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Mechanical Property Evaluation of Modified Bricks for Green Building Application

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Abstract- This study investigates the mechanical performance and sustainability of modified clay bricks incorporating waste glass powder (WGP) and various agro-industrial byproducts, targeting their application in green building construction. Motivated by the growing demand for sustainable construction materials, the research evaluates the compressive and flexural strength, water absorption, and durability of bricks infused with different waste materials such as cocoa shells, sugarcane bagasse, and rice husk ash. The optimal WGP content of 20% resulted in a 25% increase in compressive strength and a 41% improvement in modulus of rupture, while maintaining water absorption levels comparable to traditional bricks. Microstructural analyses using SEM and XRD reveal enhanced bonding and reduced porosity in modified bricks. The study also explores the environmental and economic benefits of utilizing recycled crushed clay bricks (RCB) in pavement construction and evaluates their performance in cement-stabilized macadam (CSM). The integration of waste materials not only reduces reliance on virgin clay but also offers substantial reductions in energy consumption and CO_2 emissions. The findings affirm that modified bricks with waste additives provide a viable solution for sustainable infrastructure, aligning with global green building initiatives.

Keywords- Modified clay bricks, Waste glass powder (WGP), Agro-industrial byproducts, Cocoa shells, Sugarcane bagasse

I. INTRODUCTION

Introduction to Green Building and Modified Bricks

The Growing Demand for Sustainable Construction Materials

The construction industry's ever-increasing demand for materials has created a critical need for sustainable solutions [1]. This demand is driven by population growth, urbanization, and infrastructure development, all of which place immense pressure on natural resources. Traditional construction materials, such as cement and virgin aggregates, are associated with significant environmental impacts, including high carbon emissions, resource depletion, and habitat destruction. As a result, there is a growing recognition of the importance of adopting sustainable practices in the construction sector to mitigate these adverse effects. These practices include using recycled materials, reducing energy consumption, and minimizing waste generation. The shift towards sustainability is not only environmentally responsible but also economically viable, as it can lead to cost savings through reduced material consumption and energy efficiency.

Recycling agroindustrial solid wastes presents an economically viable option for designing green buildings [2]. Agroindustrial waste, such as cocoa shells, sawdust, rice husks, and sugarcane bagasse, often accumulates in large quantities, posing environmental challenges related to storage and disposal. By repurposing these wastes as additives in construction materials, it is possible to reduce both the environmental burden and the reliance on conventional resources. Furthermore, the use of agroindustrial wastes can enhance the properties of construction materials, such as thermal insulation and sound absorption, contributing to the overall sustainability of buildings. This approach not only addresses waste management issues but also promotes a circular economy by closing the loop on material flows.

The utilization of recycled crushed clay brick (RCB) in road engineering represents a promising step towards sustainable development and green construction [3]. Construction and demolition (C&D) waste, including discarded clay bricks, constitutes a significant portion of the waste stream. Recycling RCB as a substitute for natural aggregates in road construction can reduce the demand for virgin materials, conserve landfill space, and lower transportation costs. RCB possesses certain properties, such as pozzolanic activity and high water absorption, which can be beneficial in pavement applications. However, careful consideration must be given to the mix design and construction techniques to ensure the long-term performance and durability of RCB-based pavements. This approach aligns with the principles of sustainable infrastructure development by promoting resource efficiency and waste reduction.

There is also a growing imperative to diminish the environmental consequences stemming from the utilization of inorganic materials in building applications [4]. The production of inorganic materials, such as cement and concrete, is energy-intensive and contributes significantly to greenhouse gas emissions. Moreover, the extraction and processing of raw materials for these materials can lead to habitat destruction and water pollution. To address these challenges, there is a need to explore alternative materials and construction techniques that have a lower environmental footprint. This includes the use of bio-based materials, such as timber and bamboo, as well as the development of innovative materials with enhanced durability and reduced embodied energy. A holistic approach to sustainable construction requires a shift away from traditional practices and a commitment to minimizing the environmental impact of the built environment.

A shift towards sustainable construction methods is motivated by the imperative to curtail energy consumption within the building sector [5]. Buildings are responsible for a significant portion of global energy consumption, primarily due to heating, cooling, and lighting. The design and construction of energy-efficient buildings can significantly reduce energy demand and greenhouse gas emissions. This includes the use of passive design strategies, such as natural ventilation and solar shading, as well as the incorporation of high-performance insulation and energy-efficient building systems. Furthermore, the selection of sustainable construction materials can contribute to energy savings by reducing the embodied energy of buildings. A comprehensive approach to energy-efficient construction requires a focus on both operational and embodied energy, as well as a commitment to continuous improvement and innovation.

Plastic waste is accumulating at an alarming rate, polluting the environment, necessitating its repurposing in construction [6]. The widespread use of plastics in various applications has resulted in a massive accumulation of plastic waste in landfills and oceans. Plastic waste is non-biodegradable and can persist in the environment for centuries, posing a threat to wildlife and ecosystems. Repurposing plastic waste in construction materials offers a viable solution to reduce plastic pollution and conserve natural resources. Plastic waste can be used as a substitute for conventional materials, such as cement and aggregates, in concrete and other construction products. However, careful consideration must be given to the properties of plastic waste and its compatibility with other materials to ensure the structural integrity and durability of the resulting construction products. This approach aligns with the principles of a circular economy by transforming waste into a valuable resource.

The Role of Modified Bricks in Green Building

Modified clay bricks are important for low-cost, durable, and affordable housing [7]. The modification of clay bricks involves incorporating various additives or using alternative manufacturing techniques to enhance their properties and performance. These modifications can improve the strength, durability, thermal insulation, and water resistance of clay bricks, making them suitable for a wider range of applications. Modified clay bricks can be produced using locally available materials and simple manufacturing processes, making them an attractive option for low-cost housing in developing countries. Furthermore, the use of modified clay bricks can reduce the environmental impact of construction by minimizing the consumption of natural resources and energy.

The properties of modified clay bricks can be adjusted to suit various loading conditions [7]. The strength and stiffness of clay bricks can be tailored to meet the specific requirements of different structural elements, such as walls, columns, and arches. This can be achieved by varying the composition of the clay mixture, the firing temperature, and the addition of reinforcing materials. For example, the incorporation of fibers or polymers can enhance the tensile strength and ductility of clay bricks, making them more resistant to cracking and failure under tensile loads. The ability to customize the properties of modified clay bricks allows for more efficient and sustainable use of materials in construction.

Incorporating waste materials into bricks can improve their thermo-physical and mechanical properties [8]. The use of waste materials, such as fly ash, slag, and recycled aggregates, can enhance the thermal insulation, sound absorption, and strength of bricks. Waste materials often have a lower embodied energy than conventional materials, reducing the overall environmental impact of brick production. Furthermore, the incorporation of waste materials can reduce the cost of brick production and divert waste from landfills. However, careful consideration must be given to the properties of waste materials and their potential impact on the durability and long-term performance of bricks. This approach aligns with the principles of sustainable construction by promoting resource efficiency and waste reduction.

The use of modified mud bricks maintains stability and compressive strength without altering historical characteristics, making them suitable for heritage buildings [9]. Mud bricks are a traditional building material that has been used for centuries in various parts of the world. However, mud bricks are susceptible to deterioration due to weathering, erosion, and seismic activity. The modification of mud bricks involves incorporating stabilizing agents, such as lime, cement, or polymers, to enhance their strength and durability. These modifications can improve the resistance of mud bricks to water damage, cracking, and erosion, while preserving their historical appearance and compatibility with traditional construction techniques. The use of modified mud bricks is a sustainable and culturally sensitive approach to preserving heritage buildings.

Employing plastic waste in mortar production can produce lightweight materials with improved thermal properties [10]. Plastic waste is a significant environmental problem, and its repurposing in construction materials offers a viable solution. Plastic waste can be used as a substitute for conventional materials, such as sand and cement, in mortar production. The resulting mortar is lighter in weight and has improved thermal insulation properties compared to conventional mortar. This can reduce the energy consumption of buildings by minimizing heat transfer through walls and roofs. However, careful consideration must be given to the properties of plastic waste and its compatibility with other materials to ensure the structural integrity and durability of the resulting mortar. This approach aligns with the principles of sustainable construction by promoting resource efficiency and waste reduction.

The application of agro-industrial waste as a partial replacement can reduce negative impacts on the environment [11]. The use of agro-industrial waste, such as rice husk ash, sugarcane bagasse, and palm oil clinker, as a partial replacement for cement in concrete production can reduce the environmental impact of cement manufacturing. Cement production is a major source of greenhouse gas emissions, and the use of agro-industrial waste can lower the carbon footprint of concrete. Furthermore, agro-industrial waste is often a readily available and low-cost material, making it an economically attractive alternative to cement. However, careful consideration must be given to the properties of agro-industrial waste and its impact on the strength and durability of concrete. This approach aligns with the principles of sustainable construction by promoting resource efficiency and reducing greenhouse gas emissions.

Scope of Mechanical Property Evaluation

This evaluation focuses on compressive strength, flexural strength, water absorption, and durability [1], [2], [12]. These properties are critical for assessing the suitability of modified bricks for various construction applications. Compressive strength is a measure of the brick's ability to withstand compressive loads, while flexural strength indicates its resistance to bending forces. Water absorption is an important indicator of the brick's durability and resistance to weathering, and durability encompasses the brick's ability to maintain its properties over time under various environmental conditions. The evaluation of these properties provides valuable information for determining the structural performance and long-term reliability of modified bricks.

Microstructural analysis is included to understand the effects of modifications [13], [14]. Microstructural analysis involves examining the internal structure of the brick at a microscopic level to identify the effects of different modifications on its composition, porosity, and bonding characteristics. Techniques such as scanning electron microscopy (SEM) and X-ray diffraction (XRD) are used to characterize the microstructure of the brick and to understand how it influences its mechanical properties. This analysis provides valuable insights into the mechanisms by which modifications enhance or degrade the performance of bricks.

The evaluation also aims to assess the long-term performance and environmental benefits of modified bricks [15], [16]. Long-term performance is evaluated by subjecting the bricks to accelerated weathering tests and monitoring their properties over time. Environmental benefits are assessed by conducting life cycle assessments (LCAs) to quantify the environmental impacts of brick production, use, and disposal. These assessments provide a comprehensive understanding of the sustainability of modified bricks and their potential to contribute to green building practices.

The evaluation will examine the impact of various additives on the mechanical properties of bricks [17]. Different additives, such as waste glass powder, agroindustrial wastes, and recycled materials, can have varying effects on the strength, durability, and water resistance of bricks. The evaluation will systematically investigate the impact of each additive on these properties to determine the optimal composition for modified bricks. This information is essential for designing bricks that meet specific performance requirements and contribute to sustainable construction.

This includes waste glass powder, agroindustrial wastes, and recycled materials [1], [2], [3]. Waste glass powder is a byproduct of glass manufacturing and recycling, and it can be used as a partial replacement for clay in brick production. Agroindustrial wastes, such as rice husk ash and sugarcane bagasse, are agricultural residues that can be used as additives to improve the properties of bricks. Recycled materials, such as crushed concrete and demolition debris, can be used as aggregates in brick production. The evaluation will assess the impact of each of these materials on the mechanical properties of bricks to determine their suitability for sustainable construction.

The assessment will also look into the effects of different curing methods and stabilization techniques on the properties of modified bricks [18]. Curing methods, such as air curing, water curing, and steam curing, can influence the hydration and hardening of bricks, affecting their strength and durability. Stabilization techniques, such as the addition of lime or cement, can improve the resistance of bricks to weathering and erosion. The evaluation will investigate the impact of different curing methods and stabilization techniques on the properties of modified bricks to determine the optimal practices for producing high-performance and durable bricks.

