Integrating Biochar in Sustainable Architecture and Environmental Resilience

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Abstract

This thesis meticulously explores the integration of biochar into cementitious materials to produce sustainable construction material, with a primary focus on working with recycled wood biochar and its influence on mechanical performance and environmental sustainability. Employing an experimental research design, the study investigates critical mechanical properties, including flexural and compression strength. The methodology involves precision in crafting mortar specimens under baseline conditions and varying flexural stress conditions, utilising the Taguchi method for optimisation. The research extends its scope to include recycled wood and wood chips, pine pellets, and walnut shells, examining diverse combinations with superplasticisers. Additionally, sieving experiments on biochar and grinding recycled wood provide insights into particle size influence. Through controlled manipulations and comprehensive analyses, the research contributes valuable insights to the sustainable construction domain, offering a pathway towards more environmentally resilient and performance-driven building materials, with a specific emphasis on the pivotal role of recycled wood biochar.

Keywords: Biochar, Recycled Wood, pyrolysis of biomass, Superplasticizer, Material Resilience

Abbreviation

SP: Superplasticizer

Biochar: BC

Recycled Wood: RW

Walnut Shells: WS

Pine Pellets: PP

PSA: Particle size analysis

μm: Micrometers

B: Blank

IAQ: Indoor air quality

SEM: Scanning electron microscopy

EDX: Energy-dispersive X-ray

TGA: thermogravimetric analysis

FTIR: Fourier-transform infrared spectroscopy

PEFC: Programme for the Endorsement of Forest Certification

MPa: Megapascal

SCMs: Supplementary Cementitious Materials

LCA: Life Cycle Assessment

C-S-H: Calcium Silicate Hydrate

CH: Calcium Hydroxide

Contents

List of Figures

List of Tables

Chapter 1

Introduction

1.1 Problem statement:

The accelerating pace of climate change and the relentless expansion of urban landscapes pose unprecedented challenges to the global community. As architects, planners, and policymakers grapple with the imperative to create resilient and sustainable built environments, innovative solutions that harmonize with nature become imperative. Among these solutions, biochar, a carbon-rich material derived from the pyrolysis of organic matter, stands as a promising yet underexplored resource in the realm of sustainable architecture and environmental resilience.

As the world confronts the consequences of carbon-intensive practices and urban sprawl, the need for transformative approaches to construction and design has never been more pressing. Biochar, produced through a process that not only sequesters carbon but also yields a versatile material, holds the potential to redefine the landscape of sustainable architecture. This thesis embarks on a journey to unravel the intricate interplay between biochar and the built environment, seeking to address critical gaps in knowledge, implementation, and understanding.

The architectural community has made significant strides in adopting environmentally conscious practices, ranging from energy-efficient designs to the utilization of recycled materials. However, the integration of biochar in architectural processes remains at the periphery of mainstream discourse. This oversight is rooted in a fragmented understanding of how biochar can be harnessed across diverse architectural elements, from building materials to landscaping, and its potential to mitigate environmental impacts.

Amidst the urgent need for carbon-neutral solutions and resilient urban ecosystems, a comprehensive exploration of biochar's applications within the architectural domain becomes paramount. This research aims to bridge the existing knowledge gap, offering a holistic perspective on how biochar can contribute to sustainable architecture, climate resilience, and environmental well-being.

1.2 Research Objectives

The study aims to assess the viability of environmentally friendly materials as substitutes for traditional cement and other construction materials, with a specific focus on their potential for increased pressure tolerance and reduced environmental pollution. The investigation seeks to identify optimal formulations, particularly those incorporating recycled wood biochar, by comprehensively evaluating mechanical properties through a series of experiments. The primary objective is to determine the most promising alternatives that not only enhance structural performance but also align with sustainability goals, thereby contributing to the discourse on eco-friendly construction materials.

1.3 Objectives of the Study

There are some questions, this thesis seeks to address them:

1- **Limited Understanding of Biochar's Architectural Applications:**

The existing literature provides a fragmented understanding of how biochar can be effectively integrated into various architectural elements, including building materials, landscaping, and infrastructure. A comprehensive exploration of its potential applications within the architectural domain is crucial.

