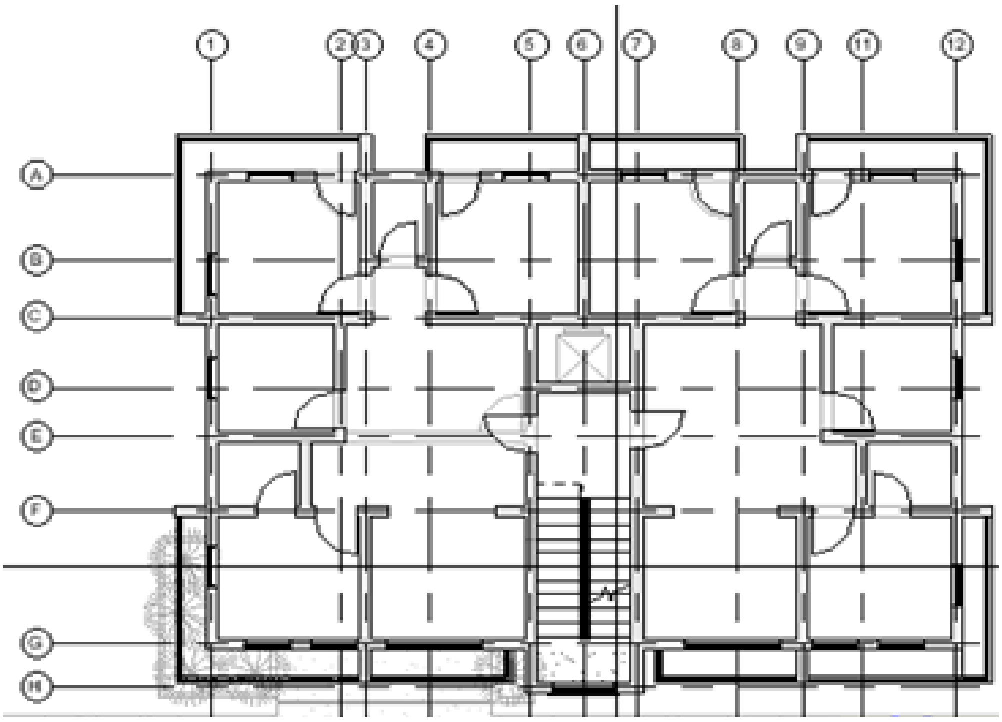


Figure 10: First Floor Plan of the Model.

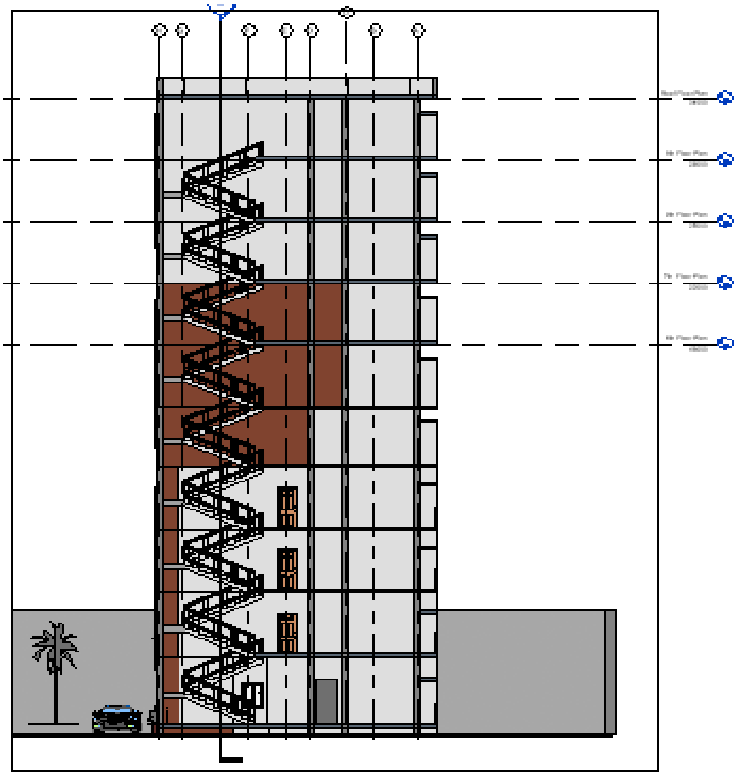


Figure 11: Sectioning Plan Model for the 10-Story Building.

Each of the two apartments that makes up the design plan has three bedrooms, a living room with a kitchen, a bathroom, and toilet. The building included a terrace and a single garage as well.

4.3 Structural Analyses

Lightweight building materials can lead to lighter structural element and less seismic force applied to the building by lowering the dead load on the structure. By reducing shear forces and bending moments by 15% and 20%, respectively, this reduction can improve earthquake resistance. The inquiry comprises a comparison of the lightweight hair-reinforced clay double skin wall system with the conventional hollow concrete block walling method. The three design models, which comprise the 4, 7, and 10-sory buildings, were subjected to the two-walling method. The parameters considered for the comparison include; seismic mass forces, maximum story drift, and period. The result was then interpreted base on the comparison made for the two different model design method. Table 4 below shows the building dimension used for the design, and table 5 shows the 20 load cases for which the structure was examined. The ASCE hazard tool was utilized to gather the seismic design data for the analysis.

Table 4: Dimension Details for the Model Design.

Story's	**10**
Height	30m
Site area	225 m^2
Typical floor-to-floor height	3 m

Table 5: Load Combination Used for the Design According to ASCE7-16 Code.

S/N	Load combination
1	1.4(dead)
2	1.2(dead)+1.6(liveNR + Leq) + 0.5(LRoof)
3	1.2(dead)+0.5(LiveR)+1.0(LiveNR+Leq) + 1.6(LRoof)
4	1.41(dead)+0.5(LivR)1.0(LiveNR+Leq) 0.2(snow) + (EXEcc+EY+EZ)
5	1.41(dead)+0.5(LivR)1.0(LiveNR+Leq) 0.2(snow) + (EXEcc-EY+EZ)
6	1.41(dead)+0.5(LivR)1.0(LiveNR+Leq) 0.2(snow) + (-EXEcc+EY+EZ)
7	1.41(dead)+0.5(LivR)1.0(LiveNR+Leq) 0.2(snow) + (-EXEcc-EY+EZ)
8	1.41(dead)+0.5(LivR)1.0(LiveNR+Leq) 0.2(snow) + (EXEcc+EY+EZ)
9	1.41(dead)+0.5(LivR)1.0(LiveNR+Leq) 0.2(snow) + (EXEcc-EY+EZ)
10	1.41(dead)+0.5(LivR)1.0(LiveNR+Leq) 0.2(snow) + (-EXEcc+EY+EZ)
11	1.41(dead)+0.5(LivR)1.0(LiveNR+Leq) 0.2(snow) + (-EXEcc-EY+EZ)
12	0.69(Dead) + (EXEcc + EY + EZ)
13	0.69(Dead) + (EXEcc - EY + EZ)
14	0.69(Dead) + (-EXEcc + EY + EZ)
15	0.69(Dead) + (-EXEcc - EY + EZ)
16	0.69(Dead) + (EXEcc + EY + EZ)
17	0.69(Dead) + (EXEcc + EY + EZ)
18	0.69(Dead) + (-EXEcc + EY + EZ)
19	0.69(Dead) + (-EXEcc - EY + EZ)
20	-EZ

Tables 6 to 11 displays the properties of the frame components with the ratio of bars used for both LHRC and conventional building model, while table 12 shows the volume of concrete for beam and column for all the three-story building Hight, and table 13 shows the steel bars for the columns and beams represented in tons for all the building stories. Different beam and column section properties were employed at different story intervals due to the varied story height. For the design model. The chosen structures are regular buildings consisting of 4, 7, and 10 stories, as defined in ASCE7-16.[61] It has a dual system contain special shear wall and special frame base on definition ACI318-19[62] to resistant the earthquake. According to the ASCE7-16, in a dual system, the moment frames must have the ability to withstand a minimum of 25% of the seismic forces specified in the design.

Table 4: Properties of Columns For 4-Story (LHRC).

story	Dimension of column	Ratio of bar	%
1-2	40×40	0.021	2.1
3-4	40×40	0.015	1.5

Table 5: Properties of Columns For 4-Story (LHRC).

