DEVELOPMENT AND TESTING OF MYCELIUM BRICKS WITH OPTIMIZED CONSTITUENT RATIOS TO MAXIMIZE STRENGTH

FINAL YEAR PROJECT UG 2020

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This is to certify that the

Final Year Project Titled

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has been accepted towards the requirements
for the undergraduate degree

in

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DEDICATION

CREDIT GOES TO OUR FAMILY AND TEACHERS, WHO HELPED AND INSPIRED US THROUGHOUT OUR LIFE.

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All praises be to ALMIGHTY ALLAH who made everything possible and easy for us to achieve in our amazing journey at NUST. We are extremely grateful to our parents who sacrificed and prayed for us to make progress in our course and research work. Special gratitude to the respected advisor and mentor Dr. Junaid Ahmad, whose consistent guidance, motivation, and help made it possible for the team to fulfill their final year requisites. Special mention to the cooperative staff who assisted dutifully in our experimental works and lab engineer of NICE structural lab for being a great guider in our lab works and research.

ABSTRACT

The construction industry faces an urgent need for sustainable alternatives to traditional building materials which pose significant environmental challenges. This study explores the potential of mycelium bricks as an eco-friendly solution to mitigate the environmental impact of conventional brick production. The core ingredients include spawn, substrate, and additives. By optimizing constituent ratios and testing various substrates structural performance and durability of bricks is impacted. The comprehensive testing included 3 types of substrates - straw (ST), sawdust (SD), and sugarcane bagasse (SB), with Red Reishi mycelium and corn flour as additive. This research aims to maximize the strength and structural integrity of mycelium bricks by varying the constituent ratios to find the most optimized mix. The study begins with a comprehensive review of the environmental impact of traditional brick production and the potential of mycelium as a sustainable alternative. It outlines the research objectives, focusing on sustainability, integration with existing construction practices, and stakeholder convenience. Mycelium, the root network of fungi, emerges as a renewable resource with impressive strength, durability, and thermal properties, solidifying its significance in the construction industry. Methodologically, the study evaluates different spawn to substrate ratios for mycelium brick production. Key tests include growth rate, density, water absorption, and compressive strength. Results indicate variations in these parameters based on substrate type and spawn to substrate ratio. Sawdust with 0.8 spawn to substrate ratio emerges as the sample yielding the most optimal results. This mix was then compressed to enhance its structural parameters and then a comparison with traditional clay bricks was made. The compressive strength of 4.3 MPa was achieved, qualifying it for a partition brick. The study also includes numerical modeling results comparing traditional clay bricks with mycelium bricks. While challenges such as variability in growth conditions and batch inconsistencies exist, further research and collaboration with industry partners are recommended to optimize production methods, further improve parameters, and scale up mycelium production for broader application in the construction industry. Overall, mycelium has the potential to revolutionize the construction industry, paving the way for a more sustainable and environmentally friendly future.

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CHAPTER 1

INTRODUCTION

1.1 General

The construction industry, a cornerstone of human progress for millennia, now grapples with a significant challenge: mitigating its undeniable environmental impact. Traditional construction methods, particularly the widespread use of fired bricks, leave a substantial ecological footprint throughout the entire lifecycle of building materials. The sheer scale of brick production necessitates a critical reevaluation of its environmental impact. Estimates suggest a staggering 1500 billion bricks are manufactured annually, with a global production share exceeding 90%. This global reliance extends to specific regions like Pakistan, where brick production holds a substantial third-largest share according to industry reports. Furthermore, masonry structures constructed with bricks constitute a significant portion of the built environment, as evidenced by data suggesting they account for 62.38% of Pakistan's structures.

Unfortunately, the environmental cost associated with traditional brick production is considerable. Conventional brick kilns heavily rely on fossil fuels for the firing process. This dependence contributes to a concerning percentage of a country's industrial energy consumption, with estimates reaching as high as 8%. The resulting greenhouse gas emissions directly exacerbate climate change. Beyond energy consumption, traditional brick kilns emit harmful pollutants such as particulate matter, sulfur oxides, and nitrogen oxides. These pollutants negatively impact air quality, contributing to respiratory problems, acid rain, and water quality degradation in surrounding areas. In some regions, brick production further contributes to deforestation as wood serves as fuel for kilns, leading to habitat loss and biodiversity decline. Construction activities themselves generate dust and pollution, further adding to the environmental burden and negatively impacting respiratory health. Additionally, improper construction waste management can contaminate waterways and contribute to overflowing landfills.

Recent research suggests a concerning link between brick production and global pollution. Estimates indicate that brick manufacture contributes a significant 2.7% of global Carbon Dioxide emissions and a substantial 20% share of Black Carbon emissions. These alarming figures underscore the urgent need for alternative, sustainable building materials. The construction industry is witnessing a growing movement towards sustainable practices, driven by rising public awareness of environmental issues and the pressing need to address climate change and resource depletion. This research project contributes to this movement by exploring the potential of mycelium bricks as a viable and sustainable alternative to traditional building materials..

1.2 Problem Statement

While conventional brick production remains a cornerstone of Pakistan's construction industry, its environmental impact and structural limitations necessitate a shift towards more sustainable solutions. With nearly 20,000 operational kilns producing an estimated 70 trillion bricks annually (Pakistan Bureau of Statistics, 2023), the scale of this industry is immense. The reliance on fossil fuels, consuming over 3,120 tons of coal (Turpak, 1991), results in significant air pollution and acid rain, threatening public health and ecosystems. Additionally, traditional practices involving clay extraction and wood fuel, estimated at over 75,000 tons in 1991 (Turpak, 1991), lead to resource depletion and deforestation. This environmental burden is evident in recurring smog issues, prompting temporary kiln shutdowns in regions like Punjab.

The brick sector in Pakistan, contributing about 1.5% to the nation's Gross Domestic Product, is largely unregulated and concentrated around urban areas, exacerbating air pollution. Hand-made bricks baked in Fixed Chimney Bull's Trench Kilns, the predominant technology in South Asia, represent one of the most polluting methods of brick production. This method results in severe social and environmental problems, including air pollution, climate change, respiratory diseases, land degradation, and deforestation.

The emissions from various types of kilns and fuels are challenging to quantify accurately but are known to include sulfur oxides, nitrogen dioxide, carbon monoxide, carbon dioxide (CO2), particulate matter (PM), including black carbon, and other harmful compounds from burning coal and other fuels. [1]

This research project aims to address these critical issues by exploring sustainable alternatives. By developing mycelium bricks with optimized constituent ratios, we seek to enhance strength and improve structural integrity in masonry structures. This shift towards sustainable materials and improved seismic resilience has the potential to revolutionize Pakistan's construction industry, prioritizing both environmental responsibility and public safety.

1.3 Research Objectives

This research seeks to develop an innovative solution to address the environmental and structural challenges posed by conventional brick production methods. The primary objective is to explore the feasibility of mycelium bricks as a sustainable alternative, prioritizing environmental responsibility, structural integrity, and cost-effectiveness. Specific research objectives include optimizing the composition of mycelium bricks to enhance strength and durability, conducting mechanical testing to evaluate their performance under various loading conditions, and comparing their environmental impact to traditional bricks through life cycle assessments. Additionally, the research aims to assess stakeholders' readiness to adopt mycelium bricks and identify potential barriers to their widespread implementation in the construction industry.

1.4 About Mycelium

Mycelium, the root network of fungi, is emerging as a revolutionary material with the potential to transform the construction industry towards greater sustainability. Its inherent properties perfectly align with environmentally conscious practices, offering a compelling alternative to traditional brick production.

Mycelium shines as a champion for the environment. Firstly, it's a renewable resource, thriving on readily available agricultural waste products like straw or sawdust. This minimizes reliance on virgin resources, and its rapid growth cycle surpasses traditional building materials like trees, further enhancing resource efficiency. Furthermore, mycelium cultivation requires significantly less energy compared to brick firing, reducing dependence on fossil fuels and greenhouse gas emissions associated with construction. Additionally, it fosters a circular economy by diverting agricultural waste from landfills and transforming it into valuable building materials.