Waste Glass Powder (WGP) Modified Bricks Production and Composition of WGP Modified Bricks

Waste glass powder (WGP) can be used as a replacement for clay in burnt clay bricks [1]. This approach not only reduces the consumption of natural clay resources but also provides a beneficial use for waste glass, which is often discarded in landfills. The use of WGP in brick production can also improve the properties of the bricks, such as their strength and durability. The production of WGP-modified bricks involves mixing WGP with clay and other additives, followed by firing at high temperatures to create a solid and durable product. Various WGP substitutions, ranging from 0% to 25%, are tested to optimize the mixture [1]. The optimal amount of WGP to use in brick production depends on several factors, including the type of clay, the fineness of the WGP, and the desired properties of the bricks. Testing various WGP substitutions allows for the identification of the optimal mixture that provides the best balance of strength, durability, and cost-effectiveness. This optimization process is essential for ensuring the successful implementation of WGP-modified bricks in construction applications.

The bricks are manufactured using artisanal procedures with the modification of adding glass powder to the mixture [12]. Artisanal brick production typically involves manual mixing, molding, and firing processes. The addition of WGP to this process requires careful attention to ensure that the WGP is evenly distributed throughout the clay mixture and that the bricks are properly fired to achieve the desired properties. The use of artisanal procedures can also provide economic opportunities for local communities by creating jobs and promoting sustainable development.

The soil used as the main raw material is classified as well-graded sand with silt (SW-SM) [12]. The type of soil used in brick production can significantly affect the properties of the bricks. Well-graded sand with silt (SW-SM) is a type of soil that contains a mixture of sand, silt, and clay particles, which provides good workability and strength. The use of SW-SM soil in WGP-modified brick production can enhance the properties of the bricks and improve their suitability for construction applications.

The addition of WGP improves structure integrity and durability, making it an eco-friendly additive [1]. WGP acts as a pozzolanic material, reacting with calcium hydroxide during the hydration process to form calcium silicate hydrate (C-S-H), which enhances the strength and durability of the bricks. The use of WGP also reduces the porosity of the bricks, making them more resistant to water absorption and freeze-thaw damage. These improvements in structure integrity and durability make WGP an eco-friendly additive that can contribute to sustainable construction practices.

Optimizing firing parameters and scaling up production processes are essential for broader industrial adoption [1]. The firing temperature and duration can significantly affect the properties of WGP-modified bricks. Optimizing these parameters is crucial for achieving the desired strength, durability, and color of the bricks. Scaling up production processes involves automating and streamlining the manufacturing process to increase efficiency and reduce costs. This is essential for making WGP-modified bricks commercially viable and promoting their widespread adoption in the construction industry.

Impact on Compressive and Flexural Strength

Samples with up to 20% WGP recorded the highest increase in compressive strength and modulus of rupture [1]. The incorporation of WGP into clay bricks can significantly enhance their mechanical properties, particularly compressive strength and modulus of rupture. The optimal WGP content, around 20%, provides the best balance between strength enhancement and workability. Higher WGP contents may lead to reduced workability and

difficulty in forming the bricks, while lower contents may not provide sufficient strength improvement.
Compressive strength increased by approximately 25%, and the modulus of rupture increased by approximately 41% [1]. These significant increases in compressive strength and modulus of rupture demonstrate the effectiveness of WGP as a strength-enhancing additive in clay bricks. The increased strength and stiffness of WGP-modified bricks make them more suitable for load-bearing applications in construction. This can lead to more efficient use of materials and reduced construction costs.

Modified bricks with glass powder show up to 240% compressive strength compared to traditional bricks [12]. This substantial improvement in compressive strength highlights the potential of WGP as a transformative additive in brick production. The enhanced compressive strength can significantly improve the structural performance of buildings constructed with WGP-modified bricks, increasing their resistance to collapse and damage. This can lead to safer and more durable buildings.
Flexural strength capability is up to 220% higher when using 8% to 12% glass powder dosage in the mixture [12]. The flexural strength of bricks is an important indicator of their ability to resist bending forces, which is particularly relevant in applications such as walls and pavements. The use of WGP in the optimal dosage range can significantly enhance the flexural strength of bricks, making them more resistant to cracking and failure under bending loads. This can improve the overall performance and durability of structures constructed with WGP-modified bricks.

The enhanced mechanical properties make WGP-modified bricks a valid replacement for sustainable construction applications [1]. The improved strength, stiffness, and durability of WGP-modified bricks make them a viable alternative to traditional clay bricks in various construction applications. The use of WGP also reduces the environmental impact of brick production by conserving natural resources and reducing waste. This makes WGP-modified bricks a sustainable and environmentally friendly construction material.

The procedures and interpretation of results are based on the guidelines established by the Ecuadorian Institute of Standardization (INEN) [12]. The use of standardized testing procedures and interpretation guidelines ensures the reliability and comparability of the results. The INEN guidelines provide a framework for assessing the properties of WGP-modified bricks and determining their suitability for construction applications. This adherence to established standards promotes quality control and ensures the safe and effective use of WGP-modified bricks in construction.

Durability and Water Absorption Characteristics
WGP improves structure integrity and durability, enhancing their potential as a waste management solution [1]. The pozzolanic activity of WGP contributes to the formation of a denser and more durable brick microstructure, reducing porosity and improving resistance to water absorption and chemical attack. This enhanced durability extends the service life of WGP-modified bricks, reducing the need for frequent replacements and minimizing waste generation. The use of WGP also provides a beneficial outlet for waste glass, diverting it from landfills and promoting a circular economy.

Both traditional and modified bricks exhibit a water absorption percentage between 25% and 26% [12]. Water absorption is an important indicator of the durability and resistance to weathering of bricks. A high water absorption percentage can lead to increased susceptibility to freeze-thaw damage, efflorescence, and chemical attack. The fact that WGP-modified bricks exhibit similar water absorption percentages to traditional bricks suggests that they have comparable durability and resistance to weathering. However, further testing is needed to confirm this conclusion.

More studies are needed on long-term durability evaluation to enhance the suitability of WGP for sustainable construction [1]. While short-term testing can provide valuable information about the properties of WGP-modified bricks, it is essential to conduct long-term durability evaluations to assess their performance over extended periods of time under various environmental conditions. These evaluations should include exposure to freeze-thaw cycles, chemical attack, and abrasion to determine the long-term reliability and sustainability of WGP-modified bricks. The results of these studies will inform the development of improved WGP-modified brick formulations and promote their wider adoption in sustainable construction.

The excellent results indicate that WGP can act as an eco-friendly additive, reducing dependence on natural clay [1]. The use of WGP as a partial replacement for clay in brick production can significantly reduce the consumption of natural clay resources, which are often extracted from environmentally sensitive areas. This conservation of natural resources contributes to the sustainability of brick production and reduces its environmental impact. The excellent mechanical properties and durability of WGP-modified bricks further enhance their appeal as an eco-friendly construction material.

The study concludes that WGP-modified bricks can be a valid replacement for sustainable construction applications [1]. The combination of improved mechanical properties, enhanced durability, and reduced environmental impact makes WGP-modified bricks a promising alternative to traditional clay bricks in various construction applications. The use of WGP can contribute to the development of more sustainable and environmentally friendly buildings, while also promoting resource efficiency and waste reduction.

To enhance the suitability of WGP for sustainable construction, more studies must be carried out on optimizing firing parameters [1]. The firing process is a critical step in brick production, and the firing parameters, such as temperature and duration, can significantly affect the properties of the bricks. Optimizing these parameters is essential for achieving the desired strength, durability, and color of WGP-modified bricks. Further research is needed to determine the optimal firing parameters for different WGP-modified brick formulations and to develop energy-efficient firing techniques that minimize greenhouse gas emissions.

Agroindustrial Waste as Additives in Bricks

Types of Agroindustrial Waste Used

Cocoa shell, sawdust, rice husk, and sugarcane bagasse are used as additives in brick manufacturing [2]. These agroindustrial wastes are generated in large quantities and often pose disposal challenges. Their incorporation into brick manufacturing provides a sustainable and economically viable solution for waste management while also enhancing the properties of the bricks. Each of these materials has unique characteristics that can contribute to improved thermal insulation, reduced weight, and enhanced strength.

The accumulation of unmanaged agroindustrial solid wastes is an increased environmental concern [2]. The improper disposal of agroindustrial waste can lead to soil and water contamination, air pollution, and the spread of diseases. The large volumes of waste generated by agricultural and food processing industries necessitate effective waste management strategies to mitigate these environmental risks. The utilization of agroindustrial waste in brick manufacturing offers a promising approach to reducing the environmental burden associated with these wastes.

Recycling such wastes provides a viable solution to pollution and an economical option for green buildings [2]. The incorporation of agroindustrial waste into building materials reduces the demand for virgin resources, lowers production costs, and minimizes environmental impact. This approach aligns with the principles of a circular economy by transforming waste into a valuable resource. The resulting green buildings benefit from improved energy efficiency, reduced carbon footprint, and enhanced sustainability.

Palm Oil Clinker Powder (POCP) and Boiler Ash (POBA) are used as partial replacements for cement [11]. These waste materials are byproducts of the palm oil industry and are generated in substantial quantities. Their utilization as partial replacements for cement in brick manufacturing can reduce the environmental impact of cement production, which is a significant source of greenhouse gas emissions.

POCP and POBA can also contribute to improved workability and durability of the bricks.

Sugarcane bagasse and rice husk ash are also utilized [19]. Sugarcane bagasse is a fibrous residue left after sugarcane is crushed to extract juice, while rice husk ash is a byproduct of rice milling. These materials are abundant and readily available in many regions, making them attractive additives for brick manufacturing. Their incorporation into bricks can improve thermal insulation, reduce weight, and enhance fire resistance.

Pomegranate peels waste (PPW) can be used as a substitute for natural clay [8]. Pomegranate peels are a waste product of the pomegranate juice industry and are often discarded in landfills. Their utilization as a substitute for natural clay in brick manufacturing can reduce the demand for virgin clay resources and minimize waste generation. PPW can also contribute to improved porosity and thermal insulation of the bricks.

Effects on Mechanical and Durability Properties

Adding agroindustrial wastes affects compressive strength, flexural strength, and durability [2]. The incorporation of agroindustrial wastes into bricks can have a significant impact on their mechanical and durability properties. The type and amount of waste material used, as well as the manufacturing process, can influence the resulting properties of the bricks. Careful optimization is required to achieve the desired performance characteristics.

Optimum amounts are obtained by mixing shell with 90% soil, producing bricks with suitable mechanical properties [2]. The optimal amount of agroindustrial waste to incorporate into bricks depends on the specific material and the desired properties of the bricks. In the case of cocoa shell, mixing it with 90% soil has been found to produce bricks with suitable mechanical properties. This optimization is crucial for ensuring that the resulting bricks meet the required performance standards for construction applications.

The use of agro-industrial waste as a partial replacement can reduce negative impacts on the environment [11]. The incorporation of agro-industrial waste into brick manufacturing reduces the demand for virgin resources, such as clay and cement, which have significant environmental impacts associated with their extraction and production. This approach also diverts waste from landfills, minimizing pollution and conserving landfill space. The reduction in environmental impact makes agro-industrial waste a sustainable and responsible choice for brick manufacturing.

Adding QL and CKD to the stabilized green specimens of different mixes can enhance their engineering properties with curing age increasing [20]. The addition of quicklime (QL) and cement kiln dust (CKD) to stabilized green bricks can improve their engineering properties, such as compressive strength and durability, over time. These additives promote pozzolanic reactions that strengthen the brick matrix and enhance its resistance to weathering and degradation. The increased curing age allows for the full development of these pozzolanic reactions, resulting in further improvements in engineering properties.

This is due to the pozzolanic reaction, which fills the pore structure with calcium silicate hydrates and calcium aluminate hydrates gel [20]. The pozzolanic reaction between QL and CKD and the clay minerals in the brick results in the formation of calcium silicate hydrates (C-S-H) and calcium aluminate hydrates gel. These compounds fill the pores in the brick structure, increasing its density and strength. The pozzolanic reaction also enhances the brick's resistance to chemical attack and weathering.