Story	Dimension of column	Ratio of bar	%
1-2	40×40	0.025	2.5
3-4	40×40	0.020	2

Table 6: Properties of Columns For 4-Story (LHRC).

Story	Dimension	Ratio of bar	%
1-2	50×50	0.020	2
3-6	50×50	0.015	1.5
7	50×50	0.010	1

Table 7: Properties of Columns For 4-Story (LHRC).

story	Dimension	Ratio of bar	%
1-2	50×50	0.025	2.5
3-6	50×50	0.02	2
7	50×50	0.015	1.5

Table 8: Properties of Column For 10-Story Building (Conventional).

Story	Dimension	Ration of bar	%
1-2	50×50	0.025	2.5
3-6	50×50	0.020	2
7	50×50	0.015	1.5
8-10	40×40	0.023	2.3

Table 9: Properties of Column For 10-Story Building (LHRC).

Story	Dimension	Ratio of bar	%
1-2	50×50	0.020	2
3-6	50×50	0.015	1.5
7	50×50	0.01	1
8-10	40×40	0.015	1.5

Although the amount of concrete has been the same for both LHRC and conventional cases, as shown in Table 12, according to Tables 6 to 11, the amount of steel bar percentage has been significantly decreased in the case of using LHRC walls. This reduction is shown in Table 13.

Table 10: Volume Of Concrete in Both Conventional and LHRC Cases.

story	Beam (m^3)	column(m^3)
4	78.36	66.40
7	192.32	122.50
10	251.12	156.10

Table 11: Comparing The Weight of Steel Bars in Columns and Beams in The Two Cases.

Story	Conventional (ton)	LHRC (ton)
4	26.5	23.80
7	39.65	34.98
10	56.10	44.97

The spectrum analysis and design of this structure utilize Hazard tools, offered by the National Emergency for the USA, to assess the hazardous location. The seismic data used for the analysis which were obtained from ASCE Hazard tool were displayed in table 14 and also, the seismic category used was D.

Table 12: Seismic Parameters Based on ACI318-19 Code.

S_S 1.916	S_1 0.672	F_a 1.2	F_v 1.4
S_{mS} 2.299	S_{M1} 0.94	S_{DS} 1.532	S_{D1} 0.627
T_L 8	PGA 0.828	PGA_M 0.994	F_{PGA} 1.2
I_e 1			

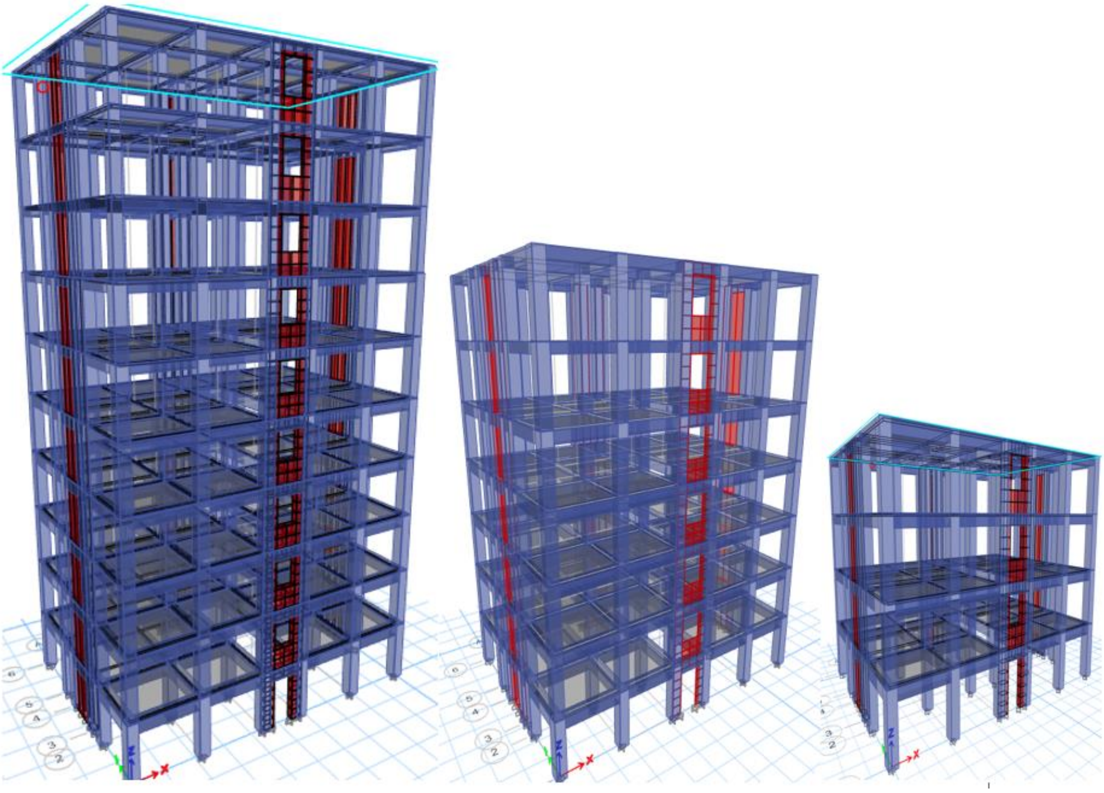
- S_S 1.916 - This is the short-period (0.2-second) mapped spectral acceleration.

- S_{MS} 2.299 - This is the one-second-period mapped spectral acceleration.
- S_{M1} 0.94 - This is the modified spectral acceleration of the Maximum Considered Earthquake (MCE) during short periods.
- S_{DS} 1.532 - This is the Design Spectral Acceleration at short intervals (0.2 s), or two-thirds of the highest acceleration for earthquakes that is taken into consideration.
- S_{D1} 0.627 - Two-thirds of the maximal acceleration thought to be caused by an earthquake is represented by this Design Spectral Acceleration at 1 second.
- PGA 0.828 - This is the Peak Ground Acceleration, which shows the ground's maximum acceleration during an earthquake.
- PGA_M 0.994 - The largest acceleration that is feasible given the worst-case scenario for earthquakes is known as the MCE Peak Ground Acceleration.
- T_L 8: long-period transition period.
- I_e 1: The seismic importance factor.
- F_a 1.2: short-period site coefficient (at 0.2-s period).
- F_v 1.4: long-period site coefficient (at 1.0-s period).

The design coefficient and factors for seismic force-resisting system were shown in table 15 below according to ASCE7-16 code and the3D frame model, sample 3D for the assign loads, and two cross-sectional area of steel bars in a sample floor beam for LHRC model (mm2) and conventional model were shown in Figures 12 to 15 respectively.

Table 13: Design Coefficient and Factors for Seismic Force-Resisting System.

zas	Overstrength Factor	Deflection Amplification Factor Cd
7	2.5	5.5



a) b) c)

Figure 12: Structural Frames of The Designed Multi-Story Buildings.