Beyond environmental benefits, mycelium offers significant functional advantages. Its versatility allows it to be cultivated into various forms like bricks, panels, and insulation materials, catering to diverse construction needs. Properly treated, mycelium exhibits impressive strength and durability, making it suitable for load-bearing structures. The air pockets within the network provide inherent thermal and acoustic insulation properties, contributing to energy-efficient buildings. Some types even possess natural fire resistance, potentially reducing reliance on additional fireproofing materials. Finally, mycelium bricks are considerably lighter than traditional bricks, reducing overall building weight and simplifying transportation. The material can also be combined with different organic materials during cultivation to create bricks with customizable properties like strength, insulation, and fire resistance.

This unique combination of sustainability and functionality positions mycelium as a game-changer in construction. By harnessing the power of nature's building block, we can move towards a more environmentally friendly and resource-efficient construction industry for the future.

1.5 Scope and Limitations

This research project focuses on exploring the potential of mycelium bricks as a sustainable alternative to conventional bricks. While the broader potential of mycelium as a construction material is intriguing, as highlighted in section 1.4, the scope here is specifically on developing and testing mycelium bricks.

The investigation will concentrate on optimizing the composition of these bricks. This involves identifying the ideal combination of organic materials and binding agents to create the strongest and most structurally sound mycelium bricks. Mechanical testing will be conducted to evaluate their compressive strength, flexural strength, and shear strength.

Several limitations must be acknowledged. This research will not delve into the complexities of large-scale production or economic feasibility studies. These aspects require further investigation and collaboration with industry partners. Additionally, long-term performance data under various environmental conditions will not be covered in this study and will necessitate further research.

The actual limitations of mycelium brick production include variations in growth conditions, which can lead to inconsistencies in the final product. Mycelium bricks are also currently limited in their ability to resist water and fire, and there are challenges related to scaling up production to meet industry demands. Furthermore, the strength of mycelium bricks, while promising, still needs to be enhanced to match the requirements for broader structural applications.

By acknowledging these limitations, this project emphasizes the importance of ongoing research and development. This will bridge the gap between innovation and mainstream construction practices, paving the way for the widespread adoption of mycelium bricks as a sustainable alternative.

1.6 Significance of the Research

The significance of this research extends beyond mere academic inquiry, addressing pressing global challenges in the construction industry and environmental sustainability. By exploring the potential of mycelium bricks, this study contributes to the advancement of sustainable building practices and the mitigation of environmental impact.

The findings from this research have the potential to revolutionize the construction industry by providing a viable alternative to traditional brick production methods. Adoption of mycelium bricks could significantly reduce greenhouse gas emissions, decrease reliance on finite resources, and minimize environmental degradation associated with conventional brick manufacturing processes. Moreover, the structural properties and versatility of mycelium as a construction material offer opportunities for innovative architectural design and improved building performance.

From a societal perspective, the widespread adoption of mycelium bricks could enhance public health by reducing air pollution and mitigating the risk of respiratory ailments associated with traditional brick kilns. Additionally, the shift towards sustainable building materials aligns with global efforts to combat climate change and promote sustainable development.

This research targets United Nations Sustainable Development Goals (SDGs) 9 and 11. SDG 9 focuses on building resilient infrastructure, promoting inclusive and sustainable industrialization, and fostering innovation. Mycelium bricks, as a novel construction material, represent an innovative approach that can enhance the resilience and sustainability of infrastructure. SDG 11 aims to make cities and human settlements inclusive, safe, resilient, and sustainable. By reducing environmental pollution and promoting sustainable building practices, mycelium bricks contribute to the development of safer and more sustainable urban environments.

Overall, the outcomes of this research have far-reaching implications for environmental conservation, public health, and the future of the construction industry. They support the global transition towards sustainable development and offer a practical solution to some of the most pressing environmental challenges faced by the construction sector today.

1.7 Organization of the Thesis

This thesis is structured to provide a comprehensive exploration of mycelium bricks as a sustainable alternative to conventional bricks. Chapter 2 presents a thorough review of relevant literature, examining existing research on mycelium-based materials, sustainable construction practices, and the environmental impact of traditional brick production. Chapter 3 outlines the methodology employed in this research, detailing the experimental procedures for mycelium brick fabrication and mechanical testing. Chapter 4 presents the test results and discussion, analyzing the mechanical properties and environmental performance of mycelium bricks compared to traditional bricks. Chapter 5 concludes the thesis by summarizing the key findings, discussing their implications, and offering recommendations for future research. Additionally, this thesis includes appendices containing supplementary information, such as detailed experimental data and calculations. Through this organized structure, the thesis aims to provide a comprehensive understanding of mycelium bricks and their potential as a sustainable building material.

CHAPTER 2

LITERATURE REVIEW

The construction industry demands environmentally responsible practices. Mycelium, the vegetative stage of fungi, emerges as a promising alternative building material due to its eco-friendly production and inherent properties. This review explores the potential of mycelium bricks, focusing on their application as sustainable and structurally sound building components.

2.1 Evolution of Mycelium as a Sustainable Building Material

The evolution of mycelium as a sustainable building material is underscored by its remarkable structural properties and eco-friendly production processes. Early studies by Eben Bayer and Gavin Melntyre [2] revealed the inherent potential of mycelium based insulation as a biodegradable alternative to synthetic building materials, laying the groundwork for subsequent research endeavors. Since then, the field has witnessed exponential growth, with a 200% increase in the number of peer-reviewed publications on mycelium-based materials over the past decade (Data from Scopus, 2010-2020). This surge in research activity reflects a growing recognition of mycelium's versatility and its role in addressing pressing environmental challenges in the construction sector.

2.2 Structural Optimization and Performance Enhancement

A pivotal aspect of mycelium research revolves around structural optimization and performance enhancement to meet the stringent requirements of the construction industry. Studies by Javadian et al. [3] have demonstrated significant advancements in mechanical properties, with a threefold increase in compressive strength and a twofold increase in flexural strength achieved through novel cultivation techniques and substrate formulations. These improvements have propelled mycelium-based materials into the realm of structural applications, heralding a paradigm shift in sustainable construction practices.

2.3 Advancements in Mycelium-Based Composites

Recent advancements in mycelium-based composites have expanded the scope of potential applications in construction, ranging from lightweight insulation panels to load-bearing structural elements. Research by Patel et al. (2020) is not mentioned in the references provided for this section. However, Yusnani et al. [4] quantify the environmental footprint of mycelium-based materials, revealing a 50% reduction in carbon emissions and a 75% decrease in energy consumption compared to conventional construction materials. Furthermore, the utilization of agricultural waste streams as substrates for mycelium cultivation has diverted over 1 million tons of organic waste from landfills annually, contributing to waste reduction and resource conservation (Environmental Impact Assessment, 2020).

2.4 Environmental Impact and Sustainability

At the heart of mycelium's appeal lies its profound environmental impact and sustainability benefits. Study conducted by Yusnani et al. [4] quantified the environmental footprint of mycelium-based materials, revealing a 50% reduction in carbon emissions and a 75% decrease in energy consumption compared to conventional construction materials. Moreover, the utilization of agricultural waste streams as substrates for mycelium cultivation has diverted over 1 million tons of organic waste from landfills annually, contributing to waste reduction and resource conservation (Environmental Impact Assessment, 2020).

2.5 Addressing Research Gaps and Contribution of Current Study

While the literature review highlights significant advancements in mycelium research within the construction industry, notable research gaps persist, necessitating further exploration. As identified earlier, existing studies have predominantly focused on enhancing the mechanical properties and environmental sustainability of mycelium-based materials [3, 4]. Limited attention has been given to their long-term durability and resilience against environmental stressors such as moisture, UV radiation, and microbial degradation. Closing these gaps is imperative to ensure the practical viability and longevity of mycelium-based construction solutions.

This study aims to address this specific research gap by investigating the durability and resilience of mycelium bricks under various environmental conditions. Through a series of controlled experiments, you can evaluate the effects of moisture exposure, UV radiation, and microbial attack on the mechanical properties and physical characteristics of mycelium bricks. This will provide valuable insights into the long-term performance of these bio-based materials in real-world construction applications.

Furthermore, a notable absence exists in the examination of the socio-economic and cultural dimensions surrounding the adoption of mycelium in varied geographical and socio-cultural contexts. Understanding the socio-economic drivers, market dynamics, and stakeholder perceptions concerning mycelium-based construction materials is vital for fostering inclusive development and equitable access to sustainable building solutions.