The ratio of QL and CKD used significantly affected the engineering properties of the specimens [20]. The optimal ratio of QL and CKD to use in stabilized green bricks depends on the specific composition of the clay and the desired properties of the bricks. Careful optimization is required to achieve the best balance of strength, durability, and workability. The ratio of QL and CKD can also influence the rate of the pozzolanic reaction and the resulting microstructure of the bricks.

Environmental and Economic Benefits

Recycling agroindustrial wastes offers an economical option to design green buildings [2]. The utilization of agroindustrial waste in building materials reduces the demand for virgin resources, which can be expensive to extract and process. This cost savings can make green building design more accessible and affordable. The reduced disposal costs associated with agroindustrial waste also contribute to the economic benefits of this approach.

Utilizing these wastes minimizes environmental burden and promotes sustainable construction [19]. The incorporation of agroindustrial waste into building materials reduces the environmental impact of construction by conserving natural resources, minimizing pollution, and reducing waste generation. This approach promotes sustainable construction practices that are environmentally responsible and economically viable. The use of agroindustrial waste also supports local economies by creating markets for waste materials.

Palm oil waste application reduces carbon dioxide emissions, contributing to a more sustainable environment [11]. The utilization of palm oil waste as a partial replacement for cement in brick manufacturing can significantly reduce carbon dioxide emissions associated with cement production. Cement production is a major source of greenhouse gas emissions, and the use of palm oil waste can lower the carbon footprint of buildings. This approach contributes to a more sustainable environment by mitigating climate change.

The incorporation of 12.5 wt% PPW showed the lowest density (1230 kg/m3), thermal conductivity (0.2 W/mK), and compressive strength (5.5 MPa), while achieving the highest water absorption (38%) and porosity (48%), which still satisfies the minimum acceptable requirements for bricks [8]. The use of PPW in brick production can result in bricks with lower density and thermal conductivity, which can improve the energy efficiency of buildings. The higher water absorption and porosity may require additional measures to protect the bricks from weathering and degradation. However, the resulting bricks still meet the minimum acceptable requirements for construction applications.

A considerable reduction in annual energy consumption of about 23.3% is attained compared to traditional bricks [8]. The improved thermal insulation properties of PPW-modified bricks can significantly reduce the energy required for heating and cooling buildings. This reduction in energy consumption can lead to substantial cost savings for building owners and a lower carbon footprint for the building sector. The energy savings also contribute to a more sustainable and resilient built environment.

The use of rice husk ash and sugarcane bagasse in clay bricks can lead to more economical construction by reducing the unit weight of the bricks [19]. The incorporation of rice husk ash and sugarcane bagasse into clay bricks can reduce their density, making them lighter and easier to handle. This can lower transportation costs and reduce the labor required for construction. The reduced weight of the bricks can also result in lower structural loads on buildings, potentially reducing the amount of materials required for foundations and supporting structures.

Recycled Crushed Clay Brick (RCB) in Construction

4.1. Properties of Recycled Crushed Clay Brick (RCB)

RCB exhibits a porous surface micro-morphology, high water absorption, and pozzolanic activity [3]. The porous nature of RCB results from the crushing process and the inherent porosity of the original clay bricks. This porosity contributes to high water absorption, which can affect the workability and durability of RCB-based construction materials. The pozzolanic activity of RCB is due to the presence of reactive silica and alumina, which can react with calcium hydroxide to form cementitious compounds, enhancing the strength and durability of the materials.

Higher RCB fine aggregate substitution ratios result in lower unconfined compressive strength [3]. The replacement of natural aggregates with RCB fine aggregates in concrete or other construction materials can lead to a decrease in unconfined compressive strength. This is due to the lower strength and higher porosity of RCB compared to natural aggregates. The extent of the reduction in compressive strength depends on the substitution ratio and the properties of the RCB.

The negative influence of RCB on unconfined compressive strength decreases gradually with curing time [3]. The pozzolanic activity of RCB can contribute to a gradual increase in strength over time, mitigating the initial reduction in compressive strength due to the replacement of natural aggregates. The pozzolanic reaction between RCB and calcium hydroxide produces cementitious compounds that fill the pores and strengthen the material matrix. This process is typically slow and can take several weeks or months to fully develop.

CSM containing RCB has an overall increasing accumulative water loss rate and accumulative strain of dry shrinkage [3]. The high water absorption of RCB can lead to increased water loss from CSM, resulting in higher accumulative water loss rates. The increased water loss can also contribute to higher accumulative strain of dry shrinkage, which can lead to cracking and other durability issues. Careful mix design and curing practices are required to mitigate these effects.

RCB with pozzolanic activity reacts slowly, mainly at later ages, enhancing the interfacial transition zone [3]. The slow pozzolanic reaction of RCB can enhance the interfacial transition zone (ITZ) between the aggregate and the cement matrix in concrete. The ITZ is a weak zone in concrete that is prone to cracking and failure. The pozzolanic reaction of RCB can densify the ITZ, improving its strength and durability.

Using waste crushed bricks in modified reactive powder concrete (MRPC) can improve its mechanical properties [21]. The incorporation of waste crushed bricks into MRPC can enhance its strength, durability, and workability. The crushed bricks act as a supplementary cementitious material, contributing to the hydration process and improving the microstructure of the MRPC. This can result in a stronger and more durable material that is suitable for a wide range of construction applications.

Application in Cement-Stabilized Macadam (CSM)

RCB can be used as a substitute for natural aggregates in cement-stabilized macadam (CSM) [3]. CSM is a composite material used in pavement construction, consisting of aggregates, cement, and water. The substitution of natural aggregates with RCB can reduce the demand for virgin materials, conserve landfill space, and lower transportation costs. However, careful consideration must be given to the properties of RCB and its impact on the performance of CSM.

Higher RCB substitution ratios lead to larger indirect tensile strength at 90 days curing time [3]. The indirect tensile strength of CSM is an important indicator of its resistance to cracking and failure under tensile stresses. The incorporation of RCB can improve the indirect tensile strength of CSM, particularly at later ages. This is due to the pozzolanic activity of RCB, which contributes to the formation of cementitious compounds that enhance the bond between the aggregate and the cement matrix.

Except for 20% RCB, which results in excellent dry shrinkage property, CSM containing RCB has an overall increasing accumulative water loss rate [3]. The high water absorption of RCB can lead to increased water loss from CSM, resulting in higher accumulative water loss rates. However, at a 20% substitution ratio, the RCB may act as an internal curing agent, reducing the overall water loss and improving the dry shrinkage properties of the CSM. This phenomenon requires further investigation to fully understand its mechanisms and optimize the mix design.

The mechanical properties of MRPC improved by replacing silica sand partially with 25% of waste crushed brick and decreased slightly when replacement reached to (50% WCB) [21]. The partial replacement of silica sand with waste crushed brick in MRPC can enhance its mechanical properties, such as compressive strength and flexural strength. However, exceeding the optimal replacement ratio can lead to a decrease in mechanical properties due to the lower strength and higher porosity of the waste crushed brick. Careful optimization of the mix design is required to achieve the best balance of performance and cost-effectiveness.

Utilizing RCB offers a promising step forward towards sustainable development and green construction [3]. The use of RCB in construction promotes resource efficiency, waste reduction, and environmental protection. This approach aligns with the principles of sustainable development and contributes to a more circular economy. The utilization of RCB can also create economic opportunities by providing a market for recycled materials and reducing the demand for virgin resources.

The study aims to assess the feasibility of cement-stabilized macadam (CSM), incorporating various RCB fine aggregate substitution ratios [3]. The feasibility assessment involves evaluating the mechanical properties, durability, and cost-effectiveness of CSM with different RCB substitution ratios. The results of this assessment will determine the optimal RCB substitution ratio that provides the best balance of performance and sustainability. This information is essential for promoting the wider adoption of RCB in pavement construction.

Mechanical and Shrinkage Properties of RCB Modified CSM

Higher RCB fine aggregate substitution ratios result in lower unconfined compressive strength [3]. This reduction in compressive strength is primarily attributed to the inherent properties of RCB, such as its increased porosity and reduced particle strength, when compared to conventional natural aggregates. The porous nature of RCB leads to a weaker internal structure, which is less capable of withstanding compressive forces. As the proportion of RCB increases within the CSM mix, the overall compressive strength diminishes due to the increased presence of these weaker particles.

The higher the RCB substitution ratio, the larger the indirect tensile strength at 90 d curing time of the late curing period [3]. This seemingly contradictory outcome, where compressive strength decreases while tensile strength increases, can be attributed to the pozzolanic activity of the RCB over extended curing periods. The RCB contains reactive silica that, when exposed to the alkaline environment created by cement hydration, undergoes a pozzolanic reaction. This reaction produces additional cementitious compounds that enhance the bond between the aggregates and the cement matrix, particularly in the interfacial transition zone. This improved bonding contributes to a higher resistance to tensile forces, leading to an increase in indirect tensile strength over time.

CSM containing RCB has an overall increasing accumulative water loss rate, accumulative strain of dry shrinkage and average coefficient of dry shrinkage [3]. The increased water loss is a direct consequence of the porous nature of RCB, which allows for greater absorption and subsequent evaporation of water. This elevated water loss leads to increased shrinkage, as the cement matrix contracts upon drying. The accumulative strain of dry shrinkage and the average coefficient of dry shrinkage are both measures of this contraction, and their increase indicates a higher propensity for cracking and deformation in the CSM.

The study explores the impact of aggregate modification and the brick-concrete ratio on recycled brick-aggregate concretes mechanical characteristics [22]. This aspect of the research delves into methods for improving the performance of RCB concrete by modifying the aggregates themselves and optimizing the proportion of brick aggregate to conventional concrete components. Aggregate modification techniques can include surface treatments or the addition of chemical admixtures to enhance the bonding characteristics and reduce water absorption of the RCB. Adjusting the brick-concrete ratio allows for a balance between the cost-effectiveness of using recycled materials and the desired mechanical properties of the final product.

Nuclear magnetic resonance and microhardness tests were performed to analyze the influence exerted by PVA modification on the interfacial transition zone (ITZ), microstructure, and pore structure [22]. These advanced testing methods provide a detailed understanding of how PVA modification affects the internal structure and properties of RCB concrete. Nuclear magnetic resonance (NMR) can be used to characterize the pore structure and water content of the# Mechanical Property Evaluation of Modified Bricks for Green Building Application

Introduction to Green Building and Modified Bricks

The Growing Demand for Sustainable Construction Materials

The construction industry's escalating need for materials highlights the urgency for sustainable alternatives [1]. This demand is driven by increasing urbanization, population growth, and the need for resilient infrastructure. Recycling agroindustrial solid wastes presents a viable and cost-effective approach to designing environmentally friendly buildings [2]. This approach not only addresses the growing demand for construction materials but also mitigates environmental concerns associated with traditional construction practices. Furthermore, the utilization of recycled crushed clay brick (RCB) in road engineering signifies a significant stride toward achieving sustainable development and promoting environmentally conscious construction methods [3].

The environmental impact of conventional building materials and construction processes is substantial, encompassing resource depletion, energy consumption, and waste generation. The accumulation of unmanaged agroindustrial solid wastes, especially in developing countries, has heightened environmental concerns, necessitating sustainable waste management strategies. Incorporating recycled materials and waste products into construction not only reduces environmental impact but also offers economic advantages, such as reduced material costs and waste disposal fees. These factors collectively underscore the growing demand for sustainable construction materials and the importance of exploring innovative approaches to meet this demand while minimizing environmental harm.
Moreover, the shift towards sustainable construction is fueled by increasing awareness among consumers, policymakers, and industry stakeholders regarding the long-term benefits of green building practices. Green buildings are designed to minimize environmental impact, enhance energy efficiency, improve indoor air quality, and promote occupant health and well-being. The use of sustainable construction materials is a crucial component of green building design, contributing to reduced carbon footprint, resource conservation, and improved building performance. As a result, the demand for sustainable construction materials is expected to continue growing in the coming years, driving innovation and adoption of new technologies in the construction industry.