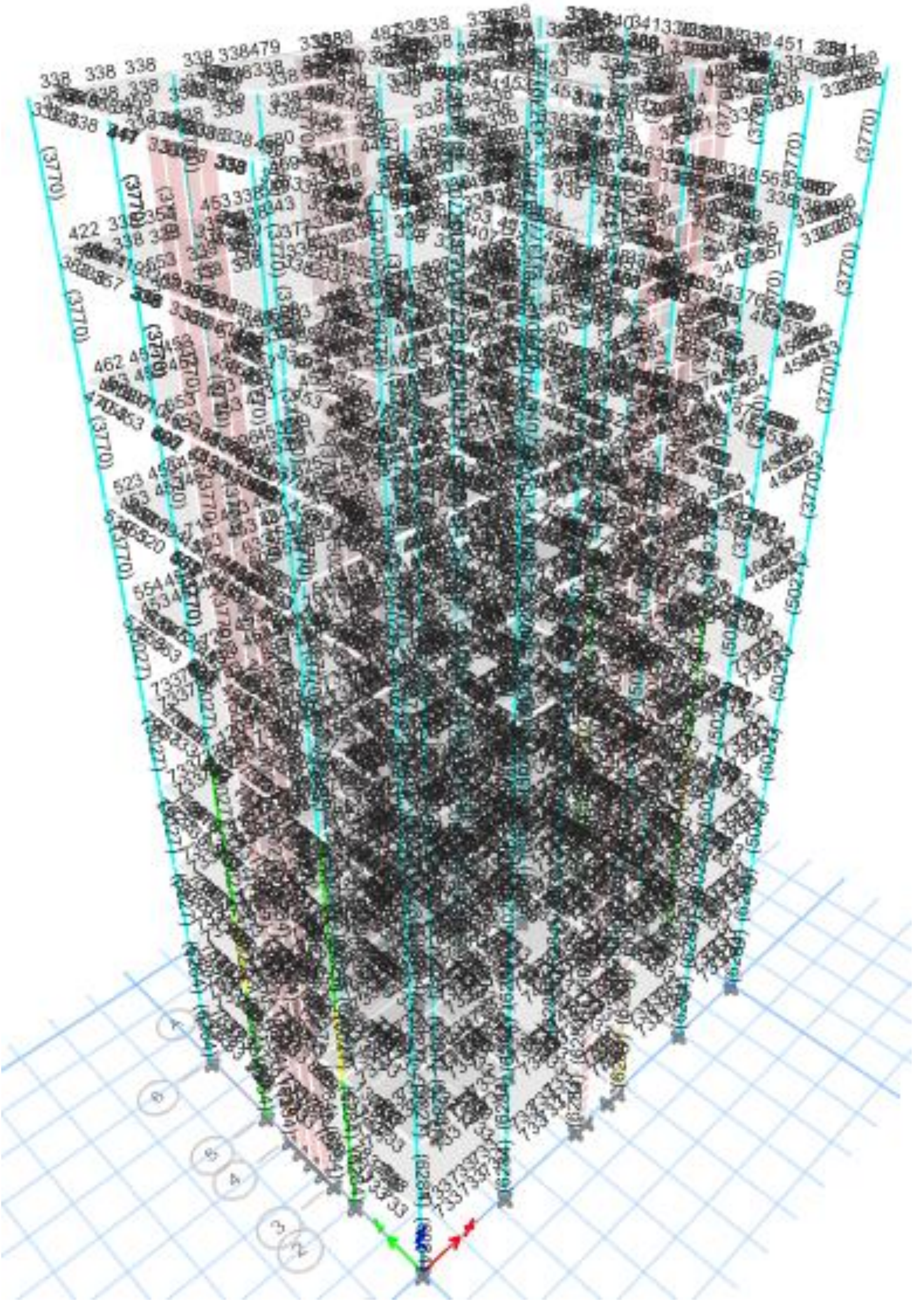


Figure 13: 3D View of the Assigned Loads For 10-Story Building.

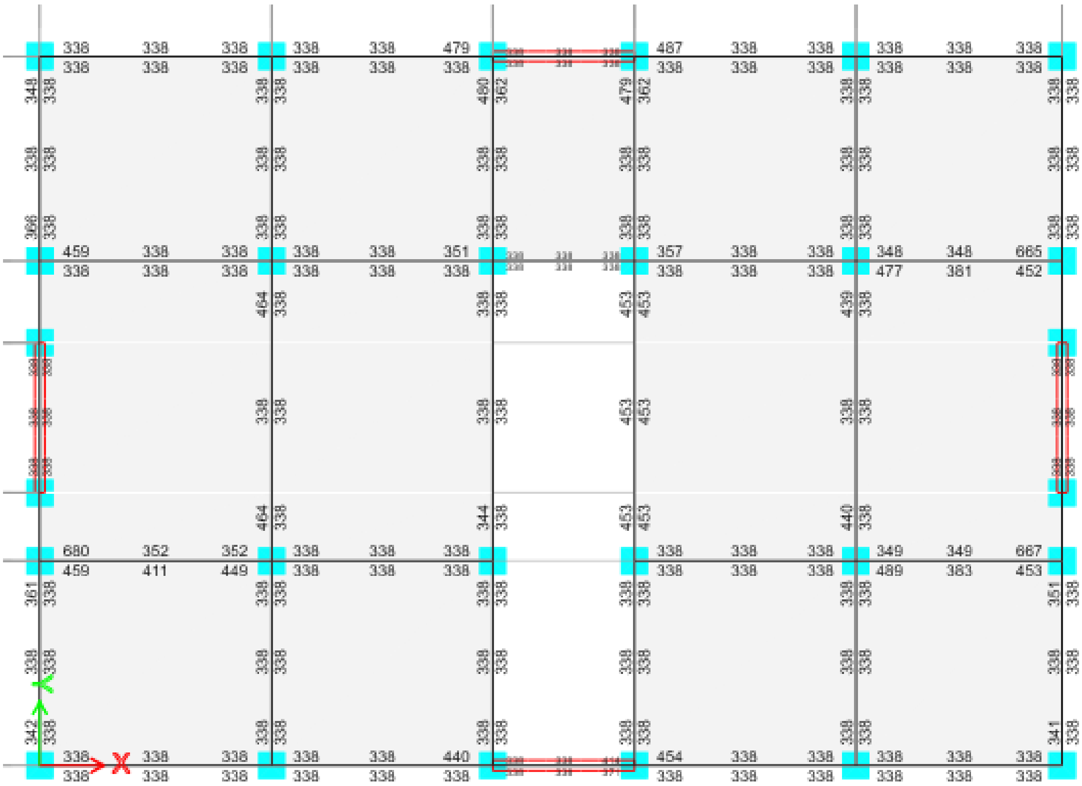


Figure 14: Cross-Sectional Area of Steel Bars in A Sample Floor Beams for LHRC Model (mm^2).

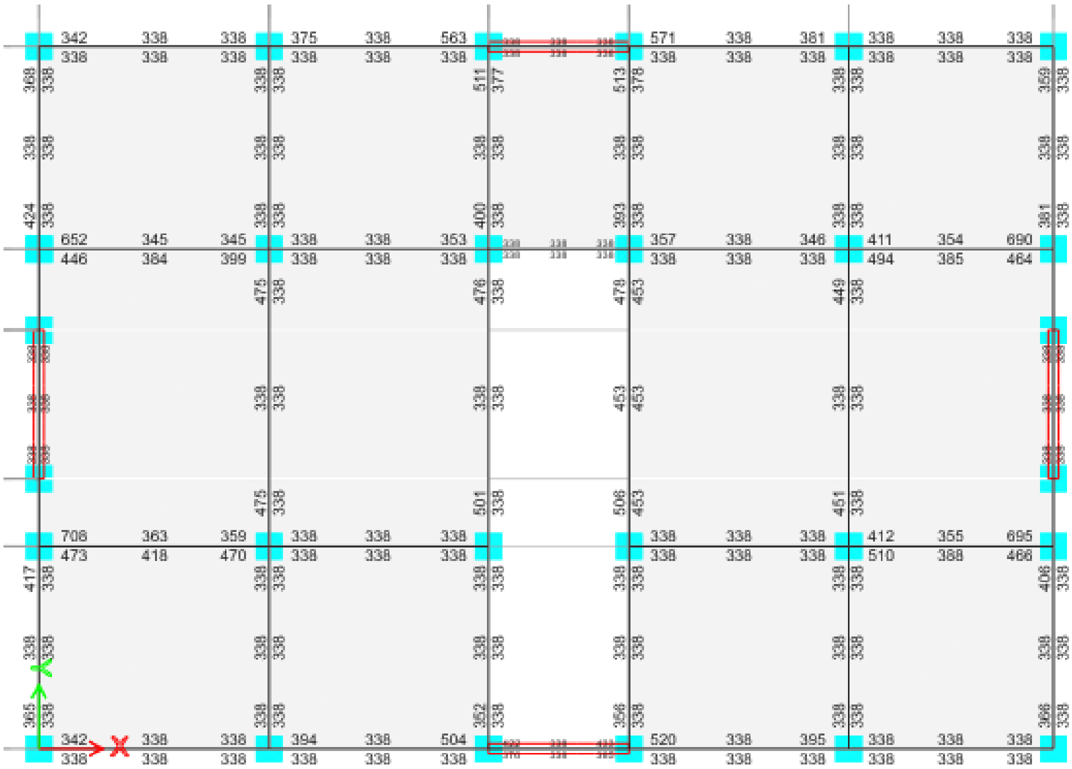


Figure 15: Cross-Sectional Area of Steel Bars for the Same Floor Beams Shown in Figure 14 for Conventional Case.