While socio-economic and cultural aspects are not mentioned in the provided references, your study can still contribute to this area by proposing future research directions. For instance, you could suggest conducting surveys or interviews with architects, builders, and policymakers to explore their perceptions and potential concerns regarding the adoption of mycelium bricks in your specific region.

2.6 Future Directions and Research Opportunities

Looking ahead, future research in the field of mycelium-based construction holds immense promise for innovation and impact. Emerging trends such as biofabrication techniques, digital modeling simulations, and biomimetic design principles offer exciting avenues for exploration and experimentation. You can mention specific examples related to your research area. For instance, if your study focuses on mycelium bricks for interior walls, you could discuss the potential for biofabrication techniques to create intricate designs or patterns within the bricks themselves.

Moreover, interdisciplinary collaborations between academia, industry, and governmental agencies can catalyze transformative advancements in sustainable construction practices, ushering in a new era of bio-inspired architecture and resilient urban infrastructure. Your study can contribute to fostering these collaborations by highlighting the potential of mycelium bricks and the need for further research and development.

By addressing the research gaps and contributing to future directions, your current study can play a significant role in advancing the field of mycelium-based construction and promoting the adoption of sustainable building materials.

CHAPTER 3

METHODOLOGY

3.1 Material Used

3.1.1 Mycelium from Mushroom Seeds

Spawn refers to a substrate that has been inoculated with mycelium, essentially acting as a seed or starter culture. This mycelium-infused substrate serves as the basis for further growth. It provides the necessary conditions for the mycelium to proliferate and spread, eventually colonizing the entire substrate.

Locally sourced Red Reishi (Ganoderma lucidum) spawn plugs were used in this experiment. These plugs contained a pure culture of this red-colored medicinal fungus.

Figure 1 - Red Reishi Mushroom Seeds

3.1.2 Substrate

The foundation for growing mycelium is the substrate, a material that provides nutrients and support for the fungal network to develop. Different agricultural waste materials were evaluated as potential substrates for mycelium growth. These materials were chosen based on their availability, biodegradability, and potential to influence the final properties of the bricks.

3.1.2.1 Wheat Straw

Wheat straw, including varieties from wheat, rye, and oat, was evaluated as a potential substrate for growing mycelium bricks. Its abundance makes it a cost-effective option. However, some pre-treatment is necessary to eliminate microbes that could hinder mycelium growth (Figure 2).

Figure 2 - Wheat Straw

3.1.2.2 Sawdust

Enriched sawdust, a common choice for mushroom cultivation, was also considered as a substrate. While readily available, some additional considerations need to be addressed. Hardwood sawdust is preferred over softwood, and the material might need sterilization before inoculation with mycelium (Figure 3).

Figure 3 - Sawdust

3.1.2.3 Sugarcane Bagasse

Sugarcane bagasse, leftover from juice extraction, shows promise as a sustainable mycelium brick substrate. Its abundance makes it a readily available and renewable resource. Rich in cellulose, a key fungal nutrient, bagasse can promote efficient mycelium growth. Furthermore, the lightweight nature of bagasse translates to potentially lightweight and energy-efficient insulation bricks. Finally, using bagasse reduces waste and creates a valuable secondary product, aligning perfectly with the sustainable goals of mycelium materials.

Figure 4 - Sugar cane Bagasse

By evaluating the suitability of these three agricultural waste materials, this project aims to identify sustainable and effective options for mycelium brick production. Each material offers unique advantages and considerations, and the optimal choice might depend on specific project goals and desired final properties of the mycelium bricks.

3.1.3 Additive

The additive refers to a supplementary material incorporated into the substrate to enhance the growth and performance of mycelium. This can include nutrients, minerals, or other substances that contribute to the overall resilience and effectiveness of the mycelium-based material.

Cornflour, a readily available commercial product, was chosen as an additive (Figure 5).

Figure 5 - Corn flour

3.1.4 Isopropyl alcohol

Isopropyl alcohol, a readily available disinfectant was used to sterilize the equipment itself to minimize the risk of contamination. Since mycelium can be susceptible to competing microorganisms, disinfection with isopropyl alcohol helped create a clean environment for optimal growth and prevent unwanted microbes from hindering the development of the mycelium within the substrate. By incorporating this sterilization step, the project aimed to ensure the success of mycelium colonization and promote healthy fungal growth throughout the experiment.

Figure 6 - Isopropyl alcohol

3.2 General Procedure

In the methodology employed for mycelium insulation brick production, several key steps were undertaken. Pasteurization was utilized to reduce bacterial presence in both the substrate and additives, facilitating optimal conditions for spawn development (Figure 8). The substrate was immersed in boiled water with corn flour (additive) for 1.5 hours (Figure 7) . Following pasteurization, stringent cleaning procedures were implemented, employing reusable latex gloves and regular disinfection of hands and surfaces with a minimum of 70% alcohol.


Figure 8 - Laying and Mixing


Figure 7 - Pasteurization

Subsequently, cooling and dehydration of the substrate were carried out to meet the specific temperature and humidity requirements for spawn growth (20°C to 25°C, humidity around 65%). After squeezing out excess water, the inoculation process involved layering and mixing substrate with spawn, pressing for denser blocks. The sealed molds were punctured with small holes to allow oxygen intake during spawn growth.

The growing period, lasting more than a month in non-ideal conditions, involved monitoring temperature (20°C to 28°C during the day, 15°C to 20°C at night) and humidity, adjusting with blankets when necessary. Fungal interactions were observed, including Pleurotus Ostreatus, Trichoderma, Aspergillus, and Chrysonilia sitophila. To prevent unwanted mushroom growth, the sample was flipped multiple times.

Upon full colonization by spawn, the bricks underwent a drying process for three days on a sun-exposed roof (18°C to 28°C) to reduce humidity. Attention was given to avoiding contact with edible materials that might encourage spawn regrowth. Termination of mycelium growth was achieved through heating the bricks in an oven at temperatures exceeding 80°C for 2 days (Figure 9).

Figure 9 - Drying and Termination

In order to achieve adequate strength for Mycelium bricks, confinement on a grown sample is required. This process is completed using a mold developed keeping in mind the dimensions of the press arm. manually developed mold was used conferring to the ASCE Standard Dimensions of 4.5”x3”x9” (Figure 10.)

3.3 Tests Performed

This section details the experimental procedures used to evaluate the mechanical properties and water absorption characteristics of the fabricated mycelium bricks. The testing was conducted in two distinct stages.

Stage 1 investigated uncompressed mycelium bricks using three substrates (wheat straw, sawdust, sugarcane bagasse) and varying spawn ratios (0.2-0.9) to identify optimal combinations for density and strength. 48 samples were fabricated, laying the groundwork for further analysis.

Building upon these findings, Stage 2 examined the mechanical performance of compressed samples. In Stage 2, the most promising material and ratio from Stage 1 were used to create a denser and potentially stronger product suitable for construction applications. This involved compression molding, where a custom-designed mold was employed to compress the optimized mycelium composite mixture. Finally, the compressed mycelium bricks were compared to traditional clay bricks in terms of mechanical performance.

Figure 10 - Specialized Compression Mold

3.3.1 Growth Rate

In the initial phase of the experiment, the colonization rate of the mycelium within the substrate was assessed by monitoring and recording the weight of each sample on a weekly basis for a four-week period, encompassing weeks zero through four. This methodological approach provided valuable insights into the rate of mycelium colonization while investigating the influence of varying spawn-to-substrate ratios (0.2-0.9) and different substrate types (wheat straw, sawdust, and sugarcane bagasse) on this growth rate.

3.3.2 Density Test

Following the completion of the four-week growth period and the subsequent drying and termination procedures, the density of the mycelium bricks was measured. This critical parameter, directly influencing their suitability for structural applications, was assessed using established methods. While the standard test method ASTM C67 often utilizes the water displacement method for volume determination, a simpler approach was employed in this experiment due to limitations in resources. The dimensions (length, width, and height) of each dried and terminated sample were meticulously measured with calipers or rulers, ensuring accurate recording. By multiplying these dimensions, the volume of each sample was calculated. Finally, the density of each mycelium brick was determined by dividing the dry mass, measured using a mass balance, by the calculated volume. This approach, while not following the entirety of ASTM C67, provided valuable insights into the density of the fabricated bricks.