2- **Inadequate Assessment of Environmental Impact:**

While biochar is recognized for its carbon sequestration capabilities, there is a lack of in-depth analysis regarding its holistic environmental impact within the context of sustainable architecture. This research aims to assess and quantify the net environmental benefits of incorporating biochar in different architectural components.

3- **Knowledge Gaps in Implementation Strategies:**

Architectural practitioners and urban planners face challenges in translating theoretical knowledge about biochar into practical, scalable, and cost-effective implementation strategies. Investigating these knowledge gaps is essential for the successful integration of biochar in sustainable architectural projects.

Chapter 2

Literature Review

2.1 Sustainable Architecture

Sustainable architecture is an approach to building design that seeks to minimize the negative environmental impact of buildings by reducing their energy consumption, waste, and carbon footprint. It involves using sustainable materials, energy-efficient systems, and environmentally responsible design practices to create functional and environmentally responsible buildings. (Bennetts et al., 2003) The goal of sustainable architecture is to create buildings that are not only environmentally friendly but also socially and economically sustainable, providing long-term benefits to both people and the planet. By adopting sustainable design principles, architects and designers can help to reduce the negative impact of buildings on the environment and create healthier, more livable spaces for people to live and work in. Sustainable architecture involves designing and constructing buildings to minimise environmental impact, optimise resource use, enhance human well-being, promote social equity, and ensure long-term viability. By integrating eco-friendly practices, renewable materials, energy-efficient systems, and consideration for local cultures and ecosystems, sustainable architecture aims to create buildings that contribute positively to the environment and the community while addressing immediate and future needs. (Van Ellen et al., 2021)

2.1.1 History of Sustainable Architecture

The history of sustainable architecture is rooted in the 1960s and 1970s environmental movements, which called for a more responsible approach to using natural resources. The term "sustainable architecture" was first coined in the 1980s, and since then, there has been a growing interest in designing environmentally responsible, socially equitable, and economically viable buildings. The history of sustainable architecture is complex and evolving, shaped by various factors, including technological advances, changing social attitudes, and economic pressures. (Bennetts et al., 2003) The notion of sustainable development has been integrated into architecture since the late 1900s and has become an established framework for shaping policies related to planning, design, and construction. Nevertheless, numerous scholars have observed a notable made for creating a better life-specific and artistic dimension within sustainable architecture. Furthermore, endeavours to actualize sustainability concepts occasionally result in highly unconventional architectural designs, which might even serve as thought-provoking trials, occasionally generating mixed reactions from the general populace. (Daugėlaitė, 2023)

Sustainable architecture is divided into four fundamental principles pillars:

1. Energy Efficiency: Energy efficiency is a vital aspect of sustainable development and climate change mitigation, involving the effective use of energy through methods like improved building design, energy-efficient appliances, and industry practices. For instance, buildings can achieve energy efficiency with double-façade architecture, utilizing insulating air gaps to minimize heating and cooling needs. Active air conditioning systems also enhance efficiency by adapting energy use based on real-time data and user behaviour. Ultimately, energy efficiency lowers consumption, cuts costs, and diminishes greenhouse gas emissions, constituting a crucial element of sustainable development and climate change mitigation. (Tariq et al., 2023)

2. Resource Conservation: Resource conservation entails the responsible management and safeguarding of natural resources like water, air, soil, minerals, and biodiversity to ensure their availability for future generations. Travertine/tufa formations contain valuable geological records, including evidence of volcanic, tectonic, and glacial activity, as well as indicators of climate and evolutionary history. Unfortunately, these landscapes are under threat due to climate change, natural disasters, and human interventions. Consequently, it's imperative to prioritize the preservation and sustainable development of global travertine/tufa resources. This necessitates the establishment of a collaborative platform involving individuals worldwide to conserve these resources. This endeavour calls for the sharing of databases, technical expertise, and wider participation in travertine/tufa conservation through cultural initiatives. (Dong et al., 2023)