Figure 14 and 15 shows the cross-section area of longitudinal steel bars in mm^2 for top and bottom are related to bars in bottom of the beam.

4.3.1 Seismic Mass Forces Result

The structural seismic mass forces for each category were documented in ton using both the double skin wall type and the traditional wall type. The results of the structural study demonstrate that there are notable differences between the seismic masses of the two building techniques:

- four-story buildings: The double skin wall seismic mass force was 599 ton, which is significantly less than the conventional wall system's 688 ton. The seismic mass force difference of 89 ton indicated a considerable reduction in the seismic load.
- seven-Story Structures: The double skin wall technique again showed a lower seismic mass force of 849 ton for seven-story buildings as compared to the conventional method 973 ton. There was a reduction in seismic mass force of 123 ton.
- ten-story buildings: 1460 ton was recorded by the conventional system, while 1274 ton was recorded using the double skin wall. These differences were the biggest ones that were found. A seismic mass difference of 185 ton was present here.

For all three scenarios four, seven, and ten stories the average percentage difference in seismic mass between the double skin wall system and the normal wall system is around 12.71%. Table 17 displayed the results' summary.

Table 14: Structural Weights and Seismic Masses of The Buildings in The Two Cases.

No. stories	LHRC walls (tonf)	Conventional walls (tonf)	Seismic mass differences (tonf)
4	599	688	89
7	849	973	123
10	1274	1460	185

The percentage difference between the conventional wall and the double skin wall can be seen in figure 16, having an average difference of 12.7% across the building heights.

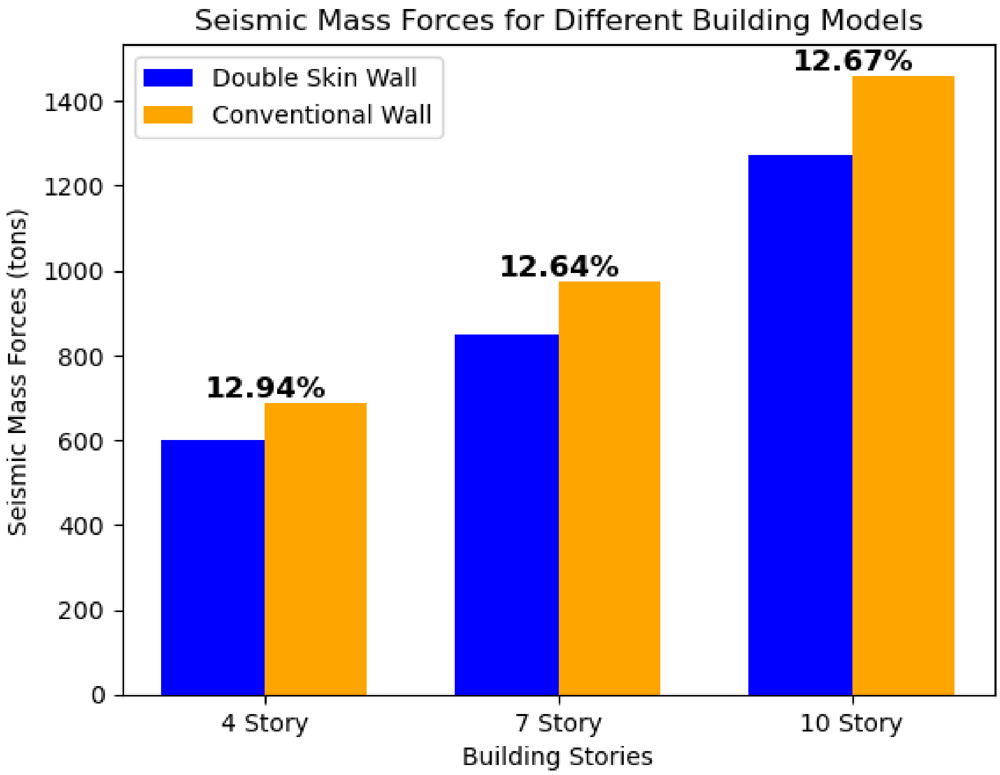


Figure 16: Percentage differences for Seismic mass forces for different building Models.

4.3.2 Result Comparison of the Drift and Period of the Two Methods

The results were shown in tabular form for LHRC wall method and conventional wall method for the drift and period. Some additional information was also shown, like shear of the structure and area of bar used in the design model. Below is all the obtained result from ETABS, this result was for 10-story, 7-story, and 4-story buildings. Comparison was made for 10-story building of LHRC model with 10-story building of the conventional model. Same method was followed for 7-story and 4-story building. The drift ratio result obtained from ETABS for 10-story building for both LHRC model and conventional model was shown in table 18 and 19.

Table 15: LHRC Model Drift Ratio For 10-Story Building.

Story	Direction	Drift ratio	Direction	Drift ratio
10	X	0.0015	Y	0.0013
9	X	0.0017	Y	0.0014
8	X	0.0018	Y	0.0015
7	X	0.0017	Y	0.0014
6	X	0.0017	Y	0.0014
5	X	0.0015	Y	0.0013
4	X	0.0014	Y	0.0012
3	X	0.0012	Y	0.0010
2	X	0.0010	Y	0.0008
1	X	0.0006	Y	0.0003

Table 16: Conventional Model Drift Ratio For 10-Story Building.

story	Direction	Drift ratio	Direction	Drift ratio
10	X	0.0017	Y	0.0014
9	X	0.0019	Y	0.0015
8	X	0.0020	Y	0.0016
7	X	0.0020	Y	0.0015
6	X	0.0019	Y	0.0015
5	X	0.0017	Y	0.0013
4	X	0.0016	Y	0.0012
3	X	0.0014	Y	0.0011
2	X	0.0011	Y	0.0008
1	X	0.0006	Y	0.0004

The LHRC model consistently has a lower drift ratio than the conventional hollow concrete block model, ranging from 12.5% to 13%. This suggests that the LHRC model performs better overall in preventing structural deformations.

The period for the 10-story building was also obtained for evaluation from ETABS, were both LHRC model and conventional building model were compared as shown in table 20 below.

Table 17: Model Periods for the 10-Story Buildings.

Mode	Period (S) conventional	Period (S) LHRC
1	0.9240	0.8690
2	0.7680	0.7230
3	0.5770	0.5520
4	0.3040	0.2860
5	0.2290	0.2160
6	0.1710	0.1590

In comparison to the conventional model, the LHRC model has relatively less time for the first few modes. In general, the periods suggest that the LHRC model may be more rigid than the traditional model. Table 21 and 22 shows the drift ratio values of 7-story building for both LHRC and conventional model.

Table 18: LHRC Model Drift Ratio For 7-Story Building.

Story	Direction	Drift ratio	Direction	Drift ratio
7	X	0.0011	Y	0.0010
6	X	0.0012	Y	0.0010
5	X	0.0012	Y	0.0011
4	X	0.0013	Y	0.0011
3	X	0.0012	Y	0.0010
2	X	0.0010	Y	0.0008
1	X	0.0006	Y	0.0004

Table 19: Conventional Model Drift Ratio For 7-Story Building.

Story	Direction	Drift ratio	Direction	Drift ratio
7	X	0.0011	Y	0.0010
6	X	0.0012	Y	0.0010
5	X	0.0013	Y	0.0011
4	X	0.0013	Y	0.0011
3	X	0.0011	Y	0.0010
2	X	0.0011	Y	0.0008
1	X	0.0006	Y	0.0004

In comparison to the LHRC model, the conventional hollow concrete block model shows a maximum drift ratio that is approximately 4.51% higher. This suggests that, given the same stress conditions, the LHRC model performs marginally better in terms of limiting structural deformations. As a result, during seismic or lateral load events, the LHRC model might be more effective in preserving structural integrity and minimizing drifts. The period for the 7-story building for both LHRC model and conventional model was shown in table 23.

Table 20: Model Periods for the 7-Story Buildings.

Mode	Period (S) Conventional	Period (S) LHRC
1	0.5630	0.5410
2	0.4550	0.4370
3	0.3510	0.3370
4	0.1650	0.1590
5	0.1250	0.1200
6	0.0950	0.0870

When compared to a conventional hollow concrete block wall model, the LHRC wall model shows shorter durations. The drift ratio values obtained from ETABS for the 4-story building was shown in table 24 and 25 for LHRC model and conventional.

