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Integrating Agricultural Waste Product in Building Material: Biochar Mixed with Dredged Material Based Tile Vault

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Abstract

The Dongshi Forestry Cultural Park Playground Vault, scheduled for completion in late 2024, utilizes compressed soil-cement tiles, thin-tile vaulting, and geogrid reinforcement to stabilize against seismic activity and aid in live-load distribution within Taiwan's west earthquake belt. Agricultural byproducts, including biochar from Tachibana orange trees, and locally sourced silty-dredged material from the Ta-Pu reservoir, are key components of the tile mixture. A study investigating the composition of the tile materials examined the impact of biochar on mechanical properties, revealing that its inclusion does not compromise compressive strength. The playground vault, featuring a tri-leg design spanning over 8 m with a rise of 2.1 m, comprises two compression systems: a tile vault as the primary structural body and parapet-railing arches for the playground railing. During construction, a temperature scaffolding and a stay-in-place pre-cut wooden formwork system will support upper tile layers and mortar with geogrid. This paper introduces the pioneering research on biochar-dredged-material tiles and their application in compression vaults, showcasing sustainable material usage through an innovative construction process as an environmentally conscious alternative in vault typology.

Keywords: Structural design, thin-tile vaults, masonry, form-finding, earthquake design, compressed-earth blocks, biochar tile, dredged material tile.

1. Background & Introduction

The Sustainable Development Goals (SDGs) set forth by the United Nations provide a comprehensive framework for addressing global challenges and fostering sustainable development across various sectors. Among these goals, mitigating climate change stands as a paramount objective, intertwined with numerous others to achieve a harmonious balance between economic growth, social inclusion, and environmental protection. One of the most pressing aspects of climate change mitigation involves reducing carbon emissions (CO_2) and controlling the emission of total volatile organic compounds (TVOCs). These pollutants not only contribute to the greenhouse effect, exacerbating global warming, but also pose significant health risks and environmental hazards. As such, strategies aimed at curbing CO_2 and TVOCs emissions are central to achieving multiple SDGs, particularly those related to climate action, health and well-being, sustainable cities and communities, and responsible consumption and production.

Biochar, a derivative of traditional charcoal production methods, has garnered renewed attention over the past decade as a versatile material with potential applications in architecture. Emerging from controlled pyrolysis of organic materials, biochar offers unique properties that make it an intriguing candidate for architectural interventions aimed at sustainability and environmental management.

Historically, the usage of charcoal in architectural contexts drawing on examples such as traditional Japanese wood-framed houses, where charcoal bags were filled the wall and roof's cavity spaces to modulate indoor environmental conditions [1] [2] [3] [4]. Furthermore, it delves into contemporary experiments, including the 2013 study by the Ithaka Institute in Switzerland, which examined biochar's potential to regulate indoor humidity levels when integrated into plaster mixtures [5]. Moreover, initiatives such as The European Biochar Certificate (EBC) have been instrumental in standardizing biochar production processes and ensuring the quality and efficacy of biochar products. The EBC provides a robust framework for assessing biochar properties, including its carbon sequestration potential, nutrient retention capacity, and impact on soil health [6]. By certifying biochar products that meet stringent criteria, the EBC enhances consumer confidence and facilitates the widespread adoption of biochar in agricultural, environmental, and industrial applications. By examining biochar's past and present roles in architecture, this paper seeks to shed light on its potential as a sustainable building material and contribute to ongoing discussions on environmental design strategies.

This paper explores the initial findings of compressed earth blocks (CEB) manufactured from a series of blended biochar and dredged material. The biochar utilized was sourced from Tachibana orange tree branches, agricultural waste obtained from a local Nantou County farmer, and subjected to pyrolysis using the pyrolysis system at Feng Chia University Green Technology Lab. The resulting biochar contains 60% to 70% fixed carbon and 1.5% to 5% ash content, meeting the specifications of EBC-BasicMaterials, although it is not certified as such. Meanwhile, the dredged material was locally acquired from Ta-Pu reservoir, with its soil classification identified as silt [7]. Furthermore, this paper delves into the design details of two vault structures. The first is a 1:1 testing vault intended for local construction at Feng Chia University, while the second is Dongshi Forestry Cultural Park Playground Vault, scheduled for completion in late 2024.

2. Material & Tile

The manufacturing methods and ingredients used for producing compressed earth blocks (CEB) have been extensively documented and published in various scholarly works [8]. These resources comprehensively detail the step-by-step processes involved in CEB production, including the selection and preparation of raw materials, the mixing and compaction techniques employed, and the curing methods utilized to ensure structural integrity and durability. Additionally, they provide valuable insights into the diverse range of ingredients that can be incorporated into CEB formulations, such as different types of soil, stabilizers, and additives, along with their respective effects on block properties and performance, including the mixture of dredged material [9] [10]. Through thorough investigation and experimentation, researchers and practitioners have contributed to the advancement of CEB manufacturing practices, leading to the development of standardized protocols and innovative approaches aimed at optimizing block quality and promoting sustainable construction practices.