3. Indoor Air Quality and Health: Indoor air quality (IAQ) refers to the quality of the air inside buildings, including homes, schools, and workplaces. It is a measure of the level of pollutants and other contaminants in the air that can affect the health and comfort of the building occupants. Indoor air pollutants can come from various sources, such as building materials, cleaning products, and outdoor air pollution that enters the building. Poor indoor air quality can cause a range of health problems, including respiratory problems, headaches, and eye irritation. Maintaining good indoor air quality is important for the health and well-being of building occupants, and can be achieved through proper ventilation, regular cleaning, and control of indoor sources of pollution. (Szabados et al., 2022)

4. Biomimicry: Biomimicry is a concept that has attracted considerable attention in engineering, architecture, and design. It involves learning from nature and emulating natural forms, processes, and ecosystems to solve human problems and create sustainable solutions. This principle takes inspiration from nature's design solutions. The concept of biochar production, which imitates natural processes like charcoal formation in soils, fits well with the biomimicry approach by emulating natural cycles in the built environment. (Mejía-Villa et al., 2023)

2.2 Environmental Resilience and Sustainability

Environmental resilience refers to the capacity of an ecosystem to withstand and recover from various disturbances, stresses, and changes while maintaining its essential functions, processes, and biodiversity. In the context of agriculture and agroecosystems, environmental resilience encompasses the ability of the natural environment to adapt to and recover from challenges such as climate change, soil degradation, and other environmental pressures, while still supporting sustainable food production and ecosystem services. (Hassan et al., 2022)

2.2.1 Environmental Resilience in Architecture

Environmental resilience in architecture extends beyond engineering resilience, focusing on the adaptability of built structures to dynamic environmental, cultural, and economic changes. It emphasizes meaningful connections with surroundings, rejecting generic designs in favour of those engaging with context at multiple scales. This approach, like the adaptive resilience framework, encourages architects to embrace uncertainty and adaptability rather than rigid predictability.

Long-term implications are crucial; buildings should have multiple useful lives, being adaptable to evolving needs and conditions. Integrating environmental resilience into architectural practice creates durable, responsive, and sustainable built environments that cater to the complexities of their surroundings. (Laboy & Fannon, 2016)

2.2.2 Sustainable Building Materials

Sustainable building materials encompass environmentally responsible resources utilized throughout the construction, renovation, and operation of buildings, prioritizing ecological efficiency and minimal impact on both built and natural surroundings. They are chosen with meticulous consideration of their life cycle, from extraction to disposal, aiming to fulfil objectives like resource and energy efficiency, CO_2 and greenhouse gas reduction, pollution prevention, noise control, and enhancement of indoor air quality. Leveraging renewable and recycled sources, these materials seek to curtail environmental footprints. Furthermore, they deliver compelling advantages to building owners, including diminished maintenance expenses, energy conservation, enhanced occupant health and productivity, cost-effectiveness in space reconfiguration, and heightened design flexibility. (Joseph & Tretsiakova-McNally, 2010)

2.3 Biochar

2.3.1 Biochar Background

Biochar, produced through pyrolysis, is a carbon-rich material with a history of enhancing agricultural productivity as a soil amendment. Its diverse physical and chemical properties, including a porous structure, contribute to water-holding capacity, aeration, and nutrient retention in soil. The material's stability ensures long-term carbon sequestration. Chemically, biochar is mainly composed of carbon, influencing reactivity, nutrient content, and sorption properties. Functional groups on its surface enhance nutrient retention and facilitate environmental chemical reactions.