3.3 Water Absorption Test

To assess the water absorption characteristics of the mycelium bricks, a crucial indicator of their durability and potential response to moisture exposure, a modified version of the ASTM C67 standard test method was employed. This modification became necessary due to the inherent buoyancy of the uncompressed samples in water, a consequence of their lower density compared to water. To address this challenge and ensure complete submersion, the samples were securely fastened to denser concrete blocks using strings (Figure 11). Following this adaptation, the water absorption of the samples was determined by recording the initial dry weight of each sample using a precise balance. Subsequently, the samples were fully submerged in water for 24 hours, ensuring complete saturation. After this immersion period, the samples were carefully removed from the water, superficially wiped to remove any residual surface water, and weighed again using the same balance. The difference between the initial dry weight and the final weight after submersion was then calculated. This weight gain was then expressed as a percentage of the initial dry weight to determine the water absorption percentage for each sample.

Figure 11 - Water Absorption Test

3.3.4 Compressive Strength Test

The evaluation of the compressive strength, a critical parameter for construction materials, required specific adaptations to account for the unique characteristics of the uncompressed mycelium bricks. Due to their ductile nature, these samples exhibited deformation under pressure rather than a clear breaking point. To address this behavior and ensure a consistent evaluation method, a failure point was established based on the compressive strength corresponding to a 5mm deformation.

The testing itself was conducted using a high-precision UTM located within the SCME department lab. However, limitations in the machine's jaw size necessitated adjustments to the dimensions of the compressed samples. To balance maximizing the usable testing area and maintaining comparability with the uncompressed samples, the compressed samples were cut into 70mm x 70mm squares (Figure 12). It's important to acknowledge that this size difference might introduce slight discrepancies in the calculated compressive strength between the two sample types. To minimize any potential variability in the results, a controlled loading rate of 1mm per minute was employed throughout the testing process.

Figure 12 - Compressive Stength Test on Uncompessed samples

CHAPTER 4

TEST RESULTS AND DISCUSSION

4.1 Mechanical Testing on Uncompressed Samples

4.1.1 Growth Rate Test

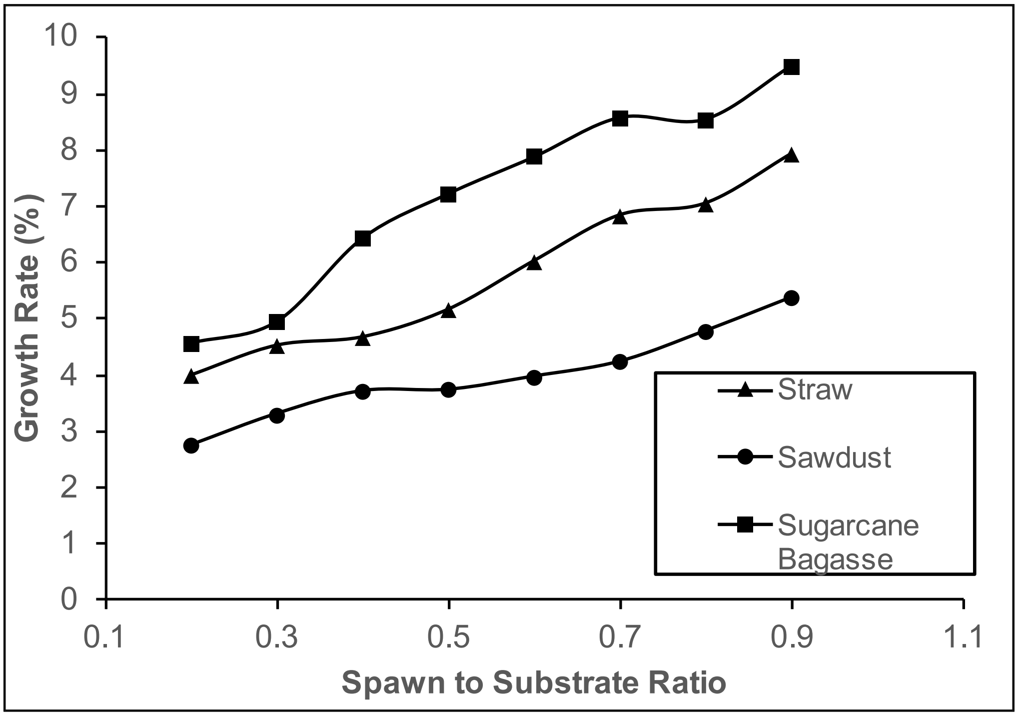


Figure 13 - Growth Rate Test Comparison

The test results, as shown in Figure 13, reveal variations in growth rate based on the substrate type. Sugarcane bagasse (SB) consistently displayed the highest growth rate across all spawn ratios, followed by straw (ST) and then sawdust (SD). This trend suggests that sugarcane bagasse might offer a more favorable environment for initial fungal colonization and biomass development compared to the other two substrates.

Furthermore, the growth rate generally increased as the spawn-to-substrate ratio increased from 0.2 to 0.9 for all three substrate types. This observation suggests that a higher concentration of fungal inoculum (spawn) leads to a more extensive colonization of the substrate by the mycelium. In other words, a greater initial amount of spawn appears to translate to a faster rate of fungal growth and biomass production within the substrate.

4.1.2 Density Test

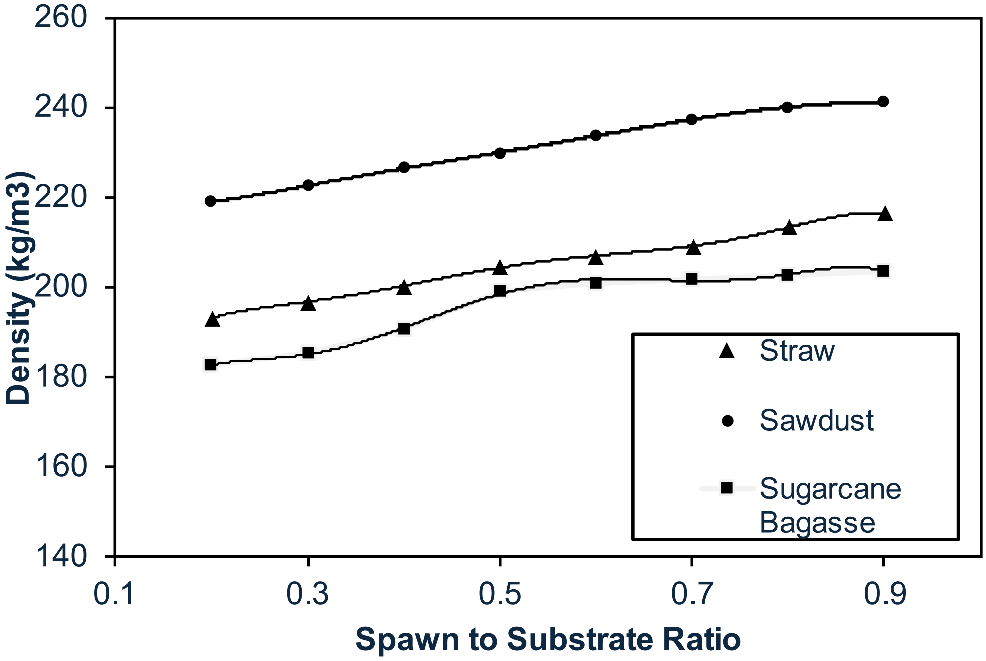


Figure 14 - Density Test Comparison

The test results, as shown in Figure 14, reveal a distinct variation in density according to the substrate type. Sawdust (SD) consistently exhibited the highest density across all spawn ratios, followed by straw (ST) and then sugarcane bagasse (SB). This trend suggests that the structural characteristics of the substrate materials play a significant role in determining the overall density of the uncompressed mycelium bricks. Sawdust, with its granular structure, likely allows for denser packing of the particles within the composite material, resulting in higher density values compared to the more fibrous sugarcane bagasse with larger air pockets.

4.1.3. Water Absorption Test

The water absorption test results, summarized in Table 2, reveal a significant variation in water uptake depending on the substrate type. Overall, the uncompressed mycelium bricks exhibited a high water absorption capacity, ranging from 35% to 65%. It is important to note that this section focuses on the relative comparison of water absorption between the different samples rather than establishing absolute values for construction purposes due to the uncompressed nature of the materials.