The Role of Modified Bricks in Green Building

Modified clay bricks play a crucial role in providing low-cost, durable, and affordable housing options, particularly in regions where traditional building materials are either scarce or expensive [7]. These bricks can be engineered to meet diverse structural requirements, making them versatile for various construction applications [7]. The incorporation of waste materials into brick production not only reduces reliance on natural resources but also enhances the bricks' thermo-physical and mechanical characteristics, contributing to improved building performance [8].

The use of modified mud bricks is particularly valuable in maintaining the structural integrity and compressive strength of historical buildings without compromising their original architectural features [9]. These bricks are often reinforced with locally sourced materials, such as plant fibers and waste products, to enhance their durability and compatibility with existing structures. Employing plastic waste in mortar production leads to the creation of lightweight materials with enhanced thermal insulation properties, reducing the energy consumption associated with heating and cooling buildings [10]. The integration of agro-industrial waste as a partial substitute for traditional brick components mitigates adverse environmental consequences and promotes sustainable resource management [11].

Modified bricks contribute to green building by reducing the embodied energy of construction materials, minimizing waste generation, and improving building energy efficiency. Embodied energy refers to the total energy consumed throughout the life cycle of a construction material, including extraction, processing, manufacturing, transportation, and disposal. By incorporating recycled materials and waste products into brick production, the embodied energy of modified bricks can be significantly lower than that of traditional bricks. This reduction in embodied energy translates to lower greenhouse gas emissions and reduced environmental impact. Furthermore, modified bricks can be designed to enhance thermal performance, improve indoor air quality, and reduce water consumption, contributing to the overall sustainability of green buildings.

Scope of Mechanical Property Evaluation

The mechanical property evaluation of modified bricks primarily assesses their compressive strength, flexural strength, water absorption, and overall durability [1] , [2] , [12]. Microstructural analysis is essential to understand how modifications affect the brick's internal structure and performance [13] , [14]. This evaluation also aims to determine the long-term performance and environmental advantages of using modified bricks in construction projects [15] , [16].

The evaluation encompasses assessing the influence of different additives, such as waste glass powder, agroindustrial wastes, and recycled materials, on the mechanical properties of bricks [17] , [1] , [2] , [3]. Additionally, the assessment explores how various curing techniques and stabilization methods impact the characteristics of modified bricks [18]. By systematically evaluating the mechanical properties of modified bricks, this research aims to provide valuable insights for optimizing their composition, manufacturing processes, and application in sustainable construction.

The scope of mechanical property evaluation also includes assessing the impact of modified bricks on the structural performance of buildings. This involves evaluating the load-bearing capacity, resistance to deformation, and overall stability of building elements constructed with modified bricks. Furthermore, the evaluation considers the durability of modified bricks under various environmental conditions, such as exposure to moisture, temperature fluctuations, and chemical attack. By comprehensively assessing the mechanical properties and durability of modified bricks, this research aims to provide evidence-based recommendations for their safe and effective use in green building applications.

Waste Glass Powder (WGP) Modified Bricks

Production and Composition of WGP Modified Bricks

Waste glass powder (WGP) offers a sustainable alternative to clay in the production of burnt clay bricks, addressing both resource depletion and waste management challenges [1]. To optimize the mixture, various proportions of WGP, ranging from 0% to 25%, are tested [1]. The manufacturing process involves traditional artisanal methods with the incorporation of glass powder into the mixture [12].

The primary raw material, soil, is categorized as well-graded sand with silt (SW-SM) [12]. The inclusion of WGP enhances the structural integrity and durability of the bricks, positioning it as an environmentally responsible additive [1]. To facilitate widespread industrial implementation, optimizing firing parameters and scaling up production procedures are crucial [1].

The production of WGP-modified bricks involves several key steps, including raw material preparation, mixing, molding, drying, and firing. The raw materials, including clay, sand, and WGP, are carefully selected and prepared to ensure consistent quality and composition. The mixing process involves thoroughly blending the raw materials in appropriate proportions to achieve a homogenous mixture. The molding process involves shaping the mixture into brick form using either manual or automated methods. The drying process involves removing excess moisture from the molded bricks to prevent cracking and warping during firing. The firing process involves heating the dried bricks to high temperatures in a kiln to achieve the desired strength, durability, and color.

Impact on Compressive and Flexural Strength

Samples containing up to 20% WGP exhibited the most significant improvements in compressive strength and modulus of rupture [1]. Specifically, compressive strength increased by approximately 25%, while the modulus of rupture rose by around 41% [1]. Modified bricks incorporating glass powder demonstrated compressive strength improvements of up to 240% compared to conventional bricks [12].

Flexural strength showed an increase of up to 220% when the mixture contained between 8% and 12% glass powder [12]. These enhanced mechanical characteristics position WGP-modified bricks as a dependable substitute for sustainable construction practices [1]. The methodologies and interpretation of results adhere to the standards set by the Ecuadorian Institute of Standardization (INEN) [12].
The enhanced mechanical properties of WGP-modified bricks can be attributed to several factors, including the pozzolanic activity of WGP, the improved particle packing density, and the formation of a glassy phase during firing. WGP reacts with calcium hydroxide, a byproduct of cement hydration, to form additional cementitious compounds, enhancing the strength and durability of the bricks. The fine particle size of WGP improves the packing density of the brick matrix, reducing porosity and increasing resistance to compressive and flexural forces. The formation of a glassy phase during firing further strengthens the brick matrix, enhancing its resistance to cracking and deformation.

Durability and Water Absorption Characteristics

WGP enhances the structural integrity and overall durability of bricks, making it a viable solution for waste management [1]. Traditional and modified bricks displayed water absorption rates between 25% and 26% [12]. Further research into long-term durability is essential to fully validate WGP's **suitability for sustainable construction applications [1].**
The positive outcomes indicate that WGP serves as an eco-friendly additive, diminishing the reliance on natural clay resources [1]. The study's findings support the use of WGP-modified bricks as a reliable alternative for sustainable construction endeavors [1]. To broaden the use of WGP in sustainable construction, optimizing firing parameters is necessary [1].

The durability of WGP-modified bricks is influenced by several factors, including the WGP content, the firing temperature, and the environmental conditions to which the bricks are exposed. High WGP content can improve resistance to chemical attack, such as sulfate attack and acid rain corrosion. Proper firing temperatures are essential to ensure the formation of a durable glassy phase and to minimize cracking and warping. Exposure to harsh environmental conditions, such as freeze-thaw cycles and high humidity, can accelerate the degradation of WGP-modified bricks, highlighting the importance of proper design and construction practices to ensure their long-term performance.

Agroindustrial Waste as Additives in Bricks

Types of Agroindustrial Waste Used

Various agroindustrial wastes, including cocoa shells, sawdust, rice husks, and sugarcane bagasse, are utilized as additives in brick manufacturing [2]. The increasing accumulation of unmanaged agroindustrial solid wastes presents a significant environmental challenge [2]. Recycling these wastes offers a sustainable solution to mitigate pollution and provides an economical option for constructing green buildings [2].

Palm Oil Clinker Powder (POCP) and Boiler Ash (POBA) are employed as partial replacements for cement in brick production [11]. Sugarcane bagasse and rice husk ash are also commonly used [19]. Pomegranate peel waste (PPW) presents another viable substitute for natural clay in brick manufacturing [8].

The use of agroindustrial waste as additives in bricks offers several benefits, including reduced reliance on natural resources, waste minimization, and improved brick properties. These wastes are often readily available and inexpensive, making them attractive alternatives to traditional brick components. Furthermore, the incorporation of agroindustrial waste can enhance the thermal insulation, water resistance, and fire resistance of bricks, contributing to improved building performance and sustainability.

Effects on Mechanical and Durability Properties

The incorporation of agroindustrial wastes influences the compressive strength, flexural strength, and overall durability of bricks [2]. Optimal results are achieved by mixing shells with 90% soil, resulting in bricks with satisfactory mechanical properties [2]. The partial substitution of traditional components with agro-industrial waste reduces negative environmental impacts [11].

Adding quicklime (QL) and cement kiln dust (CKD) to stabilized green specimens enhances their engineering properties as they cure [20]. This improvement is attributed to the pozzolanic reaction, which fills the pore structure with calcium silicate hydrates and calcium aluminate hydrates gel [20]. The proportions of QL and CKD significantly affect the engineering properties of the resulting specimens [20].

The effects of agroindustrial waste on brick properties depend on several factors, including the type and amount of waste used, the brick composition, and the manufacturing process. Some agroindustrial wastes, such as rice husk ash and sugarcane bagasse, contain high levels of silica, which can react with calcium hydroxide to form additional cementitious compounds, enhancing the strength and durability of the bricks. Other wastes, such as cocoa shells and sawdust, can increase the porosity of the bricks, improving their thermal insulation properties. The key is to carefully optimize the waste content and brick composition to achieve the desired balance of mechanical and durability properties.

Environmental and Economic Benefits

Recycling agroindustrial wastes provides an economical pathway to designing green buildings [2]. Utilizing these waste materials reduces environmental burden and supports sustainable construction practices [19]. The application of palm oil waste reduces carbon dioxide emissions, promoting a more environmentally sustainable approach [11].

Incorporating 12.5 wt% PPW results in the lowest density (1230 kg/m3) and thermal conductivity (0.2 W/mK), while maintaining a compressive strength of 5.5 MPa, which meets minimum brick requirements [8]. This incorporation also achieves the highest water absorption (38%) and porosity (48%) [8]. This approach leads to a significant reduction in annual energy consumption, approximately 23.3% compared to traditional bricks [8]. Using rice husk ash and sugarcane bagasse in clay bricks can lead to more economical construction by reducing the unit weight of the bricks [19].

The environmental benefits of using agroindustrial waste in brick manufacturing include reduced greenhouse gas emissions, resource conservation, and waste minimization. By substituting traditional brick components with waste materials, the embodied energy of the bricks is reduced, leading to lower carbon footprint. The use of agroindustrial waste also reduces the demand for natural resources, such as clay and sand, conserving these valuable resources for future generations. Furthermore, the incorporation of waste materials into bricks diverts them from landfills, reducing the environmental impact of waste disposal.

Recycled Crushed Clay Brick (RCB) in Construction

Properties of Recycled Crushed Clay Brick (RCB)

Recycled crushed clay brick (RCB) exhibits a porous surface, high water absorption, and pozzolanic activity, making it a viable material for sustainable construction [3]. Higher substitution ratios of RCB fine aggregate result in reduced unconfined compressive strength [3]. The adverse effect of RCB on unconfined compressive strength diminishes over time with increased curing [3].

Cement-stabilized macadam (CSM) containing RCB demonstrates an increasing accumulative water loss rate and dry shrinkage [3]. The pozzolanic activity of RCB occurs gradually, primarily at later stages, enhancing the interfacial transition zone within the material [3]. Using waste crushed bricks in modified reactive powder concrete (MRPC) can enhance its mechanical properties, providing a sustainable alternative to traditional materials [21].

The properties of RCB are influenced by several factors, including the source of the clay bricks, the crushing method, and the particle size distribution. Clay bricks from different sources may have varying mineralogical compositions and physical properties, affecting the performance of RCB in construction applications. The crushing method can also influence the particle shape and surface texture of RCB, impacting its water absorption and pozzolanic activity. Proper particle size distribution is essential to ensure good packing density and workability of RCB mixtures.

Application in Cement-Stabilized Macadam (CSM)

RCB can be effectively used as a substitute for natural aggregates in cement-stabilized macadam (CSM) for road construction [3]. Increased RCB substitution ratios lead to greater indirect tensile strength after 90 days of curing [3]. Except for mixtures with 20% RCB, which show excellent dry shrinkage properties, CSM containing RCB generally exhibits an increasing accumulative water loss rate [3].

The mechanical properties of modified reactive powder concrete (MRPC) improve when silica sand is partially replaced with 25% waste crushed brick, but decrease slightly when the replacement reaches 50% WCB [21]. Utilizing RCB is a promising step toward promoting sustainable development and environmentally responsible construction practices [3]. This approach assesses the feasibility of using cement-stabilized macadam (CSM) with various RCB fine aggregate substitution ratios [3].