With high carbon content, biochar effectively sequesters carbon, aiding in greenhouse gas emission reduction. Its porous structure makes it attractive for enhancing concrete performance. In sustainable construction, biochar improves soil, sequesters carbon, and reduces the environmental impact of construction materials. Explored in various construction applications, including cement-based composites, it aligns with the demand for eco-friendly practices, presenting significant potential for sustainable development. (Barbhuiya et al., 2024)

2.3.2 Biochar Properties

The physical properties of biochar, such as their porosity, are important for their current uses. When biomass is heated, a skeleton of carbon is left as fine-grained, highly porous charcoal. Porous biochar can modify the soil texture to reduce soil density, which helps to relieve compaction. Biochar has been used in growing media as a renewable substitute for manufactured media such as vermiculite, facilitating improved water retention, nutrient absorption, and microbial activity in soil ecosystems. (Tagliaferro, 2020)

2.3.3 Biochar Production Methods

Biochar production methods can be traditional or modern, with each having its own set of conditions and applications. Traditional methods include burning biomass in pits and slow or fast pyrolysis, while modern methods include gasification, torrefaction, hydrothermal carbonization, electro-modification and modified traditional methods. The choice of method can significantly impact the properties of the biochar produced, including yield and quality, and the type of feedstock used can also influence the properties of the resulting biochar. The diverse range of biochar production methods provides flexibility in tailoring biochar properties to meet specific agricultural and environmental needs, making biochar a versatile and valuable soil health conditioner and environmental remediation tool. (Zhou et al., 2021)

2.3.4 Biochar Characterization

The characterization of biochar involves analyzing its physical, chemical, and structural properties to understand its behaviour and potential applications. This includes assessing its thermal stability, surface area, pore volume, functional groups, elemental composition, and morphological features. Characterization techniques such as scanning electron microscopy (SEM), energy-dispersive X-ray (EDX) analysis, thermogravimetric analysis (TGA), and Fourier-transform infrared spectroscopy (FTIR) are commonly used to study biochar properties. Additionally, the characterization may involve evaluating its impact on soil microbial biomass, greenhouse gas reduction, ammonia adsorption, and long-term carbon sequestration. Overall, biochar characterization aims to provide a comprehensive understanding of its properties and potential uses in various environmental and industrial applications. (Reza et al., 2020)

2.3.5 Biochar Utilization in Cement Composites

1. Enhanced Mechanical Properties: The integration of biochar into cement composites yields notable benefits, particularly in augmenting flexural strength and toughness. Various studies have consistently demonstrated an increase in flexural strength upon the addition of biochar sourced from different origins to the cement mixture.

2. Moisture Regulation and Internal Curing: Biochar's porous architecture enables efficient water absorption and retention, thereby facilitating moisture regulation and internal curing within the concrete.

3. Reduced Heat Evolution: Incorporating biochar into cement composites offers the advantage of mitigating heat evolution during the cement hydration process. This reduction in heat generation is particularly advantageous for averting thermal cracking, especially in regions characterized by warm climates.

4. Carbon Sequestration: Biochar exhibits the potential to sequester carbon, thereby contributing to the reduction of greenhouse gas emissions. By integrating biochar into cement composites, carbon sequestration within the material is achievable, thus promoting environmental sustainability.

5. Waste Management: The utilization of biochar in cement composites presents an eco-friendly solution for waste management by effectively utilizing biomass feedstock and promoting the recycling of waste materials. (Senadheera et al., 2023)

2.3.6 Biochar from Wood Chips

Wood chips are small pieces of wood that are typically produced by chipping or shredding larger pieces of wood, such as logs or branches. They are commonly used as a source of fuel for heating or electricity generation, as well as for landscaping and gardening purposes. Wood chips can be made from a variety of tree species and can vary in size and shape depending on the method of production.

Wood chips are a byproduct of the forestry and wood processing industries. They are typically produced by chipping or shredding larger pieces of wood, such as logs or branches, into smaller pieces. The resulting wood chips can be used for a variety of purposes, including as a source of fuel for heating or electricity generation, as well as for landscaping and gardening purposes. (Pipíška et al., 2022)