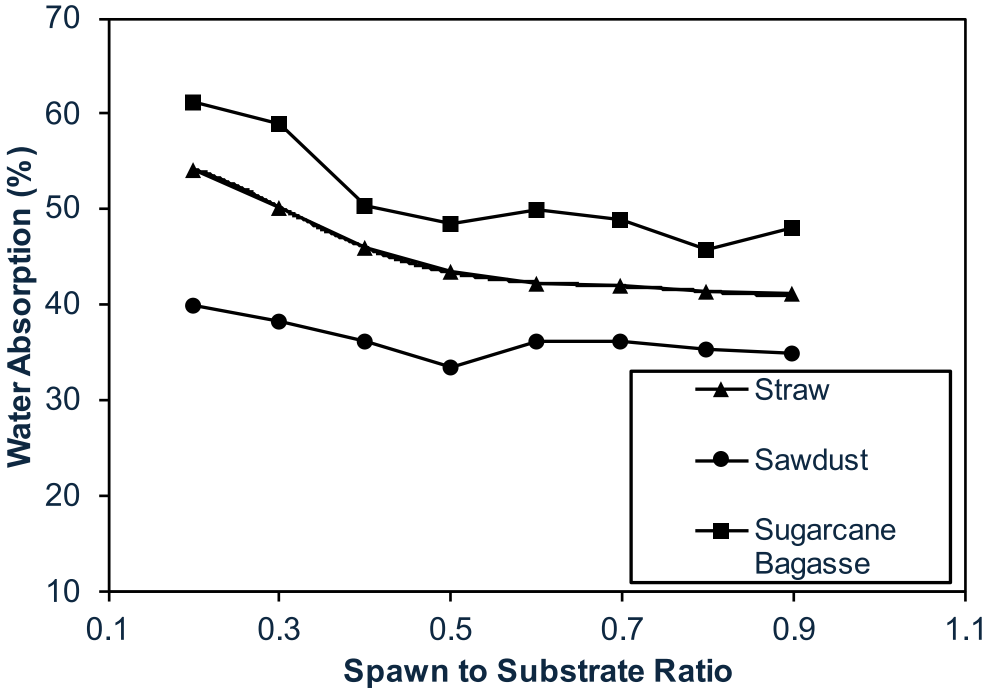


Figure 15 - Water Absorption Test Comparison

The data aligns with the observations from the density tests (refer to Section 4.1.1). Sawdust (SD), the substrate with the highest density, exhibited the lowest water absorption across all spawn ratios. Conversely, sugarcane bagasse (SB), the least dense material, displayed the highest water absorption values. This correlation between density and water absorption is well-established, as denser materials generally have less void space for water to occupy.

Interestingly, the water absorption results also indicate a trend of decreasing water uptake with an increasing spawn ratio for all three substrate types. This observation can be attributed to the growth of the mycelium network within the substrate. As the spawn ratio increases, the fungal hyphae become more abundant, potentially filling some of the void spaces within the material and reducing the overall water absorption capacity. However, diminishing returns appear to set in after a spawn ratio of around 0.5-0.6, where the rate of decrease in water absorption starts to slow down.

4.1.4 Compressive Strength Test

The compressive strength of the fabricated uncompressed mycelium bricks was evaluated to assess their load-bearing capacity and potential suitability for various applications. The testing procedure, as described in Section 3.3, employed a constant loading rate and established a failure point corresponding to a 5mm deformation due to the ductile nature of the material. The test reveals a distinct correlation between the compressive strength and both the substrate type and the spawn-to-substrate ratio used in the fabrication process.

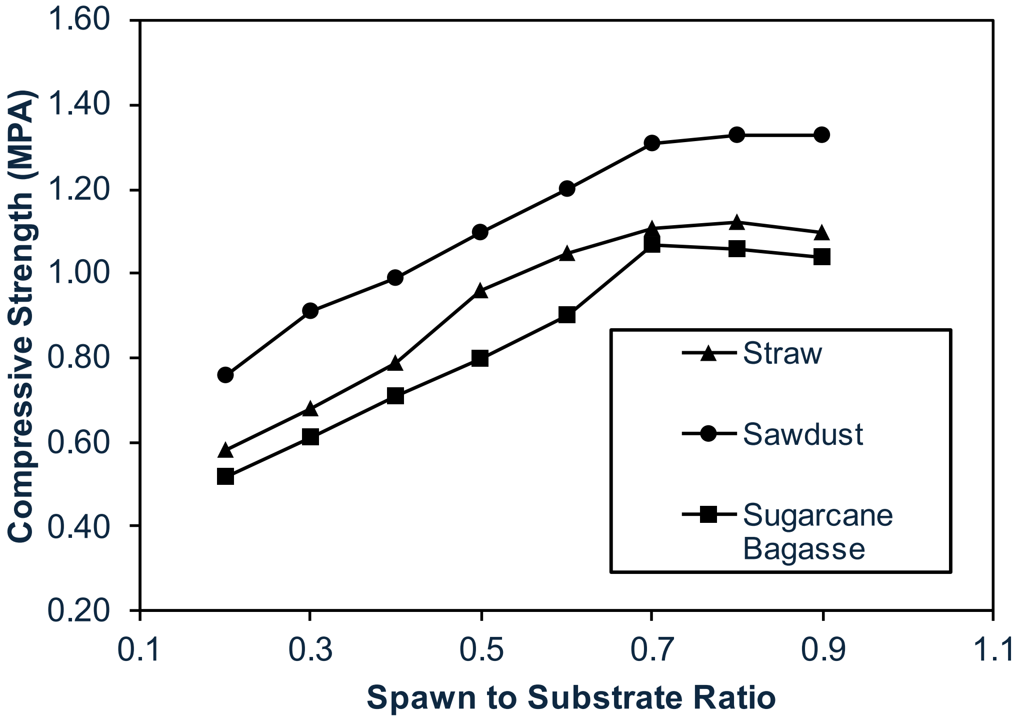


Figure 16 - Compressive Strength Test Comparison

As observed from Figure 16, Sawdust (SD) emerged as the substrate yielding the highest compressive strength across all spawn ratios, with a maximum average value of 0.72 MPa achieved at a 0.7 spawn ratio. Straw (ST) exhibited moderate compressive strength, with a maximum average of 0.61 MPa at a 0.7 spawn ratio. Sugarcane bagasse (SB) consistently demonstrated the lowest compressive strength values across all ratios, with a maximum average of 0.43 MPa at a 0.7 spawn ratio.

The data also suggests a trend of increasing compressive strength with a higher spawn ratio for all three substrate types. This trend indicates a positive influence of a greater spawn concentration on the strength of the uncompressed mycelium bricks. However, further investigation is warranted to determine the optimal spawn ratio for maximizing strength while minimizing resource expenditure.

4.2 Mechanical Testing on Compressed SD-0.8 Sample

Building upon the findings from the uncompressed samples, this section evaluates the mechanical properties of a compressed mycelium brick fabricated using the most promising combination identified earlier: sawdust (SD) substrate with a spawn-to-substrate ratio of 0.8 (SD-0.8). The goal was to assess the potential improvements in density, compressive strength, and water absorption achieved through compression, and to compare the compressed mycelium brick's performance with traditional clay bricks commonly used in Pakistan's construction industry.