Table 21: LHRC Model Drift Ratio For 4-Sytory Building.

Story	Direction	Drift ratio	Direction	Drift ratio
4	X	0.0008	Y	0.0008
3	X	0.0008	Y	0.0008
2	X	0.0007	Y	0.0007
1	X	0.0004	Y	0.0004

Table 22: Conventional Model Drift Ratio For 4-Story Building.

Story	Direction	Drift ratio	Direction	Drift ratio
4	X	0.0009	Y	0.0009
3	X	0.0009	Y	0.0009
2	X	0.0009	Y	0.0009
1	X	0.0005	Y	0.0005

For the 4-story building, the conventional hollow concrete block model shows a maximum drift that is approximately 8% higher than the LHRC model. This suggests that, given the same loading conditions, the LHRC model limits structural deformations more effectively. For this particular building height and layout, the LHRC model may therefore be more successful in preserving structural integrity and minimizing drifts during seismic or lateral load occurrences. The period for the 4-story building result was obtained from ETABS as shown in table 26 for the LHRC model and conventional model respectively.

Table 23: Model Periods For 4-Story Buildings.

Model	Period (S) conventional	Period (S) LHRC
1	0.320	0.300
2	0.239	0.225
3	0.182	0.170
4	0.082	0.077
5	0.061	0.058
6	0.045	0.043

In comparison to the conventional model, the LHRC model has relatively less time for the first few modes. In general, the periods suggest that the LHRC model may be more rigid than the traditional model.

The design response spectrum used was shown in figure 17 and the seismic response of two different types of structures were shown in figure 18 to 20 for conventional and LHRC to the standardized design spectrum is contrasted in this graph. It illustrates how the two designs react to seismic loads differently, with the conventional structure only meeting the design spectrum at certain times and the LHRC structure generally doing better (lower acceleration).

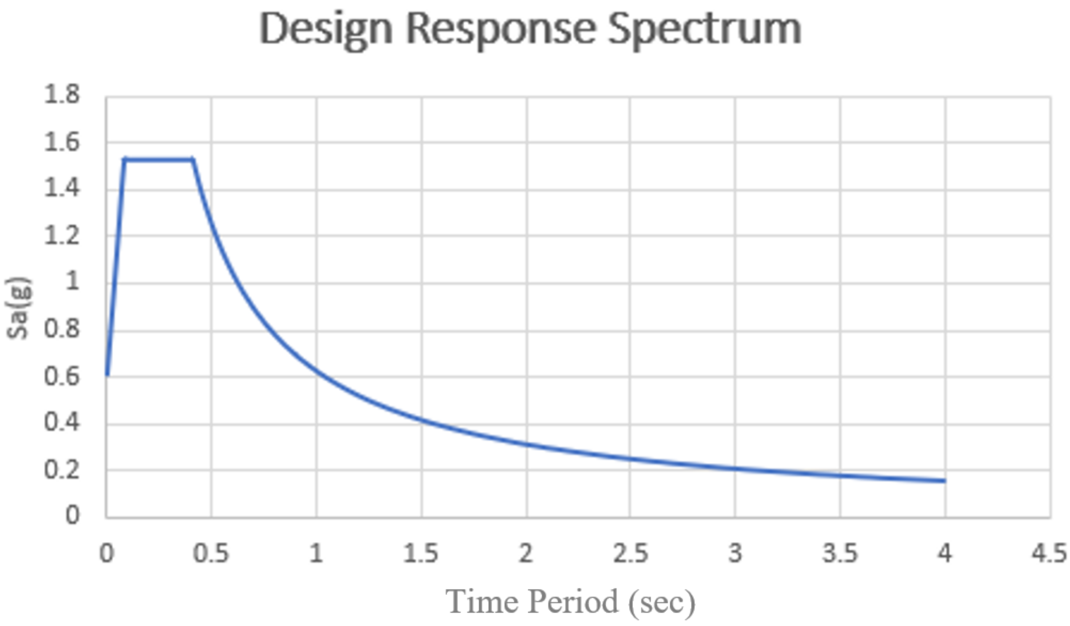


Figure 17: Design Response Spectrum.

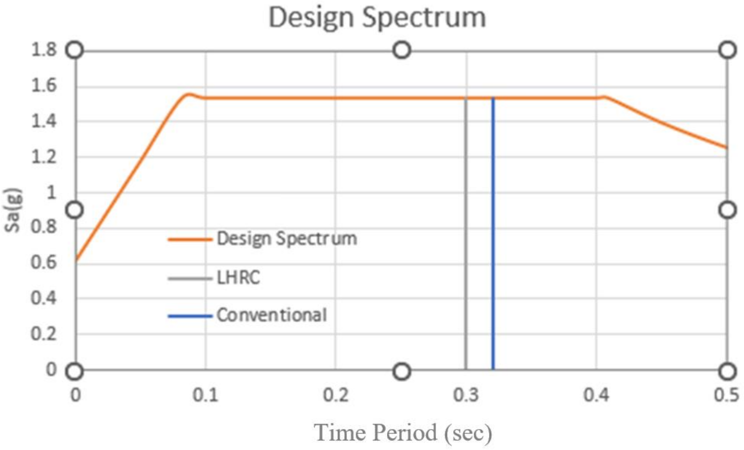


Figure 18: 4-Story Buildings Period Change Effect on The Acceleration Response for LHRC And Conventional Cases.

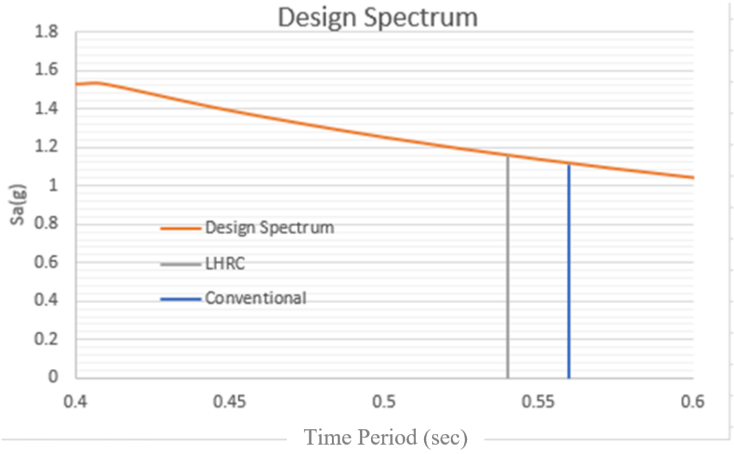


Figure 19: 7-Story Buildings Period Change Effect on The Acceleration Response for LHRC And Conventional Cases.

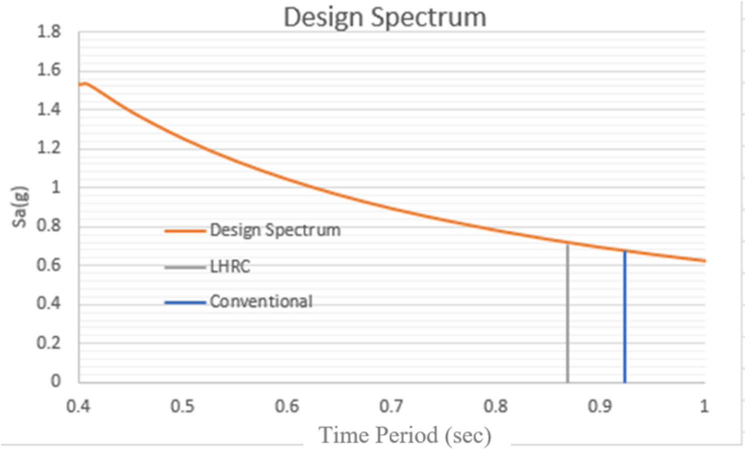


Figure 20: 10-Story Buildings Period Change Effect on The Acceleration Response for LHRC And Conventional Cases.

It is seen in Figures 18 to 20 that the effect of period change in the spectral responses of the buildings in the two cases is negligible for all heights. However, it should be noted that these periods are valid in elastic analysis, and if nonlinear analysis is performed the behavior of buildings in the two cases, would be possibly more different.