2.3.7 Biochar from Recycled Wood

Biochar from recycled wood is produced through the pyrolysis of biomass, specifically recycled wood materials, resulting in a stable form of carbon with a porous structure. This material has the potential for carbon sequestration in soil and improving soil fertility. The synergies between biochar production and the use of wood ash as an additive to enhance carbon sequestration potential. The use of recycled wood aligns with sustainability principles by repurposing waste materials, and it can contribute to carbon-negative technologies like bioenergy carbon capture and storage. Additionally, the economic and environmental implications of incorporating wood ash in biochar production, highlight potential cost savings, increased carbon sequestration, and nutrient recycling. (Buss et al., 2019)

2.3.8 Biochar from Pine Pellet

The production process for the biochar derived from pine pellets involved subjecting the pine pellet residues to slow pyrolysis within a muffle furnace. This process occurred under controlled conditions of an inert atmosphere and atmospheric pressure. Varied temperature settings, including 200, 280, and 570 °C, were employed alongside different residence times, ranging from one hour to half an hour. Additionally, the heating rates during pyrolysis were adjusted within 5 to 30 °C min^-1. These diverse parameters were meticulously manipulated to generate a range of biochar samples, each with unique characteristics tailored to the experimental requirements.(Santos et al., 2015)

2.3.9 Biochar from Walnut Sells

The production method of biochar from walnut shells typically involves slow pyrolysis, a thermochemical conversion process that transforms biomass into a carbon-rich material in the absence of oxygen. Slow pyrolysis is a controlled process where the walnut shell biomass is heated to moderate temperatures (generally between 300-600°C) in a low-oxygen environment. This slow heating rate helps in the decomposition of the organic components of the walnut shells into biochar, bio-oil, and syngas. Through this method, the walnut shells are effectively converted into biochar, a valuable carbonaceous material with various applications in agriculture, environmental remediation, and carbon sequestration efforts. (Alfattani et al., 2021)

2.3.10 Enhanced Compressive Strength in Concrete: Understanding the Impact of Biochar Addition

1. Pozzolanic Reaction: Biochar, when added to cementitious systems, can undergo pozzolanic reactions. These reactions involve the formation of calcium silicate hydrate (C-S-H) gel, which contributes to the strength and durability of concrete. The pozzolanic reaction consumes calcium hydroxide (CH) and produces additional C-S-H gel, thereby enhancing the strength of the cement matrix.

2. Microfiller Effect: Biochar particles, particularly when finely ground, can act as microfilters within the cement matrix. These particles fill voids and interstitial spaces between cement grains, resulting in a denser and more compact structure. This densification improves the packing density of the concrete, leading to increased strength.

3. Water Reduction: Biochar can absorb excess water in the concrete mixture, thereby reducing the water-to-cement ratio. A lower water-to-cement ratio results in improved hydration of cement particles, leading to enhanced strength development over time.

4. Improved Bonding: The surface characteristics of biochar, such as its high surface area and porosity, can promote better bonding between the cement paste and aggregate particles. This improved bonding enhances the transfer of stress between the cement matrix and aggregates, ultimately leading to higher compressive strength.

5. Reduced Shrinkage: Biochar's ability to mitigate shrinkage by absorbing excess water and reducing drying shrinkage can contribute to the overall durability and strength of the concrete. By minimizing shrinkage-related cracking, the integrity of the concrete structure is preserved, leading to higher compressive strength. (Gupta et al., 2018)

2.3.11 Insights from the School of Biochar Workshop

The 7° Biochar School 2023 - Biochar and the City was held in person on 19 and 20 October 2023 in Torino. The Biochar school addresses issues relating to biochar, a stable vegetal carbon deriving from by-products, waste or biomass of vegetal and/or animal origin.

The recent School of Biochar workshop convened experts and enthusiasts alike to delve into innovative strategies for sustainable urbanization, particularly focusing on the integration of biochar into various urban applications. The discussions underscored the multifaceted nature of sustainability, emphasizing the intersectionality of factors such as legality, origin, traceability, and certification in forest management.

PEFC stands for the Programme for the Endorsement of Forest Certification. It is an international non-profit organization that promotes sustainable forest management through independent third-party certification. PEFC provides a framework for forest certification systems to ensure that forests are managed responsibly, taking into account environmental, social, and economic considerations. Certification under PEFC verifies that wood and wood-based products come from sustainably managed forests, assuring consumers that they are making environmentally responsible choices.