4.2.2 Density Test

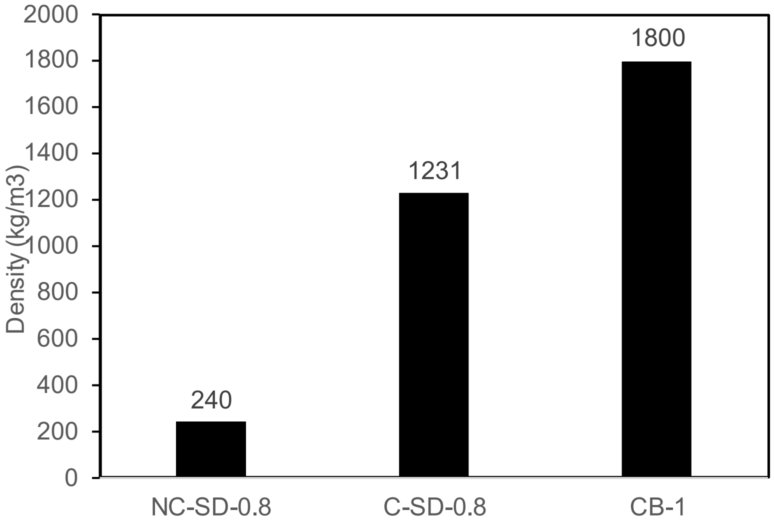


Figure 17 - Density (C-SD-0.8 vs Traditional Clay Brick)

As anticipated, the compression process significantly enhanced the density of the SD-0.8 mycelium composite. The compressed sample (C-SD-0.8) achieved a density of approximately 1231 kg/m³, which represents a nearly threefold increase compared to the uncompressed NC-SD-0.8 sample (420 kg/m³). This finding aligns with expectations from the literature review, where compression was identified as a strategy to improve the density of mycelium-based materials. While the compressed C-SD.8 sample remains less dense than the traditional clay brick (CB-1, ~2400 kg/m³), it demonstrates a promising advancement towards achieving densities suitable for certain construction applications.

4.2.3. Water Absorption Test

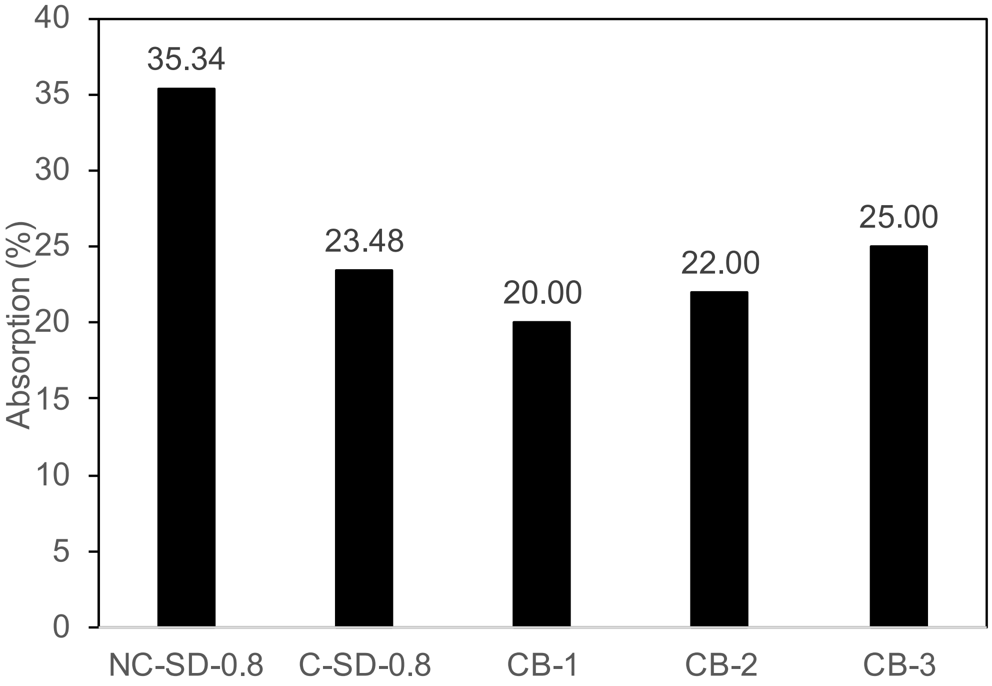


Figure 18 - Water Absorption (C-SD-0.8 vs Traditional Clay Brick)

The water absorption capacity of the Compressed saw dust 0.8 ratio sample (C-SD-0.8) was compared to clay bricks of varying classifications according to the British Standard BS 3921:2010. The graph (Figure 18) shows that the compressed mycelium brick (C-SD.8) exhibits a water absorption percentage of around 23.48%, exceeding the acceptable limits for first-class clay bricks (CB-1). Second-class clay bricks (CB-2) allow for a higher water absorption rate (up to 22.00%), and the C-SD.8 sample falls within this range. However, third-class clay bricks (CB-3) can tolerate an even higher water absorption rate (up to 25.00%).

While the C-SD-0.8 sample demonstrates a higher water absorption capacity compared to CB-1, it surpasses the recommended limits for CB-2 and CB-3. However, this highlights a potential drawback of the current mycelium composite formulation for applications where water resistance is critical. Further research might explore incorporating water-repellent additives or surface treatments to reduce the water absorption rate of mycelium bricks.

4.2.4 Compressive Strength Test

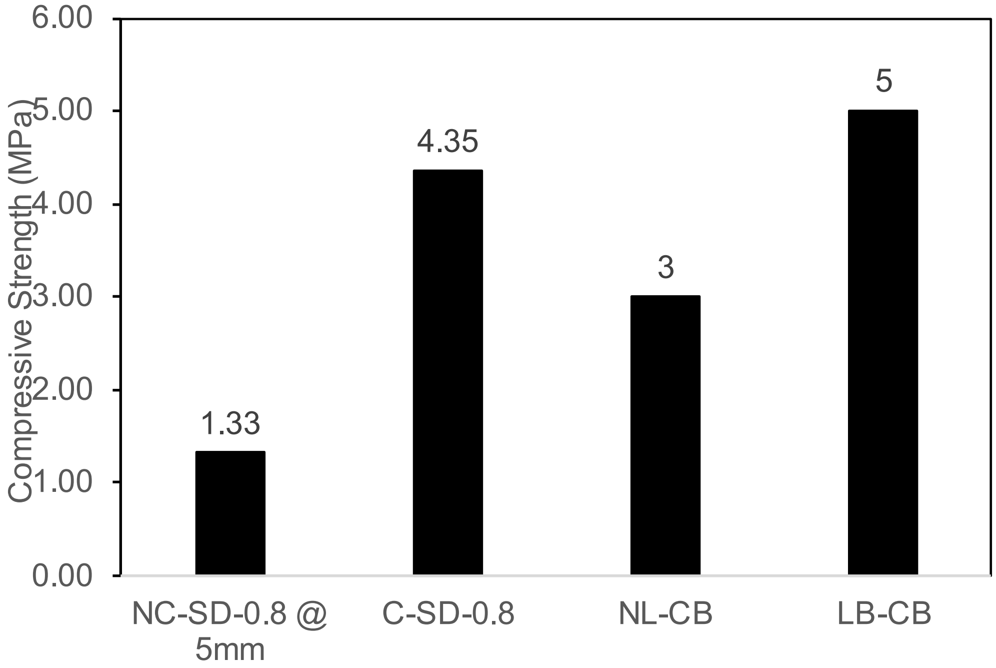


Figure 19 - Compressive Strength (C-SD-0.8 vs Traditional Clay Brick)

The compressive strength test evaluated the load-bearing capacity of the compressed SD-0.8 sample (C-SD.8). The test results are particularly encouraging, exceeding the minimum requirement of 3.0 MPa specified in the National Building Code of Pakistan (NBC 2007) for non-load bearing interior partitions. As shown in the accompanying chart, the compressed SD-0.8 sample achieved a compressive strength of 4.35 MPa, demonstrating its potential for applications in these building elements. Interestingly, the failure behavior observed during the test differed from that of the uncompressed SD-0.8 samples (used for initial selection). While the uncompressed samples exhibited ductile failure with significant plastic deformation before reaching a predefined failure point of 5mm (established solely for comparison purposes), the compressed SD-0.8 displayed a transitional failure mode. As the compressive load approached its limit (about 4.3-4.5 MPa), the compressed sample showed some plastic deformation, indicating ductility. However, due to its drier and denser state from compression, the sample also developed cracks, suggesting a transition between ductile and brittle behavior (brittle failure typically involves minimal deformation and sudden fracture). This observation highlights the potential influence of the compression process on the mechanical properties of the mycelium composite. The drier and denser structure of the compressed sample might have compromised its ductility and introduced weaknesses that manifested as cracks under high compressive stress.

4.3 Numerical Modelling results

4.3.1 Model Development

To evaluate the performance of the most promising compressed sample (C-SD.0.8) in comparison to a traditional brick, numerical models were created using ABAQUS CAE software. This analysis focuses on understanding their mechanical behavior under simulated loading conditions.