4.4 Cost Analyses

This investigation compares the economic benefits of innovative lightweight hair-reinforced clay wall system with typical reinforced concrete block wall construction. The estimated cost of construction of concrete block wall in the United State of America ranges between 15 to 30 US Dollars per square meter, according to the information available on the internet. Although concrete block wall construction is well renowned for its strength, durability, and fire resistance, it is also associated with significant material and labor expenses due to the weight of the components and the complexity of the construction process. On the other hand, the proposed hair-reinforced clay wall system increases the tensile strength of the walls while reducing their overall weight by combining locally generated clay with natural fibers, notably hair. The anticipated decrease in material costs and construction time associated with this approach may have positive economic effects. Firstly, the estimated cost of the concrete block wall construction was shown in the table 27 below, and the total wall area for all the different story height was also shown.

Table 24: Summary of The Estimated Cost of Conventional Wall.

No. of story building	Wall area m^2	Cost per square meter (15-30$)	Average cost ($)
4-story	1812.76	27,191-54,382	40,786
7-story	2963.85	44,458-88,915	66,686
10-story	4222.26	63,333-126,667	95,000

The average estimated cost of the conventional concrete block wall construction for all the story height was shown in table above. Secondly, wall made up of lightweight hair reinforced clay cost estimate was shown below;

Wall area of 4-story building = 1812.76m^2

- Area of a single LHRC block 0.406 × 0.203 = 0.08242
- Number of blocks required = wall area/block area

  1812.76/0.08242 = 21952 blocks
- Volume of the single block =length × width × height

  0.203 × 0.203 × 0.406 = 0.0168 cubic meter
- Total volume for the blocks required

  V_T = volume of one block × No. of blocks required

  0.0168 × 21952 = 370.48m^3
- Total mass of clay required = V_T × Density of the material

  $M_T = 370.48 \times 1370$ kg/m^3 = 507,356.6kg
- Converting kg to metric tons

1 metric ton is equivalent to 1000kg

- Total mass in tons = 507,356.6/1000 = 507.36 tons .

The average cost of clay per ton in the United state of America according to the information available on the internet, ranges between 15-25$. Consequently, for the 4-story building the total amount of clay needed to make the LHRC block wall was 15 × 507.36 which is equivalent to 7605$. Assuming that by adding the prices of foam, hair reinforcement, plastic grid and labor. This value would be double (say 14000$), which still this price would be much lower than the concrete block wall. For the remaining 7 and 10-story building, the estimated amount of clay required base on the wall area was shown below;

Wall area of 7-story building = 2963.85m^2

- Area of a single LHRC block 0.406 × 0.203 = 0.08242
- Number of blocks required = wall area/block area

  2963.85/0.08242 = 35,960 blocks
- Volume of the single block =length × width × height

  0.203 × 0.203 × 0.406 = 0.0168 cubic meter
- Total volume for the blocks required

  V_T = volume of one block × No. of blocks required

  0.0168 × 35,960 = 604.13m^3
- Total mass of clay required = V_T × Density of the material

  M_T = 604.13 × 1370 kg/m^3 = 828,658kg
- Converting kg to metric tons

  1 metric ton is equivalent to 1000kg
- Total mass in tons = 828,658/1000 = 828 tons.

The total cost of the clay required for the block wall will now be 828 × 15 = 12,415$. Assuming that by adding the prices of form, hair reinforcement, plastic grid and labor. This value would be double (say 25000$). Still the price is lower than the concrete block wall cost.

Lastly, for the 10-story building the estimated amount of clay required in ton for the LHRC wall is given in steps below.

Wall area of 10-story building = 4222.26m^2

- Area of a single LHRC block 0.406 × 0.203 = 0.08242
- Number of blocks required = wall area/block area

  4222.26/0.08242 = 51,228 blocks
- Volume of the single block =length × width × height

  0.203 × 0.203 × 0.406 = 0.0168 cubic meter
- Total volume for the blocks required

  V_T = volume of one block × No. of blocks required

  0.0168 × 51,228 = 860m^3
- Total mass of clay required = V_T × Density of the material

  M_T = 860 × 1370 kg/m^3 = 1178,200kg
- Converting kg to metric tons

  1 metric ton is equivalent to 1000kg
- Total mass in tons = 1178,200/1000 = 1178 tons.

The total cost of the clay required for the block wall will now be 1178 × 15 = 17.670$. Assuming that by adding the prices of form, hair reinforcement, plastic grid and labor. This value would be double (say 35000$). Still the price is lower than the concrete block wall cost. The summary of the estimated cost was shown in table 28 and also cost percentage difference was also shown below in figure 21 for both conventional hollow concrete block wall and LHRC wall.

Table 25: Estimated Cost Summary for LHRC Wall.

Story	Wall area (m^2)	No. blocks required	Total volume of blocks	Total mass clay required	Total mass in Tons	Total cost of clay ($)	Estimated total cost ($)
4	1812.76	21952	370.48	507356.6	507.36	7605	14000
7	2963.85	35960	604.13	828658.0	828.00	12415	25000
10	4222.26	51228	860.00	1178200.0	1178.00	17670	35000

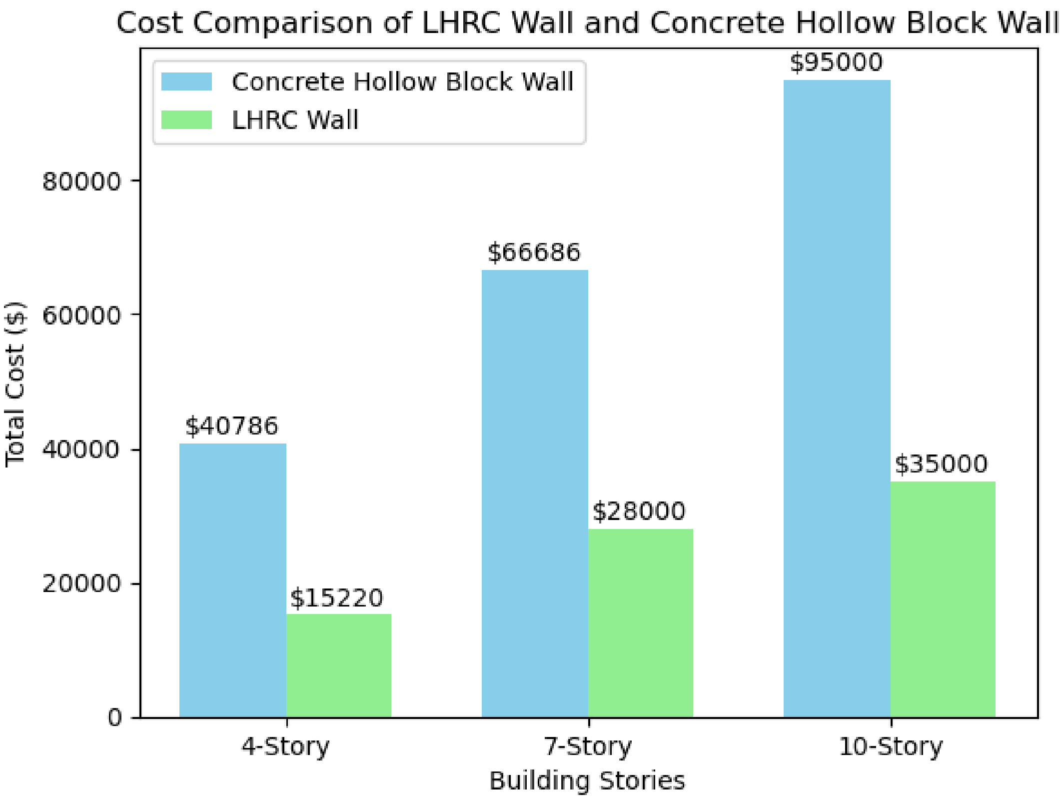


Figure 21: Cost Percentage Difference Between the Two-Wall Method.

When comparing Lightweight Hair-Reinforced Clay walls with conventional hollow concrete block walls, the average percentage cost reduction was approximately 63.8%.

This notable decrease highlights the LHRC wall system's economic benefits over conventional building wall method.

In addition to the reduction of walls' weigh because of using LHRC, the amount of required steel bars in the building skeleton is also remarkable, as shown in Table 13, and the resulted cost reduction should be added to the reduction mentioned in Figure 21 accordingly.