One pivotal theme that emerged from the discourse was the urgent need to address the looming challenge of urbanization, which not only exacerbates the "Nature deficit syndrome" but also engenders a substantial rise in temperatures, with cities potentially experiencing a staggering 5°C increase. Amidst these pressing concerns, the potential of biochar to mitigate air pollution, reduce CO_2 emissions, regulate temperatures, enhance property values, and create communal spaces emerged as a beacon of hope.

In exploring the urban application of biochar, the workshop participants delved into its transformative impact on soil quality, highlighting its ability to augment pH levels, organic matter content, and soil hydration. Particularly noteworthy was its role in CO_2 reduction along the soil profile, presenting a viable strategy for combating greenhouse gas emissions, even in unconventional spaces such as airports. The Helsinki project's endeavour to achieve carbon neutrality through biochar utilization exemplified the scalability and adaptability of this approach.

The discourse extended to innovative applications of biochar in urban landscapes, including its integration in rooftop gardens to mitigate water runoff, enhance aesthetics, and promote environmental and social well-being. While such initiatives hold immense promise, challenges persist, including the high costs and limited production of biochar in Italy.

Moreover, discussions delved into cutting-edge research on biochar's interaction with cement, exploring avenues for achieving carbon neutrality and enhancing material properties. Artificial intelligence emerged as a powerful tool in optimizing biochar parameters and improving material efficiency, underscoring the symbiosis between technological innovation and sustainability.

Notably, the workshop also shed light on biochar's diverse applications, from shielding radio waves to enhancing the thermomagnetic properties of cement. The potential of biochar in photovoltaic cells and its role as a conductive electrode showcased the versatility and ingenuity of this carbonaceous material in advancing sustainable technologies.

In conclusion, the School of Biochar workshop provided a platform for interdisciplinary dialogue and collaboration, elucidating the transformative potential of biochar in fostering sustainable urbanization and environmental resilience. As we navigate the complexities of urbanization and climate change, biochar stands as a beacon of innovation and hope, offering tangible solutions to build a more sustainable future. (Italian Biochar School - Ichar - Italian Biochar Association, 2023)

Chapter 3

Methodology

3.1 Research Design

This study employed an experimental research design to investigate the integration of biochar as a sustainable construction material in the context of architectural applications and environmental resilience. The experimental approach allowed for controlled manipulation of variables, facilitating an objective assessment of biochar's potential impact on architectural performance and sustainability in the face of environmental challenges. With a focus on working on mechanical properties such as flexural and compression strength.

3.2 Experimental Process on Blank

3.2.1 Mortar Specimens (Baseline Condition)

In the initial stages of the experimental phase, mortar specimens were meticulously crafted to exact specifications, ensuring precision in composition, dimensions, and curing conditions for a comprehensive and accurate analysis of their mechanical and structural properties.

Creating mortar (table 1) for construction involves a meticulous process of combining essential ingredients to achieve a cohesive and durable bonding material. The key components include cement, which serves as the binding agent, water to activate them, and sand. The proportions of these elements are carefully measured to ensure the mortar's optimal performance. Mixing is a critical step, requiring thorough blending to achieve a uniform consistency. Curing is the subsequent stage, allowing the cement to undergo hydration, and strengthening the mortar over time. The completion of this process results in a robust and reliable mortar that contributes significantly to the stability and integrity of construction projects.

Table 1. The measurement of the blank.

Experiment	Cement(g)	H_2O(g)	Sand(g)	W/C
Blank	64.12	35.62	213.72	0.55

Using the provided data:

Water-to-cement ratio = Mass of water / Mass of cement

Water-to-cement ratio = 35.62 g / 64.12 g

Water-to-cement ratio ≈ 0.556

Step 1:

Greasing the Mold (figure 1):

1. Start by meticulously applying a thin and uniform layer of grease underneath the mold, ensuring comprehensive coverage of all corners.