The application of RCB in CSM offers several benefits, including reduced reliance on natural aggregates, waste minimization, and improved pavement performance. By substituting natural aggregates with RCB, the demand for virgin materials is reduced, conserving these valuable resources. The use of RCB also diverts waste materials from landfills, reducing the environmental impact of waste disposal. Furthermore, RCB can improve the strength, durability, and skid resistance of CSM pavements, enhancing their long-term performance and safety.

Mechanical and Shrinkage Properties of RCB Modified CSM

Higher RCB fine aggregate substitution ratios result in reduced unconfined compressive strength, impacting the overall load-bearing capacity of the material [3]. Conversely, an increased RCB substitution ratio leads to greater indirect tensile strength after 90 days of curing, indicating improved resistance to cracking [3]. CSM containing RCB generally demonstrates an increasing accumulative water loss rate, accumulative strain of dry shrinkage, and average coefficient of dry shrinkage, which can affect its long-term stability [3].

The study explores the influence of aggregate modification and the brick-concrete ratio on the mechanical characteristics of recycled brick-aggregate concretes, providing valuable insights into material optimization [22]. Nuclear magnetic resonance and microhardness tests analyze the effects of PVA modification on the interfacial transition zone (ITZ), microstructure, and pore structure, offering a deeper understanding of material behavior [22]. RCB can effectively improve the performance of concrete by reducing water absorption and enhancing strength [23].

The mechanical and shrinkage properties of RCB-modified CSM are influenced by several factors, including the RCB content, the cement content, the water-cement ratio, and the curing conditions. High RCB content can reduce the workability of the mixture, requiring adjustments to the water-cement ratio to maintain proper consistency. Proper curing is essential to ensure adequate hydration of the cement and to minimize shrinkage cracking. The use of additives, such as fly ash and silica fume, can further improve the mechanical and shrinkage properties of RCB-modified CSM.

Waste Clay Bricks (WCB) in Cemented Tailings Backfill (CTB)

Preparation of CTB with Waste Clay Bricks

Two types of cemented tailings backfill (CTB) are created using broken waste clay bricks (WCB) to enhance sustainability in construction [24]. In this process, a portion of the cement is replaced with brick powder, and a portion of the tailings are substituted with brick aggregate, optimizing resource utilization [24]. The mechanical properties of the resulting modified CTB are then thoroughly investigated to ensure structural integrity [24].

This approach also explores the effects of polyvinyl alcohol (PVA) solution in modifying recycled aggregates, assessing its potential to enhance material performance [22]. Basic physical properties, energy-dispersive spectroscopy (EDS), X-Ray diffraction (XRD), and scanning electron microscopy (SEM) are employed to study these effects and mechanisms at a microstructural level [22]. By breaking up the waste clay bricks (WCB) from dismantled buildings and replacing part of the cement with brick powder and part of the tailings with brick aggregate [24].

The preparation of CTB with WCB involves several key steps, including WCB collection and processing, tailings preparation, binder selection, mixing, and curing. WCB is collected from construction and demolition sites and processed to remove contaminants and achieve the desired particle size distribution. Tailings are prepared by adjusting their moisture content and particle size distribution to ensure proper workability and consolidation. The binder, typically a combination of cement and supplementary cementitious materials, is selected based on the desired strength, durability, and cost-effectiveness. The mixing process involves thoroughly blending the WCB, tailings, and binder in appropriate proportions to achieve a homogenous mixture. The curing process involves maintaining the CTB mixture at a controlled temperature and humidity to promote cement hydration and strength development.

Effects on Mechanical Properties of CTB

Incorporating 10% brick powder content in CTB leads to a 16.24% increase in strength after a 28-day curing period, demonstrating the beneficial effects of this modification [24]. The strength of brick aggregate with less than 20% content can be increased at each curing age [24]. The strength of 15% brick aggregate at curing ages of 7 d and 28 d is increased by 65.54 and 58.8% [24].

The failure strain of CTB containing brick powder decreases as the curing time extends, indicating improved material stiffness [24]. Similarly, the failure strain of CTB containing brick aggregate significantly decreases at the curing age of 7 days, further enhancing its structural performance [24]. The optimal mechanical properties for recycled brick aggregate concrete (RAC) occur when the replacement rate is 30% and the brick-concrete ratio is 1:1 [22].

The mechanical properties of CTB with WCB are influenced by several factors, including the WCB content, the binder type and content, the tailings properties, and the curing conditions. High WCB content can reduce the workability of the mixture, requiring adjustments to the water-binder ratio to maintain proper consistency. The use of supplementary cementitious materials, such as fly ash and slag, can improve the strength and durability of CTB with WCB. Proper curing is essential to ensure adequate hydration of the cement and to minimize shrinkage cracking.

Damage Constitutive Model for CTB

A three-stage damage constitutive model is developed based on the study's findings, providing a comprehensive framework for understanding the behavior of CTB under stress [24]. The laboratory test results of CTB under uniaxial compression align effectively with the model, demonstrating its accuracy and reliability [24]. The compressive strength is 44.2 MPa, the bending strength is 15.6

MPa, and the splitting tensile strength is 3.85 MPa [22].

Additionally, the modification with PVA results in a higher percentage of transition pores, while simultaneously reducing the percentage of macropores [22]. There is an uptick in the frequency of harmless and less harmful pores, and a declining proportion of harmful and more harmful pores [22]. The ITZs structural morphology in the RAC is effectively improved by the coating structure formed through the bonding of the polymer with cement hydration products, and PVA modification reduces the thickness of this zone [22].

The damage constitutive model for CTB with WCB provides a valuable tool for predicting the material's response to various loading conditions and for designing safe and reliable structures. The model incorporates several key parameters, including the elastic modulus, the Poisson's ratio, the compressive strength, and the tensile strength. By accurately characterizing these parameters, the model can predict the stress-strain behavior of CTB with WCB under various loading scenarios, such as uniaxial compression, uniaxial tension, and shear.

Paper Waste Incorporation in Fired Clay Bricks

Mixing Ratios and Firing Temperatures

Paper waste is combined with clay in specific ratios of 2.5, 5.0, 7.5, and 10 wt%, allowing for a systematic evaluation of its impact on brick properties [25]. The green bricks, prepared with these varying compositions, are then fired at controlled temperatures ranging from 900 to 1100°C for one hour in an air environment [25]. The fired bricks are then subjected to rigorous analysis to determine their resulting mechanical properties [25].

With increase ratio, strength decreased [8]. The impact of adding PPW on compressive strength, total porosity, water absorption, bulk density, thermal conductivity microstructure characteristics has been assessed at 900, 1000 1100 C [8]. The study is intended to evaluate the effects of paper waste addition on physical properties and strength fired clay bricks [25].

The mixing ratios and firing temperatures are critical parameters in the production of paper waste-incorporated fired clay bricks. The paper waste content affects the workability of the mixture, the drying shrinkage, and the firing behavior. High paper waste content can reduce the workability of the mixture, requiring adjustments to the water content to maintain proper consistency. Proper firing temperatures are essential to ensure complete combustion of the paper waste and to achieve the desired strength and durability of the bricks.

Effects on Physical Properties

The addition of paper waste leads to an increase in the porosity of the fired clay bricks [25]. This increase in porosity subsequently results in lower density and reduced shrinkage values, altering the overall physical characteristics of the bricks [25]. The resulting highly porous brick exhibits low thermal conductivity, suggesting enhanced insulation capabilities [25].

The impact of adding on compressive strength, total porosity, water absorption, bulk density, thermal conductivity microstructure characteristics has been assessed at 900, 1000 1100 C [8]. The modified unfired bricks demonstrated enhanced crack resistance, increased ductility, and superior thermal insulation properties [16]. Temperature measurements revealed that houses constructed with unfired bricks consistently maintained cooler indoor temperatures compared to those made with fired bricks, indicating improved thermal efficiency [16].

The physical properties of paper waste-incorporated fired clay bricks are influenced by several factors, including the paper waste content, the clay composition, the firing temperature, and the cooling rate. High paper waste content can increase the porosity and reduce the density of the bricks, improving their thermal insulation properties. The clay composition affects the strength and durability of the bricks. Proper firing temperatures are essential to ensure complete combustion of the paper waste and to achieve the desired physical properties.

Impact on Compressive Strength and Thermal Conductivity

The increased porosity due to paper waste incorporation correlates with a reduction in compressive strength, attributed to the introduction of weaknesses in the brick structure [25]. However, the inclusion of paper waste residue provides excellent thermal insulation, even while maintaining adequate structural strength [25]. Therefore, residue inclusion is excellent insulating behavior, while adequate could be still maintained [25].

The optimal PRL content (2.5%7.5% by cement weight) enhances compressive strength, reduces water absorption, and improves durability, meeting the Thai industrial standard (TIS 77-2545) [16]. Incorporating 12.5 wt% PPW showed the lowest density (1230 kg/m 3) and thermal conductivity (0.2 W/mK), while still satisfying minimum acceptable requirements for bricks [8]. An apparent decrease in the values of thermal conductivity coefficient (k) by a percentage of (50%) to (60%) compared to an ordinary mortar [10].

The impact of paper waste incorporation on compressive strength and thermal conductivity is a trade-off between structural performance and thermal insulation. High paper waste content can significantly reduce the compressive strength of the bricks, limiting their use in load-bearing applications. However, the increased porosity due to paper waste incorporation can significantly improve the thermal insulation properties of the bricks, reducing the energy consumption for heating and cooling buildings. The key is to carefully optimize the paper waste content to achieve the desired balance of compressive strength and thermal conductivity.

Plastic Waste Utilization in Brick Manufacturing

Types of Plastic Waste Used

Polyethylene terephthalate (PET) derived from plastic bottles is utilized as a substitute for sand and cement in varying proportions, promoting waste reduction and resource conservation [10]. Polypropylene (PP) waste is processed into fibers and incorporated into brick mixtures, enhancing their mechanical properties [15]. Plastic waste is combined with fibers to make non-conventional bricks [6].

This study uses polyethylene terephthalate (PET) combined with fibers make non-conventional bricks [6]. To promote sustainable construction practices, pp waste is used in plastic brick to replace waste material often discarded in landfills and burned [15]. The study uses polyethylene terephthalate (PET) combined with fibers make non-conventional bricks [6].

The use of different types of plastic waste in brick manufacturing offers several advantages, including reduced reliance on natural resources, waste minimization, and improved brick properties. PET is a strong and durable plastic that can enhance the strength and water resistance of bricks. PP fibers can improve the toughness and crack resistance of bricks. The key is to carefully select the appropriate type of plastic waste and to optimize its content in the brick mixture to achieve the desired performance characteristics.

Effects on Mechanical Properties

The compressive strength of mix 2, containing a specific proportion of plastic waste, reaches 426kg, the highest among the tested plastic bricks [15]. Plastic bricks containing 25% and 40% weight PET are subjected to compressive strength and hardness tests to evaluate their structural performance [6]. The waste plastics were repurposed for use in the construction industry [15]. Modified bricks with glass powder show up to 240% compressive strength and 220% flexural strength capability compared to traditional bricks when using 8% to 12% glass powder dosage in the mixture [12]. This study aims to investigate the feasibility of utilizing plastic wastes to produce a cost-effective and lightweight plastic brick for use in construction [15]. The paper shows that an apparent decrease in the values of thermal conductivity coefficient (k) by a percentage of (50%) to (60%) compared to an ordinary mortar [10].

The effects of plastic waste incorporation on the mechanical properties of bricks depend on several factors, including the type and amount of plastic waste used, the brick composition, and the manufacturing process. Some plastic wastes, such as PET and PP, can enhance the strength and toughness of bricks. However, high plastic waste content can reduce the workability of the mixture and may require adjustments to the water content or the use of additives to maintain proper consistency.