4.5 Thermal Transmittance

By calculating the thermal conductivity value (K-value) of each material from a manufacturer's website and certain numbers from other research publications, the mathematical calculation of the building's wall-to-wall heat transfer rate was performed. The U-value, also known as thermal transmittances, was then computed using these K-values. Table 29 displays the material combined ratio for both the new recommended material and the standard conventional approach.

Table 26: Composition of The Material LHRC.

Material	Thermal Conductivity (W/mK)	Proportion (%)
Clay	1.0	65.0
Hair	0.37	5.0
Recycled Plastic Bags	0.33	3.0
Foam	0.025	2.0
Air	0.028	25.0

4.5.1 Effective thermal conductivity of LHRC block

The effective thermal conductivity was estimated using a weighted average of the thermal conductivities of the different components, weighted by their relative quantities in the combination:

Equation 5. Effective thermal conductivity

$K_{eff} = \sum_{i=1}^{n}(k_i \times p_i)$

Where;

K_{eff} is the effective thermal conductivity of the composite

k_i is the thermal conductivity of each component

pi is the proportion of each component material in the composite

$K_{eff} = (1.0 \times 0.65) + (0.37 \times 0.05) + (0.33 \times 0.03) + (0.025 \times 0.02) + (0.028 + 0.25)$

$K_{eff} = 0.65 + 0.0185 + 0.0099 + 0.0005 + 0.007$

K_{eff} 0.6859W/mK.

We calculate the double skin wall's thermal transmittance (U-value) using the layers and conditions given, as per the process outlined in the ISO 6946:2017 standard for calculating the thermal transmittance of building components [62].

$$R_i = \frac{d_i}{\lambda_i} \quad (1)$$

$$R_{tot} = R_{si} + \sum R_i + R_{se} \quad (2)$$

$$U = \frac{1}{R_{tot}} \quad (3)$$

1. Internal Gypsum Plaster

Thickness (*d*): 0.015 m

Thermal conductivity (λ): 0.4 W/mK

2. External Cement Plaster

Thickness (*d*): 0.015 m

Thermal conductivity (λ): 0.721 W/mK

3. LHRC Block

Thickness (*d*): 0.2032 m

Thermal conductivity (λ): 0.6859 W/mK

4. Air Cavity

Thickness (*d*): 0.1 m

Thermal conductivity (λ): 0.028 W/mK.

Three layers the LHRC material layer, the exterior plaster layer, and the internal plaster layer were taken into consideration for the wall type in order to determine the thermal transmittance of the lightweight hair reinforced clay wall. For the inside layer, gypsum plaster was utilized, and for the external layer, cement mortar.

Each layer's thermal resistance (R) is determined using equation (1):

- Internal gypsum plaster $R = 0.015 \div 0.4 = 0.0375\text{m}^2\text{K/W}$
- External cement plaster $R = 0.015 \div 0.721 = 0.0208\text{m}^2\text{K/W}$
- LHRC block $R = 0.2032 \div 0.6859 = 0.2962\text{m}^2\text{K/W}$
- Air cavity $R = 0.1 \div 0.028 = 3.5714\ \text{m}^2\text{K/W}$.

The computation uses 0.13 and 0.04 m2K/W for internal and external surface resistance [62]. Equation (2) was utilized to get the total thermal resistances.

$R_{tot} = 0.13 + 0.0375 + 0.0208 + 0.2962 + 3.5714 + 0.04 = 4.096\text{m}^2\text{K/W}$

The reciprocal of the total thermal resistance is the thermal transmittance, or U-value as shown in equation 3:

$U = 1 \div R_{tot} = 1 \div 4.096$

$U = 0.244\text{W/m}^2\text{K}$.

The thermal transmittance for the conventional concrete block wall was also calculated for the comparison. The block having a thickness of 200mm, external cement plaster thickness of 15mm, and internal gypsum plaster thickness of 15mm. the wall have a total thickness of 230mm. the thermal conductivity values of the wall layers are shown below in table 30.

Table 27: Wall Material Property.

Material	Thermal conductivity W/m.k
Concrete hollow block	0.6
Cement plaster	0.8
Gypsum plaster	0.4

4.5.2 Thermal resistance of the materials (R-value)

R-value = material thickness/thermal conductivity of the material

Concrete hollow block: = 0.2/0.6 = 0.3333 m^2K/W

External cement plaster = 0.015/0.721 = 0.0208 m^2K/W

Internal gypsum plaster = 0.015/0.4 = 0.0375 m^2K/W.

The computation uses 0.13 and 0.04 m^2K/W for internal and external surface resistance [62].

R_{tot} = 0.13 + 0.3333 + 0.0208 + 0.0375 + 0.04 = 0.5616 m^2K/W

The thermal transmittance value (U-value) = 1/ R_{tot} = 1/0.5616 = 1.780 W/m^2K

using the same formulation method used above. This U-value is the rate of heat transfer through the wall per unit area per unit temperature differential across the wall. It is used to assess the thermal efficiency of building materials; lower values denote better insulating properties. Table 31 displays the computation summary for the LHRC wall.

Table 28: Summary of The Result.

Description	Formula	Calculation Result
Effective Thermal Conductivity (Keff) of LHRC Block	$K_{eff} = \sum_{i=1}^{n}(k_i \times p_i)$	*K*eff=0.6859 W/mK = 0.6859W/mK
Thermal Resistance of Internal Gypsum Plaster	$R_i = \frac{d_i}{\boldsymbol{\lambda_i}}$	*R*=0.0375 m2K/W*R*=0.0375m2K/W
Thermal Resistance of External Cement Plaster	$R_i = \frac{d_i}{\boldsymbol{\lambda_i}}$	*R* =0.0208 m2K/W*R*=0.0208m2K/W

Thermal Resistance of LHRC Block	$R_i = \frac{d_i}{\boldsymbol{\lambda_i}}$	R = 0.2962 m^2K/W
Thermal Resistance of Air Cavity	$R_i = \frac{d_i}{\boldsymbol{\lambda_i}}$	R = 3.5714 m^2K/W
Total Thermal Resistance (Rtot)	$R_{tot} = R_{si} + \sum R_i + R_{se}$	R_{tot} = 4.096 m^2K/W
Thermal Transmittance (U-value)	$U = \frac{1}{R_{tot}}$	U=0.244 W/m^2K

This data shows a considerable boost in thermal efficiency when compared to the double skin wall's calculated U-value of 0.244 W/m^2K. The lower U-value of a double skin wall indicates higher insulation and less heat conduction through the wall. Thanks to this better insulation, less energy is required to maintain proper indoor temperatures, which results in significant energy savings as well as a decrease in utility costs and the environmental impact of decreased energy usage. Furthermore, the double skin wall's benefits for the economy and environment are well supported by the long-term increases in energy cost savings. The comparison study demonstrates that the double skin wall is an eco-friendlier option that adheres to energy-saving goals and supports sustainable building practices. The percentage difference for the thermal transmittance value between the two-wall methods was shown in Figure 22.