On the contrary, while the CEB has been extensively studied and documented, the understanding and research surrounding biochar blocks or bricks are relatively limited and underexplored. Despite the growing interest in biochar as a sustainable building material, there remains a scarcity of comprehensive studies and publications elucidating the manufacturing processes, properties, and applications of biochar-based blocks or bricks [11].

The relative lack of research on biochar blocks can be attributed to several factors. Firstly, biochar as a building material is a relatively novel concept, with its application in construction still in its infancy compared to traditional materials like bricks or concrete. Consequently, there is a dearth of standardized methodologies and established best practices for manufacturing biochar blocks, resulting in a fragmented body of knowledge within the research community. Moreover, the complexity of biochar as a material poses unique challenges in terms of characterization and performance evaluation, given its wide range of properties influenced by factors such as feedstock type, pyrolysis conditions, and post-treatment methods. Therefore, comprehensive research efforts are needed to systematically investigate the influence of these variables on the structural integrity, thermal properties, and environmental impact of biochar blocks. Despite these challenges, the nascent field of biochar-based construction presents immense opportunities for sustainable building practices. By bridging the gap in understanding and research, future studies have the potential to unlock the full potential of biochar blocks, paving the way for innovative, environmentally friendly building solutions that contribute to the transition towards a more sustainable built environment.

In this paper, the researcher undertakes two distinct investigations: research on material mixture and research on tiles. These investigations aim to deepen our understanding of how biochar influences the proposed biochar-dredged-material tile. The research on material mixture follows CNS1010, which is comparable to the ASTM C109 Compression Test of Hydraulic Cement Mortars. Similarly, the research on tiles adheres to CNS 382, equivalent to the ASTM C67 Standard Test Methods for Sampling and Testing Brick and Structural Clay Tile. Each material mixture undergoes 7 and 28 days of compression testing. This standardized testing procedure ensures rigorous evaluation of the material composition, allowing for precise analysis of the impact of biochar on various properties such as compressive strength and durability.

2.1. Raw materials, Mixing and Compaction Technique

In this experiment, the biochar-dredged-material tile consists of four key components: biochar, dredged material, clay, and cement. The biochar undergoes a process where it is crushed and ground into a fine powder before being immersed in a 5% calcium hydroxide solution (biochar with calcium hydroxide solution, BS-CH). This solution-to-biochar ratio is meticulously calibrated at 1.85% to ensure optimal hydration of the biochar without saturating it excessively. This precise balance allows the biochar particles to absorb moisture effectively, facilitating hydration while preventing overwatering that could compromise the integrity of the final tile. By controlling the hydration process in this manner, researchers aim to optimize the properties of the biochar and enhance its performance within the tile matrix. Additionally, dredged material serves as a filler, and clay acts as a binding agent to ensure structural integrity, while cement enhances strength and durability. Together, these ingredients combine to create a sustainable and resilient building material.

A series of ingredient combinations were introduced with the aim of maintaining consistency by limiting variables. To achieve this, the ratio of clay to cement was kept constant throughout the experiment, at 24% clay and 8% cement. The only variations made involved the incorporation of BS-CH and the introduction of dredged material into the mixture. The clay ratio ranged from 16% up to 24% based on known study [10], while the BS-CH ranged from 17.5% to 32% (see Table 1). By keeping the clay and cement ratio constant, researchers could isolate the effects of BS-CH and dredged material on the properties of the final product. The dredged material ration is also based on the known publication [10] [12]. Additionally, a separate study is being conducted to investigate the impact of adding pure calcium oxide (i.e., simulated from burning freshwater shell) on the overall mechanical properties and strength enhancement. Each mixture ratio was molded into a 50 x 50 x 50 mm cube sample and subjected to compression testing after 7 and 28 days (see Figure 1). In the compression testing after 7 days of curing time, specimen A can withstand up to 14.2 kgf/cm^2, specimen B can withstand up to 11.4 kgf/cm^2, specimen C can withstand up to 16.1 kgf/cm^2, specimen D can withstand up to 11.7 kgf/cm^2, and specimen E can withstand up to 22.0 kgf/cm^2. Based on the primary data study, adding biochar powder could possibly increase the carrying load. The specimens tested after 28 days, specimen A can withstand up to 13.4 kgf/cm^2, specimen B can withstand up to 10.3 kgf/cm^2, specimen C can withstand up to 11.6 kgf/cm^2, specimen D can withstand up to 16.2 kgf/cm^2, and specimen E can withstand up to 13.40 kgf/cm^2. The result of 7 days and 28 days of compression testing demonstrates that the results are alike. It consists of tile vault literature that tile can be used in construction after 7 days.