2. Place 4 or 2 grease dots on each plate within the mold.

3. While meticulously distributing the grease on the plates, gently and precisely insert them into the mold, starting with the outer ones before moving on to the inner

ones. (Note: If necessary, apply grease on the back of the glove and spread a little more).

4. Additionally, take great care to apply an impeccably thin layer of grease on the top surface of the mold.

5. Following greasing, change gloves precisely to maintain a pristine working environment.

6. Should any excess grease be present on the mold, meticulously remove it using a spatula. The procedure was completed with utmost precision.

Figure 1. Sample frames with greasing are used in mortar testing.

Step 2:

Mix Preparation (figure 2):

NB: precise measurements, at least up to the second decimal place.

1. Prepare three beakers meticulously, ensuring they are impeccably clean and free from contamination or water, with at least one beaker from plastic to prevent undesired reactions.

2. Make sure the weight is accurately balanced and level.

3. Weigh the amount of cement required in a glass beaker precisely.

4. Similarly, measure the precise quantity of sand in another glass beaker, maintaining meticulous accuracy throughout.

5. Fill the spray bottle with water and gradually pour it into the plastic beaker.

6. In case of any surplus water, meticulously use a pipette to remove it. Mix preparation is carried out meticulously.

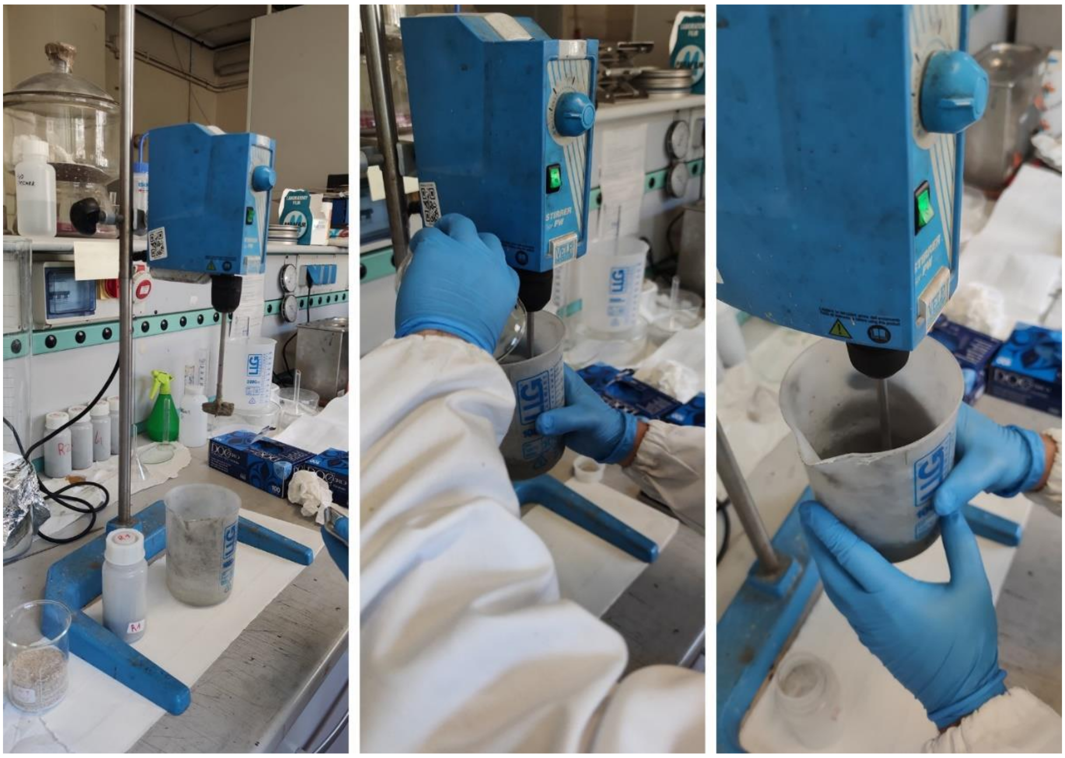


Figure 2. Mixing process of mortar samples.