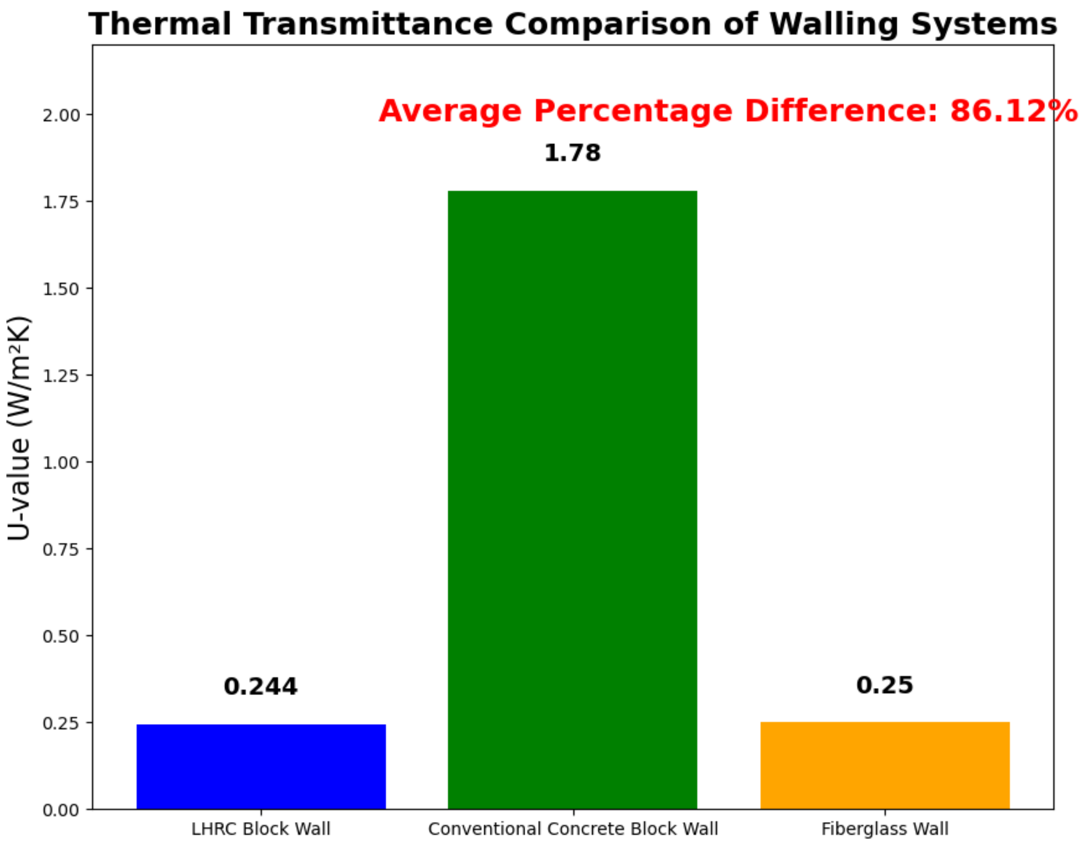


Figure 22: Comparison of the Thermal Transmittance Value for The Two-Wall Method.

When it comes to thermal insulation, the fiberglass wall and the LHRC block wall perform better than the traditional concrete block wall, with LHRC wall a little better than fiberglass. With a U-value of 0.25 W/m²K, the fiberglass wall significantly outperforms the traditional concrete block wall, which has a U-value of 1.78 W/m²K. This significant contrast demonstrates how well the fiberglass wall and the LHRC block wall work to stop heat transmission. For the purpose of preserving interior heat and cutting energy costs, both materials offer an improvement in thermal insulation of over 85%. Regarding that, according to the architectural plan, the percentage of external walls in the considered buildings is around 60%, using LHRC walls would result in almost 0.6×0.85=0.51 (51%) increase in the thermal insulation efficiency of the buildings.

There is a noticeable decrease in heat loss and an improvement in energy efficiency when the fiberglass wall or the LHRC block wall are used. Due to these materials' exceptional ability to keep buildings cool in the summer and warm in the winter, energy costs associated with heating and cooling buildings are reduced. As a result, switching from traditional concrete blocks to either the fiberglass wall or the LHRC block wall would greatly improve energy efficiency and save long-term energy expenses.

The significant difference in U-values suggests not only the thermal performance of the building envelope but also the potential for significant energy efficiency gains in building envelopes constructed using state-of-the-art materials and architectural methods.

Chapter 5

CONCLUSION AND RECOMMENDATION

5.1 Introduction

This chapter provides a comprehensive review of the study on the double skin wall method, also known as the lightweight hair-reinforced clay wall, as a cutting-edge and eco-friendly building material. We have looked into and contrasted LHRC with conventional building materials to look at its thermal properties, economic aspect, and structural performance. The findings demonstrate that LHRC may significantly reduce the economic impact of the building industry while still offering structural advantages. In this chapter, we will review the primary objectives and research questions that acted as the study's compass.

The following will provide an overview of the key findings from the analysis of structural weight effect on the seismic performance of the buildings, economic viability, and thermal efficiency of the wall element. We will also discuss the broader implications of the findings for sustainable construction practices, with an emphasis on how LHRC could assist the building sector in achieving its economic sustainability goals. This chapter also covers the challenges and limitations encountered during the study, providing information on topics requiring further investigation. We aim to demonstrate the significance of LHRC wall as a competitive alternative to traditional wall method.

The chapter concludes with recommendations for additional research and potential avenues for the wider deployment of LHRC in the construction industry, emphasizing the technology's importance in promoting and economic viability.

5.2 Summary of Key Findings

- Structural Weight Differences: The study discovered that the double skin wall method regularly lowers the seismic mass forces of the building's structural by about 12.71% at three distinct building heights: four stories, seven stories, and ten stories. The building's performance during earthquakes may be enhanced by this drop in seismic mass caused by the structural weight reduction.

  Drift: Across a different building height, LHRC walls consistently display lower maximum drift values, indicating improved performance in minimizing structural deformations.

  Modal Periods: Little change in modal periods indicate that LHRC walls do not make any significant shift in spectral values for seismic analysis.
- Thermal Transmittance: The LHRC wall's U-value of 0.244 W/m²K, as opposed to the traditional hollow concrete blocks' 1.7 W/m²K, indicates a notable increase in thermal efficiency. Because the LHRC wall satisfies usual building code standards for energy efficiency, it can be categorized as an insulating material with a U-value of less than 0.3 W/m²K. For instance, several nations' building codes place restrictions on materials' U-values, requiring them to be less than 0.3 W/m²K in order to qualify as effective insulators. By utilizing materials with low thermal transmittance, these regulations such as those set forth by the UK Building Regulations and the Energy Conservation Building Code (ECBC) aim to promote energy savings and increased indoor thermal comfort.

- Economic implication: When compared to traditional hollow concrete block wall, the hair-reinforced clay wall method offers significant cost reductions. For walls across different building heights (four-story, seven-story, and ten-story), in comparison Lightweight Hair-Reinforced Clay walls with conventional hollow concrete block walls, the average percentage cost reduction was approximately 63.8%. This notable decrease highlights the LHRC wall system's economic benefits over conventional building wall method.

5.3 Benefits from economic Sustainability Point of View

The benefits of the thesis about LHRC can be perceived from the angle of sustainability, encompassing environmental, social, and economic dimensions. The construction industry is one of the most voracious in terms of resource and energy consumption, making sustainable practices essential.

Economically, LHRC is a cost-effective alternative to conventional building materials. The thesis demonstrates that material costs for LHRC are lower because the materials used are locally available and inexpensive. The reduced weight of LHRC makes it cheaper in terms of labor and faster in construction, enhancing its economic viability. Over the building's lifecycle, maintenance costs associated with LHRC are expected to be lower due to its increased durability and reduced environmental degradation, resulting in significant long-term economic savings. Furthermore, using LHRC supports local economies through locally sourced materials, reduced transportation costs, and the creation of local employment opportunities.

5.4 Recommendations for Future Research

To improve understanding and application of lightweight hair reinforced clay (LHRC) in the construction sector, future research should concentrate on several important areas. First and foremost, it is crucial to have uniform policies and certification procedures for the manufacturing and application of LHRC. In order to ensure uniformity and reliability in LHRC materials and to increase acceptance among engineers and architects, it will be easier to adopt if consistent quality benchmarks and performance criteria are established.

The durability and climate resistance of LHRC under varied environmental conditions, such as moisture, temperature changes, and other climatic elements over longer periods of time, must be evaluated by long-term performance tests. When comparing LHRC to conventional building materials, this data is essential for confirming its sustainability and long-term dependability. In order to verify LHRC's viability in earthquake-prone areas, extensive research should also assess the building's seismic resilience. This evaluation should concentrate on how the building functions under seismic pressures and consider possible retrofitting methods for already-existing structures.

Economic viability is yet another important topic for further investigation. There should be thorough cost-benefit evaluations that compare LHRC with conventional building materials. These analyses should include lifecycle cost assessments, which take into consideration the building's potential savings over time as well as initial construction costs, maintenance, and energy efficiency. The economic benefits and drawbacks of LHRC in various market situations will become more evident as a result of these evaluations.

Finally, it should be noted that the analysis of buildings in this study was limited to linear equivalent and spectral method of the seismic design code, and however, it would be much more reliable if nonlinear time history analyses by using the accelerograms of selected earthquakes are performed, the behavior of buildings in the two cases, would be possibly more different, and the effect of using LHRC walls would show it effect more clearly from seismic behavior point of view.

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