Table 1: Mixture ratios in each specimen, Slit is the dredged material.

5*5*5 Test Group	Calcium Hydroxide +Biochar	Calcium Oxide	Silt	Clay	Cement	Water
A	18%	18%	16%	24%	8%	16%
B	18%	0%	37%	24%	8%	13%
C	11%	0%	44%	24%	8%	13%
D	22%	0%	34%	24%	8%	12%
E	33%	0%	24%	24%	8%	11%

Figure 1: Group A to Group E cube specimens.

2.2. Tile Manufacturing & Product Testing

The manufacturing process of the CEB tiles involves the use of an Auram Press 3000 manual pressing machine, applying 15 tons of force to ensure thorough compression and create tiles with precise dimensions of 290 x 140 x 50 mm. This manual pressing guarantees meticulous attention to detail, ensuring uniformity and durability suitable for diverse construction applications. To maintain quality and reliability, a comprehensive quality control procedure will be implemented. This involves randomly selecting 10 out of 200 tiles for examination following the CNS 382/ASTM C67 procedure, evaluating their durability and compression strength. This standardized testing will provide valuable insights into performance characteristics, allowing for identification and resolution of any manufacturing issues, ensuring overall quality and reliability of the CEB tiles.

3. Tile Vaults Design

The design of the tile vault follows the natural resolution of forces towards the ground, closely mimicking catenary geometry while reflecting Nantou County, Taiwan's misty, hilly topography. The vault geometry study is initially based on two simulation software plug-ins: RhinoVault2 and Kangaroo 2 Physics. RhinoVault2 utilizes Thrust Network Analysis (TNA) developed by the Block Research Group, while Kangaroo 2 Physics simulates spring physics. Having two software options allows architecture students to quickly use Kangaroo 2 Physics to simulate form-finding geometry and iterate the design, while RhinoVault2 is used to create the final compression geometry (Fig 2).

The tri-legged playground vault spans over 8 m with a rise of 2.1 m, comprising two different compression systems: a tile vault as the main structural body and parapet-railing arches as the playground railing. Through 3D printed models, it was discovered that RhinoVault2's generated geometry is more stable than Kangaroo 2 Physics due to the vault's center geometry, allowing for pure compression. The form is an ongoing research investigation.

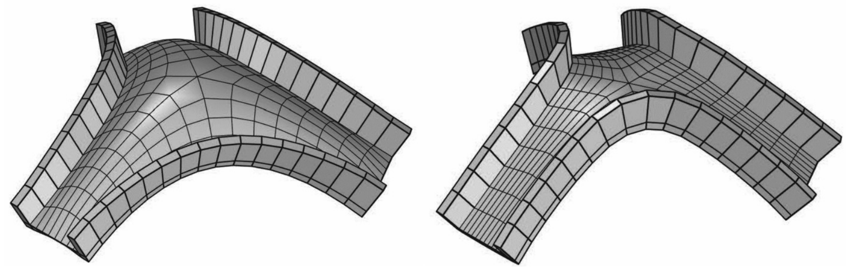

Figure 2: RhinoVault2 generated design (Left) and Kangaroo 2 Physics generated design (Right)

Additionally, considering the site's susceptibility to seismic activity in Dongshi Forestry Cultural Park, Taiwan, the research team proposed two tile vault details for seismic stabilization. One method involves using a reinforced plastic geogrid as the reinforcement layer between the tiles [13] [14] (Fig 3 Left), while the other utilizes steel wire reinforcement (Fig 3 Right). In the summer of 2024, the tile vault with reinforced plastic geogrid will be constructed locally at the university on a 1:1 scale to test its load capacity and determine its safety factor. If this vault's load capacity meets the required safety standards, the steel wire reinforcement will not be utilized for the final construction at Dongshi Forestry Cultural Park. During construction, a temperature scaffolding and a stay-in-place pre-cut wooden formwork system will be erected to support the upper layers of tiles and mortar (Fig 4).