Thermal Conductivity and Density

Mortar modified with plastic waste exhibits a notable reduction in thermal conductivity coefficient (k) ranging from 50% to 60%, indicating improved thermal insulation [10]. The incorporation of plastic waste results in a lighter weight mortar, reducing the overall load on building structures [10]. There is an increase in waste production among the Indian population [15].

The paper shows that an apparent decrease in the values of thermal conductivity coefficient (k) by a percentage of (50%) to (60%) compared to an ordinary mortar [10]. There is also a significant amount of plastic waste in the country [15]. The purpose of this study is to investigate the feasibility of utilizing plastic wastes to produce a cost-effective and lightweight plastic brick for use in construction [15].

The reduction in thermal conductivity and density due to plastic waste incorporation can significantly improve the energy efficiency of buildings. Lighter weight bricks reduce the structural load on the building, allowing for more efficient use of materials and potentially reducing construction costs. The improved thermal insulation properties of plastic waste-modified bricks can reduce the energy consumption for heating and cooling, leading to lower utility bills and reduced greenhouse gas emissions.

Fiber Reinforcement in Bricks

Types of Fibers Used

Common reed fibers (Arundo donax L.) are incorporated into bio-lime based mortar to enhance its flexural toughness, improving its resistance to bending and cracking [4]. Polypropylene fibers (PPFs) are utilized to improve the mechanical properties of recycled brick concrete, increasing its strength and durability [26]. Basalt fibers are integrated into the production process of modified bricks, contributing to their overall performance characteristics [27].

This study explores the potential of cork-modified mortars reinforced with basalt fabric, focusing on optimizing both mechanical and hygroscopic properties [5]. The study uses polyethylene terephthalate (PET) combined with fibers make non-conventional bricks [6]. The article focuses on brick products, the production of which is based on natural components, such as lime (CaO), quartz sand (SiO2) and water (H2O), and which are created during the process of the so-called hydrothermal treatment [27].

The use of different types of fibers in brick manufacturing offers several advantages, including improved mechanical properties, enhanced durability, and reduced cracking. Natural fibers, such as reed fibers and cork, are renewable and biodegradable, making them environmentally friendly alternatives to synthetic fibers. Synthetic fibers, such as PP fibers and basalt fibers, offer high strength and durability, improving the long-term performance of bricks.

Effects on Flexural Toughness and Mechanical Properties

The addition of reed fibers enhances the flexural toughness of bio-lime based mortar, making it more resistant to cracking and deformation under bending loads [4]. Polypropylene fibers improve the mechanical properties of RBA concrete, increasing its compressive strength, tensile strength, and flexural strength [26]. The compressive strength of PLCNF/GO brick 4 is 16.092 MPa compared to control and commercial concrete brick with value of 8.482 and 15.681 MPa, respectively [28].

The optimal mechanical properties for recycled brick aggregate concrete (RAC) occur when the replacement rate is 30% and the brick-concrete ratio is 1:1 [22]. The compressive strength is 44.2 MPa, the bending strength is 15.6 MPa, and the splitting tensile strength is 3.85 MPa [22]. This study examines the workability, strength, and microstructure of high strength eco-concrete incorporating recycled clay brick aggregate calcined clay [29].

The effects of fiber reinforcement on the mechanical properties of bricks depend on several factors, including the type and amount of fiber used, the brick composition, and the manufacturing process. Fibers can improve the tensile strength, flexural strength, and impact resistance of bricks by bridging cracks and preventing their propagation. The key is to carefully select the appropriate type of fiber and to optimize its content in the brick mixture to achieve the desired performance characteristics.

Impact on Crack Resistance and Ductility

Modified unfired bricks demonstrate enhanced crack resistance and increased ductility, improving their ability to withstand stress and deformation without fracturing [16]. PPFs significantly improve the toughness of RBA concrete, enhancing its resistance to crack propagation and improving its overall durability [26]. The addition of fibers can improve physical mechanical properties as well fiber/matrix interfacial adhesion [4].

These advancements are credited to the polymer film network formed from PRL during the hydration process, which strengthens particle bonds and reduces porosity [16]. However, PRL content exceeding 7.5% leads to performance reductions, attributed to thicker polymer films and particle aggregation, which create larger voids within the material [16]. Micro-computed tomography was first used to assess the homogeneity of the mixtures, followed by flow tests to evaluate workability [5].

The improvement in crack resistance and ductility due to fiber reinforcement is a critical factor in enhancing the long-term performance and durability of bricks. Fiber reinforcement can prevent the formation and propagation of cracks, reducing the risk of structural failure and extending the service life of buildings. The increased ductility of fiber-reinforced bricks allows them to deform under stress without fracturing, providing a warning sign of potential structural problems and allowing for timely repairs.

Chemical and Mineral Admixtures

Types of Admixtures Used

Cement kiln dust (CKD) and quicklime (QL) are employed to activate ground granulated blast-furnace steel slag (GGBS), enhancing its cementitious properties and promoting sustainable construction practices [20]. Nano-kaolin and silica fume are utilized to reinforce mud bricks, improving their strength, durability, and resistance to environmental degradation [9]. Slag and fly ash are incorporated as admixtures in concrete three-hole bricks, contributing to their# Mechanical Property Evaluation of Modified Bricks for Green Building Application

Introduction to Green Building and Modified Bricks

The Growing Demand for Sustainable Construction Materials

The construction industry's escalating demand for materials necessitates the exploration of sustainable alternatives to mitigate environmental impact [1]. Recycling agroindustrial solid wastes presents a viable and economical pathway towards green building design, addressing both pollution concerns and resource efficiency [2]. Furthermore, utilizing recycled crushed clay brick (RCB) in road engineering and building construction represents a promising stride towards achieving sustainable development and promoting green construction practices [3].

The growing awareness of environmental issues has led to a significant push for reducing the ecological footprint of building materials [4]. The construction sector's shift towards sustainable methods is primarily motivated by the urgent need to curtail energy consumption [5]. Addressing the accumulation of plastic waste, which poses a severe threat to the environment, necessitates innovative repurposing strategies within the construction industry [6].

T**he Role of Modified Bricks in Green Building**

Modified clay bricks play a crucial role in fostering low-cost, durable, and affordable housing solutions

[7]. The adaptability of these bricks allows for the customization of their properties to meet diverse loading conditions and structural requirements [7]. Incorporating waste materials into brick manufacturing enhances their thermo-physical and mechanical properties, contributing to resource conservation and improved building performance [8].

Modified mud bricks offer a sustainable approach to maintaining the structural integrity and compressive strength of heritage buildings without compromising their historical character [9]. The utilization of plastic waste in mortar production yields lightweight materials with enhanced thermal insulation properties, reducing the energy demand for heating and cooling [10]. Moreover, the integration of agro-industrial waste as a partial replacement for traditional brick components can significantly diminish the negative environmental impacts associated with conventional construction practices [11].

Scope of Mechanical Property Evaluation

This evaluation focuses on assessing key mechanical properties such as compressive strength, flexural strength, water absorption, and overall durability to determine the suitability of modified bricks for green building applications [1], [2], [12]. Microstructural analysis is employed to gain insights into the effects of various modifications on the internal structure and performance characteristics of the bricks [13], [14]. The evaluation also aims to comprehensively assess the long-term performance, environmental benefits, and economic viability of utilizing modified bricks in sustainable construction projects [15], [16].

The assessment extends to examining the impact of a wide array of additives on the mechanical properties of bricks, including waste glass powder, agroindustrial wastes, recycled materials, and chemical admixtures [17], [1], [2], [3]. Different curing methods and stabilization techniques are evaluated to determine their influence on the properties of modified bricks, ensuring optimal performance and longevity [18].

Waste Glass Powder (WGP) Modified Bricks Production and Composition of WGP Modified Bricks

Waste glass powder (WGP) presents a promising alternative as a partial replacement for clay in the production of burnt clay bricks, contributing to waste reduction and resource conservation [1]. To optimize the mixture and assess its impact on brick properties, various WGP substitution levels, ranging from 0% to 25%, are rigorously tested [1]. The manufacturing process typically involves artisanal procedures, with the key modification being the incorporation of glass powder into the mixture [12]. The soil used as the primary raw material is generally classified as well-graded sand with silt (SW-SM), providing a suitable matrix for the integration of WGP [12]. The addition of WGP enhances the structural integrity and durability of the bricks, positioning it as an eco-friendly additive that reduces the dependence on natural clay resources [1]. For broader industrial adoption, optimizing firing parameters and scaling up production processes are essential steps to ensure consistent quality and cost-effectiveness [1].

Impact on Compressive and Flexural Strength

Incorporating up to 20% WGP in brick mixtures has shown the most significant increase in compressive strength and modulus of rupture [1]. Specifically, compressive strength experiences an approximate increase of 25%, while the modulus of rupture sees a substantial improvement of around 41% [1]. Furthermore, modified bricks containing glass powder exhibit up to 240% higher compressive strength compared to traditional bricks, demonstrating the potential for significant structural enhancements [12].

The flexural strength capability can be up to 220% greater when using an optimal glass powder dosage of 8% to 12% in the mixture [12]. These enhanced mechanical properties position WGP-modified bricks as a viable and sustainable alternative for construction applications [1]. The procedures for manufacturing and testing WGP-modified bricks, along with the interpretation of results, adhere to the guidelines established by the Ecuadorian Institute of Standardization (INEN), ensuring compliance with recognized quality standards [12].

Durability and Water Absorption Characteristics

The incorporation of WGP in brick production leads to improved structural integrity and enhanced durability, positioning it as an effective waste management solution [1]. Interestingly, both traditional and WGP-modified bricks exhibit a similar water absorption percentage, typically ranging between 25% and 26% [12]. To fully leverage the potential of WGP for sustainable construction, further research is needed to evaluate long-term durability and optimize its performance under various environmental conditions [1].

The promising results obtained from WGP-modified bricks highlight its potential as an eco-friendly additive that reduces reliance on natural clay resources, contributing to more sustainable construction practices [1]. The study concludes that WGP-modified bricks can serve as a valid replacement for traditional bricks in sustainable construction applications, offering improved mechanical properties and environmental benefits [1]. However, to enhance the suitability of WGP for widespread use, further studies are essential to optimize firing parameters, evaluate long-term durability, and scale up production processes [1].

Agroindustrial Waste as Additives in Bricks

Types of Agroindustrial Waste Used

Various types of agroindustrial waste, including cocoa shell, sawdust, rice husk, and sugarcane bagasse, can be effectively utilized as additives in brick manufacturing, promoting waste reduction and resource efficiency [2]. The accumulation of unmanaged agroindustrial solid wastes poses a significant environmental concern, particularly in developing countries, necessitating sustainable waste management strategies [2]. Recycling these wastes not only offers a viable solution to pollution but also provides an economical option for designing green buildings, aligning environmental and economic benefits [2].

Palm Oil Clinker Powder (POCP) and Boiler Ash (POBA) are also used as partial replacements for cement in brick production, reducing the reliance on traditional cement and lowering carbon emissions [11]. Sugarcane bagasse and rice husk ash are other examples of agricultural waste materials that can be incorporated into brick mixtures, contributing to sustainable waste management [19]. Pomegranate peels waste (PPW) presents yet another alternative as a substitute for natural clay, further diversifying the range of agroindustrial wastes that can be utilized in brick manufacturing [8].

Effects on Mechanical and Durability Properties

The addition of agroindustrial wastes to brick mixtures can significantly affect compressive strength, flexural strength, and overall durability, depending on the type and proportion of waste used [2]. Optimal results are often achieved by mixing shell with 90% soil, resulting in bricks with mechanical properties suitable for secondary raw material production [2]. Utilizing agro-industrial waste as a partial replacement for traditional brick components can reduce negative impacts on the environment, promoting more sustainable construction practices [11].

Adding quicklime (QL) and cement kiln dust (CKD) to stabilized green specimens can enhance their engineering properties with increasing curing age [20]. This enhancement is attributed to the pozzolanic reaction, which fills the pore structure with calcium silicate hydrates and calcium aluminate hydrates gel, improving the brick's overall strength and durability [20]. The ratio of QL and CKD used significantly affects the engineering properties of the specimens, highlighting the importance of optimizing the mixture composition for desired performance characteristics [20].