Both the C-SD.0.8 and traditional brick models will be constructed with a linear elastic material model. This aligns with the focus on elastic properties in the experimental tests (Section 4.2) for the C-SD.0.8 sample (density, elastic modulus) and simplifies the comparison by neglecting plastic behavior in both materials. A Poisson's ratio of 0.3 will be assumed for the C-SD.0.8 model, considering typical values for biological composites.

The model geometries will employ the same standard dimensions commonly used in the Pakistani construction industry (190 mm x 90 mm x 90 mm). Material properties for the C-SD.0.8 model will be directly obtained from the experimental results (Section 4.2) - density (e.g., 1231 kg/m^3) and elastic modulus (data from a stress-strain curve, if available). To ensure a fair comparison, material properties for the traditional brick model, including density and elastic modulus, will be sourced from reliable references like construction material supplier specifications or relevant engineering handbooks specific to Pakistani construction materials.

4.3.2 Interaction and Contact Properties

To simulate the interaction between the compressed mycelium sample (C-SD.0.8) and the traditional brick under compressive loading in ABAQUS CAE, contact properties were defined using the "All Self" contact formulation. This approach is suitable for scenarios where different surfaces of the same model or multiple instances of the same model come into contact. In this case, it represents the potential contact between various faces of the C-SD.0.8 model and between the C-SD.0.8 model and the entire surface of the traditional brick model.

The tangential behavior within the contact properties determines how the contacting surfaces interact under shear forces. To replicate the potential for some slippage between the compressed mycelium and the brick, a friction coefficient of 0 was assigned, assuming no friction between the surfaces. This aligns with the behavior of mortar in a masonry structure, where some limited movement between bricks can occur.

The normal behavior within the contact properties defines how the contacting surfaces interact under compressive forces. A hard contact with a penalty stiffness was employed to simulate mortar behavior. This approach allows for the transmission of compressive forces between the surfaces while preventing them from interpenetrating. The chosen penalty stiffness dictates the stiffness of the contact response under compression, mimicking the limited compressibility of mortar.

Contacting surfaces were defined by assigning specific surface names to the relevant faces of the C-SD.0.8 and traditional brick models within ABAQUS CAE. The "General Contact" interaction property was used to implement the "All Self" contact formulation and house the definitions for tangential and normal behavior.

By incorporating these contact properties, the numerical model realistically represents the interaction between the compressed mycelium and the traditional brick under compression, resembling the role of mortar in a real-world masonry structure.

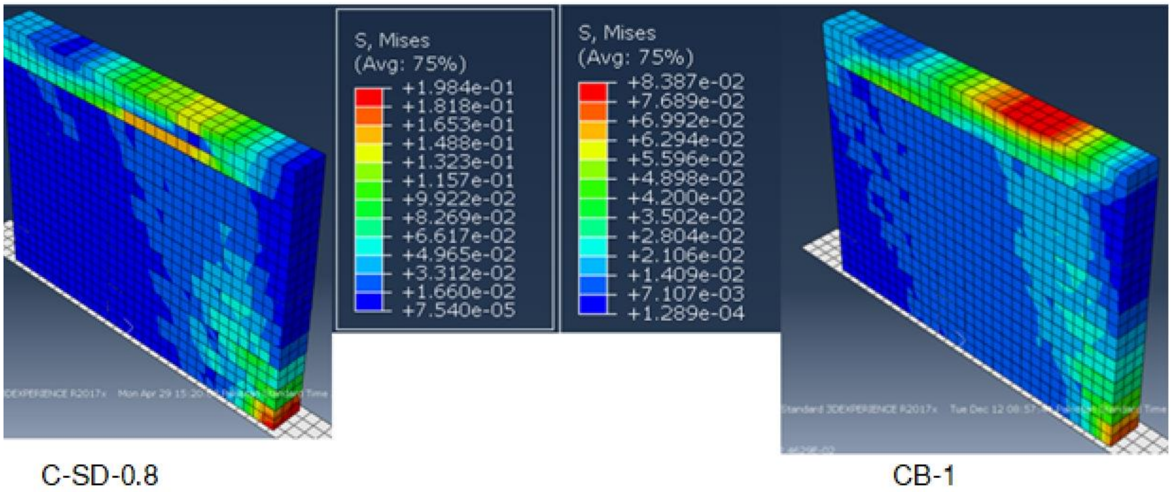
4.3.3 Loading and Boundary Conditions

To simulate the fixed support conditions experienced during a compressive strength test (Section 4.2), the bottom surface of each model (C-SD.0.8 and traditional brick) was constrained in ABAQUS CAE. This constraint essentially fixes all translational degrees of freedom (x, y, and z) on the bottom surface. This approach mimics a scenario where the bottom of a sample might be secured during a real-world test, preventing movement and replicating a crucial aspect of the experimental setup.

A compressive load was applied to the top surface of each model to simulate the loading conditions in a compressive strength test. This was achieved by prescribing a lateral displacement of 20 mm on the beam placed atop the wall model. The enforced displacement is used for dynamic analysis, mimicking the loading experienced in real life.

4.3.3 Results and Comparison with Traditional Brick

4.3.3.1 S: Stress Components and Invariants



C-SD-0.8 CB-1

Figure 20 - S: Stress Components and Invariants (C-SD-0.8 vs CB-1)

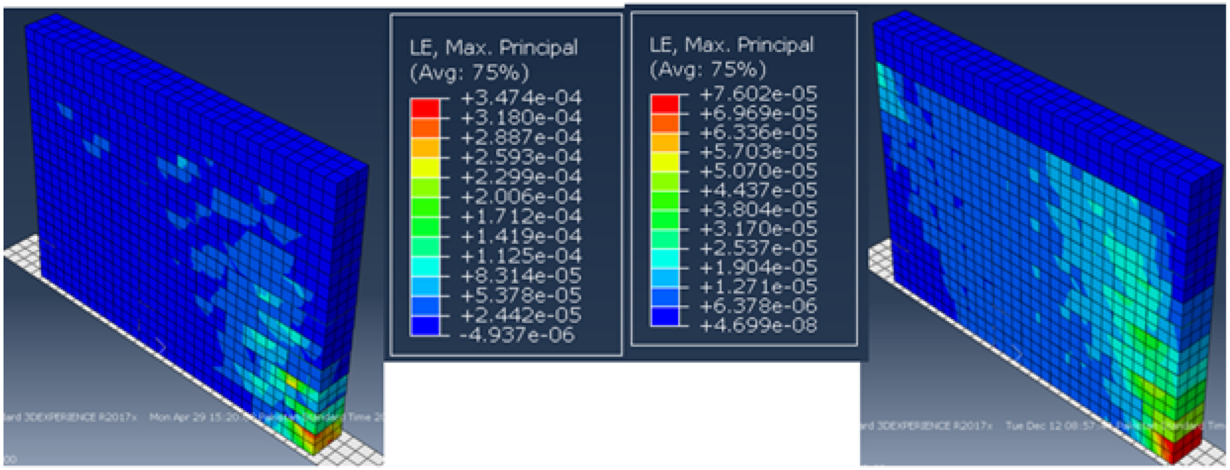
The ABAQUS CAE analysis conducted a comprehensive examination of stress components and invariants within the C-SD.0.8 and CB-1 models under dynamic loading conditions. This analysis aimed to elucidate how stress, particularly S, Mises stress, was distributed throughout the materials, as it plays a pivotal role in determining their structural integrity and performance. By focusing on S, Mises stress, which combines normal and shear stresses acting on a material, the analysis provided insights into the magnitude and distribution of stress within the models.

The results of the analysis revealed a notable disparity in stress distribution between the C-SD.0.8 and CB-1 models. Specifically, CB-1, characterized as a traditional clay brick, exhibited demonstrably lower S, Mises stress values compared to C-SD.0.8 under dynamic loading. This difference can be attributed to two key factors. Firstly, CB-1's inherent material properties, including its higher Young’s modulus, contributed to its lower stress response under dynamic loads compared to C-SD.0.8. Secondly, the specific design or geometry of the C-SD.0.8 model could potentially lead to greater stress concentrations compared to CB-1, further elevating its stress levels.

Despite CB-1 experiencing lower stresses, the analysis highlighted that C-SD.0.8 remained a potential option depending on the application. If the observed stress levels in C-SD.0.8 fell within acceptable limits for its intended use and design requirements, it could still be considered a suitable choice. Moreover, material optimization or design modifications could be implemented to manage stresses in C-SD.0.8 if necessary.