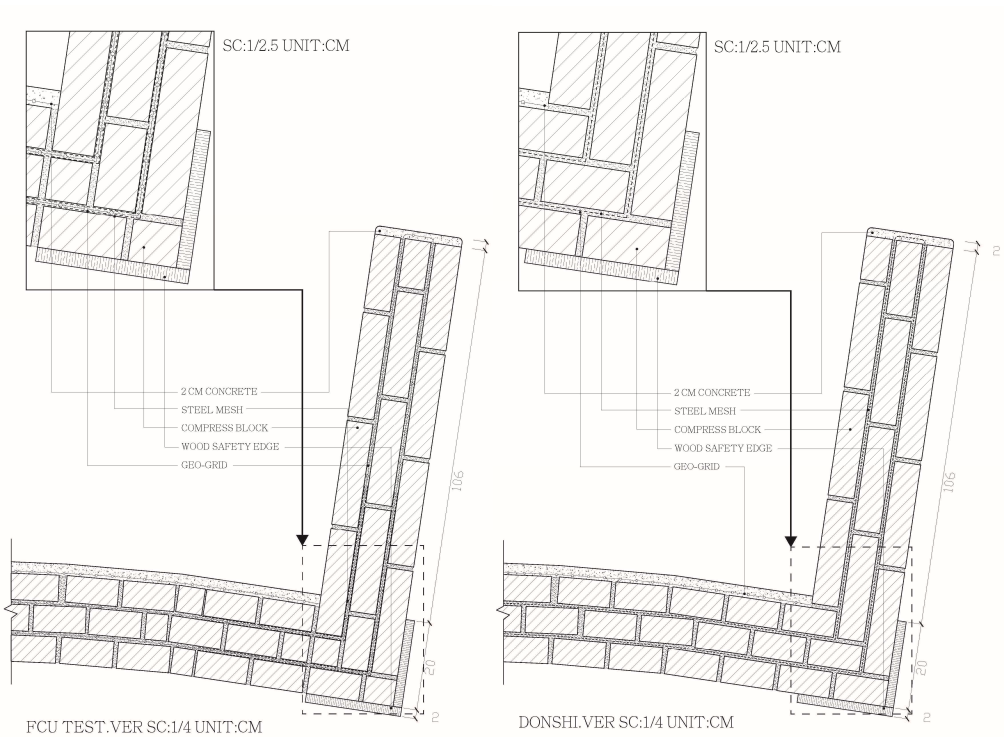

Figure 3: 1:1 Design detail, Feng Chia University prototype testing detail with plastic geogrid, and Dongshi Forestry Cultural Park potential construction detail with steel wire.

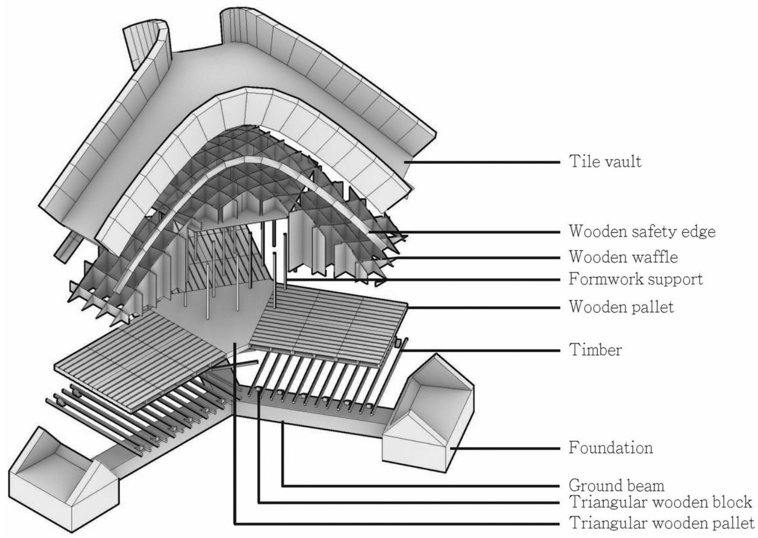

Figure 4: Overall vault construction review

3. Conclusion: submission of contributions

The research findings suggest that incorporating biochar with calcium hydroxide solution (BS-CH) into the tile mixture holds promise for enhancing load strength. However, to validate and comprehensively understand this effect, a thorough study is essential. Additionally, the biochar content within BS-CH requires further scrutiny due to potential inconsistencies in biochar particles. Observations have revealed that different batches of biochar, stemming from varying conditions during the pyrolysis process, yield different outcomes, ranging from light powder particles to gritty sand particles. Therefore, additional investigation is necessary to address this variability and ensure consistency in performance.

Expanding on the findings, it is imperative to conduct detailed analyses to assess the impact of biochar content variation on tile properties and performance. This may involve exploring different biochar production methods and their effects on particle size and distribution within the tile mixture. Furthermore, comprehensive testing protocols should be established to evaluate the mechanical properties and durability of tiles containing BS-CH under various loading conditions and environmental factors.

To construct a seismic-proof tile vault, reinforcement is proposed, necessitating a 1:1 scale load condition test to ascertain the potential impact of the proposed reinforcement method on the structure's integrity. In this test, simulated seismic loads will be applied to evaluate the effectiveness of the reinforcement in enhancing stability and preventing collapse during seismic events. Detailed analysis will include monitoring displacement, stress distribution, and overall structural response under various seismic conditions. Through this comprehensive testing program, the objective is to validate the proposed reinforcement method and ensure the seismic resilience of the tile vault structure.

Overall, addressing these aspects through further research and experimentation will contribute to optimizing the use of biochar in tile production, enhancing load strength, and ensuring consistent performance and reliability in applications.

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