Environmental and Economic Benefits

Recycling agroindustrial wastes offers an economically viable option for designing green buildings, aligning environmental sustainability with cost-effectiveness [2]. Utilizing these wastes minimizes environmental burden and promotes sustainable construction practices, contributing to a circular economy approach [19]. Palm oil waste application reduces carbon dioxide emissions, contributing to a more sustainable environment and mitigating the impact of climate change [11].

The incorporation of 12.5 wt% PPW results in the lowest density (1230 kg/m3) and thermal conductivity (0.2 W/mK), while still satisfying the minimum acceptable requirements for bricks [8]. Furthermore, a considerable reduction in annual energy consumption of about 23.3% can be achieved compared to traditional bricks, demonstrating the potential for significant energy savings [8]. The use of rice husk ash and sugarcane bagasse in clay bricks can lead to more economical construction by reducing the unit weight of the bricks, lowering transportation costs and overall construction expenses [19].

Recycled Crushed Clay Brick (RCB) in Construction

Properties of Recycled Crushed Clay Brick (RCB)

Recycled crushed clay brick (RCB) exhibits a porous surface micro-morphology, high water absorption, and pozzolanic activity, making it a potentially valuable material for construction applications [3]. Higher RCB fine aggregate substitution ratios generally result in lower unconfined compressive strength, requiring careful optimization of the mixture to maintain structural integrity [3]. However, the negative influence of RCB on unconfined compressive strength tends to decrease gradually with increasing curing time, suggesting long-term strength development [3].

Cement-stabilized macadam (CSM) containing RCB exhibits an overall increasing accumulative water loss rate and accumulative strain of dry shrinkage, which should be considered in pavement design to mitigate potential cracking and deformation [3]. The pozzolanic activity of RCB, while slow, enhances the interfacial transition zone at later ages, contributing to improved bonding and durability [3]. Utilizing waste crushed bricks in modified reactive powder concrete (MRPC) can improve its mechanical properties, further expanding the potential applications of RCB in construction [21].

Application in Cement-Stabilized Macadam (CSM)

RCB can be effectively used as a substitute for natural aggregates in cement-stabilized macadam (CSM), reducing the demand for virgin materials and promoting sustainable construction practices [3]. Higher RCB substitution ratios can lead to larger indirect tensile strength at 90 days curing time, indicating improved resistance to cracking under tensile stresses [3]. Except for mixtures with 20% RCB, which exhibit excellent dry shrinkage properties, CSM containing RCB generally shows an overall increasing accumulative water loss rate, requiring appropriate design considerations [3].

The mechanical properties of MRPC can be improved by partially replacing silica sand with 25% waste crushed brick, demonstrating the potential for enhancing concrete performance through RCB incorporation [21]. Utilizing RCB offers a promising step forward towards sustainable development and green construction, aligning environmental benefits with practical applications [3]. The study aims to assess the feasibility of cement-stabilized macadam (CSM) incorporating various RCB fine aggregate substitution ratios, providing valuable insights for optimizing RCB utilization in pavement construction [3].

Mechanical and Shrinkage Properties of RCB Modified CSM

Higher RCB fine aggregate substitution ratios typically result in lower unconfined compressive strength, necessitating careful mixture design and optimization [3]. However, increasing the RCB substitution ratio can lead to larger indirect tensile strength at 90 days curing time, suggesting enhanced resistance to tensile stresses [3]. Cement-stabilized macadam (CSM) containing RCB generally exhibits an overall increasing accumulative water loss rate, accumulative strain of dry shrinkage, and average coefficient of dry shrinkage, requiring appropriate design considerations to mitigate potential issues [3].

The study explores the impact of aggregate modification and the brick-concrete ratio on the mechanical characteristics of recycled brick-aggregate concretes, providing valuable insights for optimizing concrete performance [22]. Nuclear magnetic resonance and microhardness tests were performed to analyze the influence exerted by PVA modification on the interfacial transition zone (ITZ), microstructure, and pore structure, contributing to a better understanding of the material's behavior [22]. The incorporation of RCB can effectively improve concrete performance, mainly by reducing water absorption and crushing index while improving strength, highlighting its potential as a sustainable construction material [23].

Waste Clay Bricks (WCB) in Cemented Tailings Backfill (CTB)

Preparation of CTB with Waste Clay Bricks

Two types of cemented tailings backfill (CTB) are prepared by breaking up waste clay bricks (WCB), offering a sustainable approach to managing construction and demolition waste [24]. In this process, part of the cement is replaced with brick powder, and part of the tailings with brick aggregate, optimizing the use of waste materials [24]. The mechanical properties of the modified CTB are then thoroughly investigated to assess its suitability for various applications [24].

This study explores the effects and mechanisms of polyvinyl alcohol (PVA) solution in modifying recycled aggregates, providing a deeper understanding of the material's behavior and potential for performance enhancement [22]. Basic physical properties, energy-dispersive spectroscopy (EDS), X-Ray diffraction (XRD), and scanning electron microscopy (SEM) are employed to study these effects and mechanisms, offering a comprehensive characterization of the modified material [22]. By breaking up the waste clay bricks (WCB) from dismantled buildings and replacing part of the cement with brick powder and part of the tailings with brick aggregate, the study aims to create a sustainable and cost-effective backfill material [24].

Effects on Mechanical Properties of CTB

Cemented tailings backfill (CTB) with 10% brick powder content exhibits a strength increase of 16.24% at 28 days curing age, demonstrating the potential for enhancing the mechanical properties of backfill materials through WCB incorporation [24]. The strength of brick aggregate with less than 20% content can be increased at each curing age, suggesting an optimal range for WCB utilization [24]. Specifically, the strength of 15% brick aggregate at curing ages of 7 d and 28 d is increased by 65.54 and 58.8%, respectively, highlighting the significant impact of WCB on CTB strength [24].

The failure strain of the CTB-containing brick powder decreases with the extension of the curing time, indicating a potential change in the material's deformation behavior over time [24]. Similarly, the failure strain of the CTB-containing brick aggregate decreases significantly at the curing age of 7 days, suggesting an early-age influence of WCB on CTB deformation characteristics [24]. The optimal mechanical properties for recycled brick aggregate concrete (RAC) occur when the replacement rate is 30% and the brick-concrete ratio is 1:1, providing valuable guidance for mixture design [22].

Damage Constitutive Model for CTB

A three-stage damage constitutive model is established based on the results of this study, providing a valuable tool for predicting the behavior of CTB under various loading conditions [24]. The laboratory test results of CTB under uniaxial compression are effectively described with high confidence using this model, validating its accuracy and reliability [24]. The compressive strength reaches 44.2 MPa, the bending strength is 15.6 MPa, and the splitting tensile strength is 3.85 MPa, demonstrating the potential for achieving high-performance CTB through WCB incorporation [22].

Additionally, the modification with PVA results in a higher percentage of transition pores, while simultaneously reducing the percentage of macropores, leading to improved material properties [22]. There is an uptick in the frequency of harmless and less harmful pores, and a declining proportion of harmful and more harmful pores, suggesting a refinement of the pore structure through PVA modification [22]. The ITZs structural morphology in the RAC is effectively improved by the coating structure formed through the bonding of the polymer with cement hydration products, and PVA modification reduces the thickness of this zone, enhancing the overall performance of the composite material [22].

Paper Waste Incorporation in Fired Clay Bricks Mixing Ratios and Firing Temperatures

Paper waste is mixed with clay in specific ratios of 2.5, 5.0, 7.5, and 10 wt% to evaluate its impact on the properties of fired clay bricks [25]. Green bricks with different variations are fired at temperatures ranging from 900 to 1100°C for 1 hour in air, allowing for a comprehensive assessment of the effects of firing temperature [25]. The fired bricks are then analyzed for mechanical properties to determine the optimal paper waste content and firing conditions for achieving desired performance characteristics [25].

With an increasing ratio of pomegranate peels waste (PPW), the strength of the resulting bricks tends to decrease, indicating a trade-off between waste incorporation and mechanical performance [8]. The impact of adding PPW on compressive strength, total porosity, water absorption, bulk density, thermal conductivity, and microstructure characteristics is assessed at 900, 1000, and 1100°C, providing a detailed understanding of its influence on brick properties [8]. The study is specifically intended to evaluate the effects of paper waste addition on the physical properties and strength of fired clay bricks, contributing to the development of sustainable building materials [25].

Effects on Physical Properties

Porosity increases with higher paper waste content, as the paper fibers burn out during firing, leaving voids within the brick structure [25]. This increase in porosity relatedly creates lower density and shrinkage values, affecting the overall weight and dimensional stability of the bricks [25]. Highly porous brick exhibits low thermal conductivity, making it a potentially valuable material for thermal insulation applications [25].

The impact of adding PPW on compressive strength, total porosity, water absorption, bulk density, thermal conductivity, and microstructure characteristics is assessed at various temperatures, providing a comprehensive understanding of its effects [8]. Modified unfired bricks demonstrate enhanced crack resistance, increased ductility, and superior thermal insulation properties, highlighting the benefits of alternative brick manufacturing techniques [16]. Temperature measurements reveal that houses constructed with unfired bricks consistently maintain cooler indoor temperatures compared to those made with fired bricks, indicating improved thermal efficiency and reduced energy consumption [16].

Impact on Compressive Strength and Thermal Conductivity

Porous content is negatively correlated with compressive strength due to the introduction of weakness in the area defect, requiring a careful balance between porosity and strength [25]. However, residue inclusion provides excellent insulating behavior, while adequate strength can still be maintained, making paper waste a potentially valuable additive for producing energy-efficient bricks [25]. Therefore, residue inclusion is excellent insulating behavior, while adequate could be still maintained, highlighting the potential for achieving both thermal performance and structural integrity [25].

The optimal para rubber latex (PRL) content (2.5%-7.5% by cement weight) enhances compressive strength, reduces water absorption, and improves durability, meeting the Thai industrial standard (TIS 77-2545), demonstrating the potential for achieving high-performance bricks through latex modification [16]. Incorporating 12.5 wt% PPW results in the lowest density (1230 kg/m3) and thermal conductivity (0.2 W/mK), while still satisfying minimum acceptable requirements for bricks, highlighting the potential for PPW to improve thermal performance [8]. An apparent decrease in the values of thermal conductivity coefficient (k) by a percentage of (50%) to (60%) compared to an ordinary mortar can be achieved by using plastic waste-modified mortar, demonstrating the potential for plastic waste to enhance thermal insulation [10].

Plastic Waste Utilization in Brick Manufacturing
Types of Plastic Waste Used

Polyethylene terephthalate (PET) from plastic bottles is used by replacing different proportions of both sand and cement in mortar mixtures, offering a sustainable approach to managing plastic waste [10]. Polypropylene (PP) waste is used in the form of fibers to reinforce brick structures, enhancing their mechanical properties and reducing the environmental impact of plastic disposal [15]. Plastic waste is combined with fibers to make non-conventional bricks, exploring innovative methods for utilizing plastic waste in the construction industry [6].

This study uses polyethylene terephthalate (PET) combined with fibers to make non-conventional bricks, contributing to the development of sustainable building materials [6]. To promote sustainable construction practices, PP waste is used in plastic brick to replace waste material often discarded in landfills and burned, addressing the environmental problems associated with plastic waste disposal [15]. The study uses polyethylene terephthalate (PET) combined with fibers to make non-conventional bricks, exploring the potential of plastic waste as a valuable resource for construction [6].

Effects on Mechanical Properties

The compressive strength of mix 2 at a load of 426kg is the highest of the three plastic bricks tested, demonstrating the potential for achieving high-strength bricks through optimized plastic waste incorporation [15]. Plastic bricks with 25% weight PET and other 40% undergo compressive strength and hardness tests, providing valuable data on the mechanical performance of plastic-modified bricks [6]. The waste plastics were repurposed for use in the construction industry, contributing to a circular economy approach and reducing reliance on virgin materials [15].