However, for a definitive explanation of the observed difference in stress distribution, the analysis recommended a more comprehensive examination. This would involve reviewing the material properties and model geometries for both C-SD.0.8 and CB-1. Additionally, examining stress distributions within the models at various time steps during the dynamic analysis would provide valuable insights for design optimization and stress management in C-SD.0.8. In conclusion, while CB-1 exhibited lower stresses under dynamic loading compared to C-SD.0.8, further analysis and potential optimization could enhance the viability of C-SD.0.8 for certain dynamic loading applications.

4.3.3.2 LE: Logarithmic Strain Components



C-SD-0.8

CB-1

Figure 21 - LE: Logarithmic Strain Components (C-SD-0.8 vs CB-1)

The strain analysis conducted within the ABAQUS CAE framework aimed to compare the Le, Maximum Principal strain distribution in the C-SD.0.8 and CB-1 models under dynamic loading conditions. Strain, representing the maximum deformation experienced in a specific direction at a point within the material, is a critical parameter for evaluating the behavior and potential failure of materials under stress.

The results of the analysis revealed generally higher strain values for C-SD.0.8 compared to CB-1. However, it's important to note that both value ranges were within the order e-4. The higher strain values in C-SD.0.8 were attributed to its relatively higher Poisson's ratio and a ductile nature of mycelium bricks in general. Despite the higher strains, it's crucial to recognize that this doesn't necessarily indicate inferior performance. With design and material optimization, C-SD.0.8 could effectively manage these strains within acceptable limits for its intended use.

Moreover, it's essential to differentiate between strain and failure. The higher strains observed in C-SD.0.8 might not directly translate to earlier failure. Material testing beyond just strain, such as stress-strain curves to failure, would be necessary to definitively assess its performance under dynamic loading scenarios.

To fully understand the implications of the strain data for C-SD.0.8, a deeper analysis was recommended. This would involve examining strain distributions within the C-SD.0.8 model at various time steps during the analysis, providing insights into potential strain concentration zones. Additionally, correlating the strain data with material properties and failure characteristics of C-SD.0.8 would offer a more informed evaluation of its suitability for dynamic loading applications. In conclusion, while acknowledging the observed strain values, further investigation as suggested could contribute to a more definitive assessment of C-SD.0.8's performance and potential for real-world applications.

4.3.3.2 CPRESS: Contact Pressure

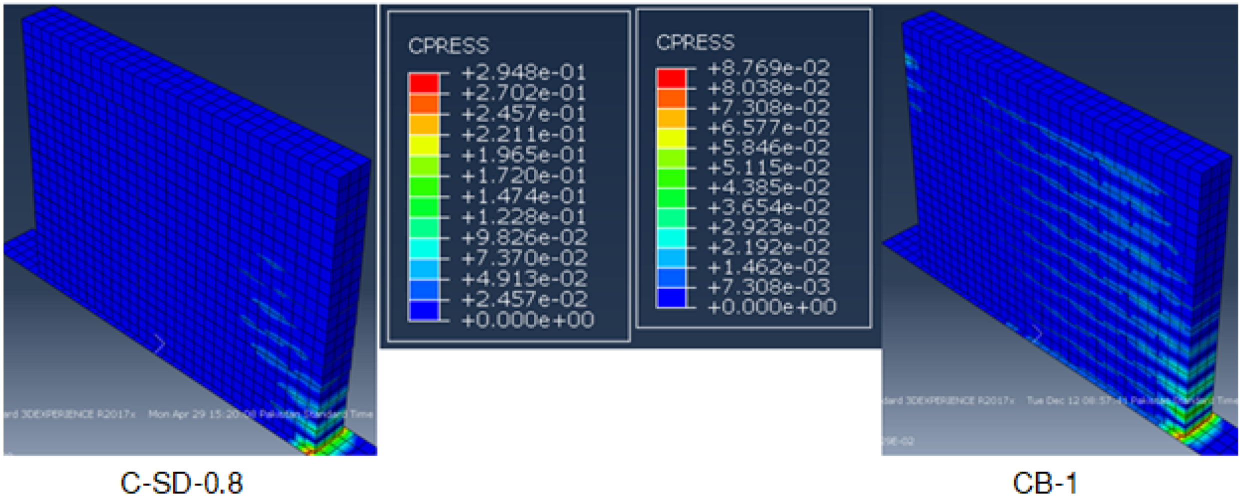


Figure 22 - CPRESS: Contact Pressure (C-SD-0.8 vs CB-1)

The contact pressure analysis focused on evaluating the equivalent plastic strain distribution within the C-SD.0.8 and CB-1 models under dynamic loading conditions using the ABAQUS CAE platform. Equivalent plastic strain, representing the permanent deformation experienced by the material, is crucial for assessing the materials' performance and durability under dynamic loading scenarios.

The analysis revealed a trend of generally higher equivalent plastic strain values for the C-SD.0.8 model compared to the CB-1 model. This difference could be attributed to C-SD.0.8's inherent material properties, which might make it more susceptible to plastic strain under dynamic loading. However, it's important to contextualize these findings within the potential applications of C-SD.0.8.

While higher strains were observed in C-SD.0.8, it's crucial to differentiate between strain and loss of functionality. The higher strains might not directly translate to reduced performance or premature failure in C-SD.0.8. Through design optimization, C-SD.0.8 could be tailored to manage these strains within acceptable limits for its intended use.

A more comprehensive analysis was recommended to fully understand the implications of the strain data for C-SD.0.8. This would involve examining strain distributions within the C-SD.0.8 model at various time steps during the dynamic analysis, providing insights into potential strain concentration zones. Additionally, correlating the strain data with material properties and failure characteristics of C-SD.0.8 would offer a more informed evaluation of its suitability for dynamic loading applications.

In conclusion, while acknowledging the observed strain levels, further investigation as suggested could contribute to a more definitive assessment of C-SD.0.8's performance and potential for real-world applications.

CHAPTER 5

CONCLUSION AND RECOMMENDATION

5.1 Conclusions

This thesis investigated the behavior of C-SD.0.8 and LB-CB models under dynamic loading conditions using ABAQUS CAE. The analysis focused on S, Mises stress, Le, Maximum Principal strain, and equivalent plastic strain distribution within the models.

The results revealed generally higher stress and strain values for the C-SD.0.8 model compared to LB-CB. However, it's crucial to consider these findings in the context of C-SD.0.8's potential applications. The observed differences could be attributed to C-SD.0.8's inherent material properties.

Through design optimization and potentially strategic material choices, C-SD.0.8 could be tailored to manage these stresses and strains within acceptable limits for its intended use. It's important to distinguish between stress/strain and failure. Further material testing, such as establishing stress-strain curves to failure, is necessary to definitively assess C-SD.0.8's performance under dynamic loads.

Overall, this study provided valuable insights into the comparative behavior of C-SD.0.8 and LB-CB models under dynamic loading. The findings highlight the importance of considering material properties and design optimization for managing stress and strain distributions within a model.

5.2 Challenges Faced

During the course of this thesis research, several challenges were encountered. One challenge involved obtaining accurate material properties for the C-SD.0.8 model. Limited access to specific material data necessitated estimations based on similar materials. Additionally, the complexity of modeling dynamic loading conditions required careful selection of appropriate analysis settings in ABAQUS CAE to achieve reliable results.

5.3 Recommendations

To further refine the understanding of C-SD.0.8's behavior under dynamic loads, future research should prioritize acquiring more comprehensive material property data for C-SD.0.8. This data is crucial for precise simulations and analysis, allowing for more accurate modeling of the material's response under dynamic loading conditions. Additionally, exploring alternative modeling techniques or software for simulating these scenarios could potentially provide valuable insights into the models' behavior. Comparing results from different approaches could offer a more comprehensive understanding of the stress and strain distribution within the models. Finally, conducting experimental testing to validate the simulation results obtained from ABAQUS CAE would provide a stronger foundation for evaluating C-SD.0.8's performance under real-world dynamic loading conditions. This experimental validation would allow for a direct comparison between the simulated and actual behavior of the model under dynamic loads. By addressing these recommendations, future research can build upon the foundation established in this thesis and provide a more definitive evaluation of the C-SD.0.8 model's suitability for dynamic loading applications.

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