Modified bricks with glass powder show up to 240% compressive strength and 220% flexural strength capability compared to traditional bricks when using 8% to 12% glass powder dosage in the mixture, demonstrating the potential for significant strength enhancements through waste material incorporation [12]. This study aims to investigate the feasibility of utilizing plastic wastes to produce a cost-effective and lightweight plastic brick for use in construction, addressing both environmental and economic considerations [15]. The paper shows that an apparent decrease in the values of thermal conductivity coefficient (k) by a percentage of (50%) to (60%) compared to an ordinary mortar can be achieved, demonstrating the potential for plastic waste to improve thermal insulation [10].

Thermal Conductivity and Density

Plastic waste-modified mortar shows an apparent decrease in thermal conductivity coefficient (k) by 50% to 60%, highlighting the potential for plastic waste to improve thermal insulation in buildings [10]. The addition of plastic waste results in lighter weight mortar, reducing the overall load on structures and potentially lowering transportation costs [10]. There is an increase in waste production among the Indian population, necessitating innovative waste management solutions such as plastic waste utilization in construction [15].

The paper shows that an apparent decrease in the values of thermal conductivity coefficient (k) by a percentage of (50%) to (60%) compared to an ordinary mortar, indicating the potential for energy savings [10]. There is also a significant amount of plastic waste in the country, highlighting the need for effective recycling and repurposing strategies [15]. The purpose of this study is to investigate the feasibility of utilizing plastic wastes to produce a cost-effective and lightweight plastic brick for use in construction, contributing to sustainable building practices [15].

Fiber Reinforcement in Bricks
Types of Fibers Used

Common reed fibers (Arundo donax L.) are added to bio-lime based mortar to improve flexural toughness, enhancing the material's resistance to bending and cracking [4]. Polypropylene fibers (PPFs) are used to enhance the mechanical properties of recycled brick concrete, improving its strength and durability [26]. Basalt fibers are used in the production process of modified bricks, exploring their potential for enhancing the performance characteristics of construction materials [27].

This study explores the potential of cork-modified mortars reinforced with basalt fabric, focusing on optimizing both mechanical and hygroscopic properties, contributing to the development of sustainable and high-performance building materials [5]. The study uses polyethylene terephthalate (PET) combined with fibers to make non-conventional bricks, exploring the potential of fiber reinforcement for improving the properties of plastic-modified bricks [6]. The article focuses on brick products, the production of which is based on natural components, such as lime (CaO), quartz sand (SiO2) and water (H2O), and which are created during the process of the so-called hydrothermal treatment, highlighting the importance of natural materials in sustainable construction [27].

Effects on Flexural Toughness and Mechanical Properties

Adding reed fibers improves the flexural toughness of bio-lime based mortar, enhancing its ability to withstand bending forces and resist cracking [4]. Polypropylene fibers improve the mechanical properties of RBA concrete, enhancing its strength, durability, and overall performance [26]. The compressive strength of PLCNF/GO brick 4 is significantly higher compared to control and commercial concrete brick, demonstrating the potential for fiber reinforcement to enhance the strength of composite bricks [28].

The optimal mechanical properties for recycled brick aggregate concrete (RAC) occur when the replacement rate is 30% and the brick-concrete ratio is 1:1, providing valuable guidance for mixture design and optimization [22]. The compressive strength reaches 44.2 MPa, the bending strength is 15.6 MPa, and the splitting tensile strength is 3.85 MPa, demonstrating the potential for achieving high-performance RAC through optimized mixture proportions [22]. This study examines the workability, strength, and microstructure of high strength eco-concrete incorporating recycled clay brick aggregate calcined clay, contributing to the development of sustainable and high-performance concrete materials [29].

Impact on Crack Resistance and Ductility

Modified unfired bricks demonstrate enhanced crack resistance and increased ductility, improving their ability to withstand stress and deformation without fracturing [16]. PPFs significantly improve the toughness of RBA concrete, enhancing its resistance to cracking and improving its overall durability [26]. The addition of fibers can improve physical mechanical properties as well as fiber/matrix interfacial adhesion, leading to enhanced performance and longevity of the composite material [4].

These advancements are credited to the polymer film network formed from PRL during the hydration process, which strengthens particle bonds and reduces porosity, leading to improved mechanical properties and durability [16]. However, PRL content exceeding 7.5% leads to performance reductions, attributed to thicker polymer films and particle aggregation, which create larger voids within the material, highlighting the importance of optimizing fiber content [16]. Micro-computed tomography was first used to assess the homogeneity of the mixtures, followed by flow tests to evaluate workability, providing valuable insights for optimizing the manufacturing process and ensuring consistent material properties [5].

Chemical and Mineral Admixtures

Types of Admixtures Used

Cement kiln dust (CKD) and quicklime (QL) are used to activate ground granulated blast-furnace steel slag (GGBS), enhancing its pozzolanic properties and improving the performance of cementitious materials [20]. Nano-kaolin and silica fume are used to reinforce mud bricks, improving their strength and durability for use in heritage building restoration [9]. Slag and fly ash are used as admixtures in concrete three-hole bricks, contributing to improved mechanical properties and sustainable waste management [30].

The liquid admixture of organic compounds, which are rich in certain elements, chemical compounds and macro-, microand ultraelements (among others colloidal silica or phosphorus) beneficial effects on a number of chemical transformations in the manufacturing process of this products, highlighting the potential for organic admixtures to enhance material properties [31]. The article focuses on brick products, the production of which is based on natural components, such as lime (CaO), quartz sand (SiO_2) and water (H_2O), and which are created during the process of the so-called hydrothermal treatment, emphasizing the importance of natural materials in sustainable construction [27]. The aim this work investigate bio-lime based mortar flexural toughness improvement due addition common reed fibers (Arundo donax L.) in order evaluate their possible application as ductile eco-compatible prefabricated bricks or laying and joint mortars masonry, exploring the potential of bio-based materials for enhancing mortar performance [4].

Effects on Engineering Properties

Adding QL and CKD to stabilized green specimens enhances their engineering properties with curing age, improving their strength, durability, and overall performance [20]. The use of surface-coating-aggregate-by-admixture mixing method improve physical and mechanical properties of concrete three-hole brick can significantly be improved, demonstrating the potential for admixtures to enhance material characteristics [30]. The quantification formed phases demonstrated a detrimental effect calcium silicate hydrates (C-S-H), portlandite ($Ca(OH)_2$) calcite ($CaCO_3$) studied samples, highlighting the importance of understanding the chemical reactions that occur during cement hydration [18].

Using activated GGBS in the manufacture of stabilized green bricks is still uncommon in Egypt in such applications, indicating a need for further research and promotion of this sustainable building material [20]. The raw materials and lab-made specimens were analyzed using particle size analysis, differential thermal analysis, X-ray fluorescence, and X-ray diffraction techniques, providing a comprehensive characterization of their physical and chemical properties [20]. The application of organic compounds to silicate products led to the creation of the following phase known as tobermorite and sometimes xonotlite, demonstrating the potential for organic admixtures to alter the microstructure and improve the performance of silicate bricks [31].

Impact on Microstructure and Strength

The pozzolanic reaction from CKD and QL fills the pore structure with calcium silicate hydrates and calcium aluminate hydrates gel, leading to a denser and stronger material with improved durability [20]. The modification effect of slag is better than fly ash, suggesting that slag is a more effective admixture for improving the properties of concrete three-hole bricks [30]. The addition of organic compounds leads to the creation of tobermorite, a calcium silicate hydrate mineral that contributes to the strength and durability of cementitious materials [31].

The use of surface-coating-aggregate-by-admixture mixing method, by changing the species and content of admixture, compressive strength, water absorption, softening coefficient of three-hole brick modified by admixture were measured, providing valuable data for optimizing admixture content and improving brick properties [30]. Adding QL and CKD to the stabilized green specimens of different mixes can enhance their engineering properties with curing age increasing, demonstrating the long-term benefits of these admixtures [20]. The SEM (Scanning Electron Microscope) examination enabled the phase composition analysis of the modified products, providing insights into the microstructure and chemical composition of the materials [31].

Durability and Long-Term Performance

Factors Affecting Durability

Acid rain corrosion affects the mechanical properties of brick masonry, leading to deterioration and reduced structural integrity over time [32]. The type of mortar and brick influence the durability of masonry, highlighting the importance of selecting compatible materials for long-term performance [32]. Exposure to freeze-thaw cycles can damage concrete, causing cracking and spalling, particularly in cold climates [23].

The durability of the mixes containing RBW yields better results compared to blends containing NA, suggesting that recycled brick waste can enhance the long-term performance of cement-treated base materials [33]. The article focuses on brick products, the production of which is based on natural components, such as lime (CaO), quartz sand (SiO2) and water (H2O), and which are created during the process of the so-called hydrothermal treatment, highlighting the potential for natural materials to contribute to long-term durability [27]. In this paper, materials were used as aggregates; slag mixed binder; all solid-waste-based permeable bricks with excellent performance prepared by forming pressure at 5 MPa, demonstrating the potential for waste materials to create durable and high-performing bricks [34].

Testing Methods for Durability Assessment

Durability is evaluated against collapsibility in water, providing an indication of the material's resistance to disintegration and erosion [20]. Freeze-thaw resistance is assessed by measuring mass loss and relative dynamic modulus of elasticity, quantifying the damage caused by repeated freezing and thawing cycles [23]. Water absorption tests are conducted to determine the water resistance of bricks, providing insights into their potential for moisture-related damage [12].

The durability of the cured specimens was evaluated against collapsibility in water, assessing their resistance to disintegration and erosion [20]. This paper evaluates the effects of graded replacement of various RBW sizes as a substitute for coarse and fine natural aggregate (NA) on the mechanical properties and durability of cement treated base (CTB), providing a comprehensive assessment of the material's performance [33]. Evaluation of the Properties of Bituminous Concrete Prepared from Brick-Stone Mix Aggregate, highlighting the importance of evaluating the long-term performance of composite materials [35].

10.3. Life Prediction Models

A life prediction model based on Weibull distribution is proposed for freeze-thaw damage, providing a tool for estimating the lifespan of concrete structures exposed to harsh winter conditions [23]. Mathematical degradation models are developed to assess material attenuation, allowing for the prediction of long-term performance and the planning of maintenance strategies [32]. The article focuses on brick products, the production of which is based on natural components, such as lime (CaO), quartz sand (SiO2) and water (H2O), and which are created during the process of the so-called hydrothermal treatment, highlighting the importance of understanding the long-term behavior of natural materials [27].

Furthermore, the durability of the cured specimens was evaluated against collapsibility in water, assessing their resistance to disintegration and erosion over time [20]. The effect mix on various the such as Marshall stability, flow, Quotient (stability to flow ratio), Indirect Tensile Strength,

II. CONCLUSION

This study demonstrates that modified clay bricks incorporating waste glass powder (WGP) and agro-industrial byproducts offer a viable, sustainable alternative to conventional construction materials. The integration of up to 20% WGP significantly enhances both compressive strength and flexural capacity, achieving increases of approximately 25% and 41%, respectively, while maintaining acceptable water absorption levels. Agro-industrial additives such as sugarcane bagasse, rice husk ash, and cocoa shells further improve the thermal and mechanical properties of bricks, enabling tailored performance for diverse applications.

Microstructural analyses confirm that the inclusion of these waste materials improves internal bonding and reduces porosity, contributing to enhanced durability. Additionally, the use of recycled crushed clay bricks (RCB) in pavement applications and cement-stabilized macadam (CSM) demonstrates potential for sustainable road construction. The findings support the use of these eco-friendly materials in green building projects, aligning with global sustainability goals by reducing the reliance on virgin resources and lowering the environmental impact through decreased CO_2 emissions and energy consumption.

Future work should focus on the long-term performance of these modified bricks under various environmental conditions and explore large-scale production methods to facilitate broader adoption in the construction industry

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