Step 3:

Mixing:

1. Position the mixer with exceptional precision, ensuring and slightly lower.

2. Add the cement to the water in the plastic beaker with the utmost care, initiating the mixing process at a precisely set speed of tick 1, performing alternating clockwise and counterclockwise rotations for precisely 30 seconds.

3. Next, incorporate the sand into the mix, continuing the meticulous mixing process for another precisely timed 30 seconds.

4. Increase the mixer speed precisely to tick three and mix for an additional precisely timed 30 seconds, Total mixing time to exactly 90 seconds.

5. Pause the mixer with absolute precision for 90 seconds, allowing the mix to undergo proper hydration.

6. After the pause, execute a final 60 seconds of high-speed mixing with utmost precision, ensuring an impeccably homogeneous blend and mixing completed with unparalleled precision.

Step 4:

Pouring into Molds:

1. Give the mix a final meticulous stir with the spatula before pouring.

2. Meticulously and gradually fill precisely half of all four spaces in the molds using the spatula.

3. Tap the molds gently (figure 3) with a precise force precisely 30 times, 15 times on each side. NB Do not apply force, and employ a gentle and precise lifting technique to eliminate any trapped air bubbles effectively.

4. Proceed to fill the molds meticulously and precisely with the mix, ensuring equal distribution and levelling.

5. Execute 30 meticulous taps, 15 on each side, to remove any remaining trapped air with utmost precision.

Pouring executed with meticulous precision.

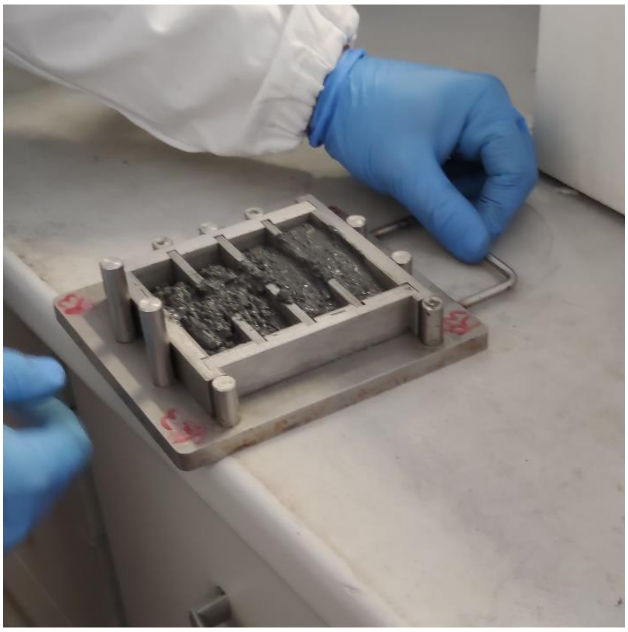


Figure 3. Taping molds 30 times for precise air bubbles removal.

Step 5:

Levelling:

NB: The mortar needs to be levelled, taking care not to remove the sand. To level the pour, making zigzag movements with a large plastic spatula is essential.

1. Utilize the plastic spatula to make meticulously precise zigzag movements across the surface (figure 4), guaranteeing an exact levelling of the poured mix.

2. Add additional mortar with absolute precision where needed to achieve an even and level surface.

3. Level everything with impeccable accuracy, maintaining a consistent height across all molds.

4. At this precise stage, level the mix flat with the spatula, careful not to disturb the sand beneath.

5. With the utmost precision, use your fingers to meticulously clean the edges of the mold, ensuring a flawless finish.

Levelling is accomplished with the highest degree of precision.

Finally, allow the molds to rest in a carefully controlled humid environment, covering them meticulously with plastic foil to ensure precise and optimal curing. The procedure was completed with unparalleled precision. One day later, the molds were carefully opened and the specimens were removed. Subsequently, they were submerged in water and were in there for 7 days. It's important to note that the 7-day curing period commenced from the moment the mortar was initially created.

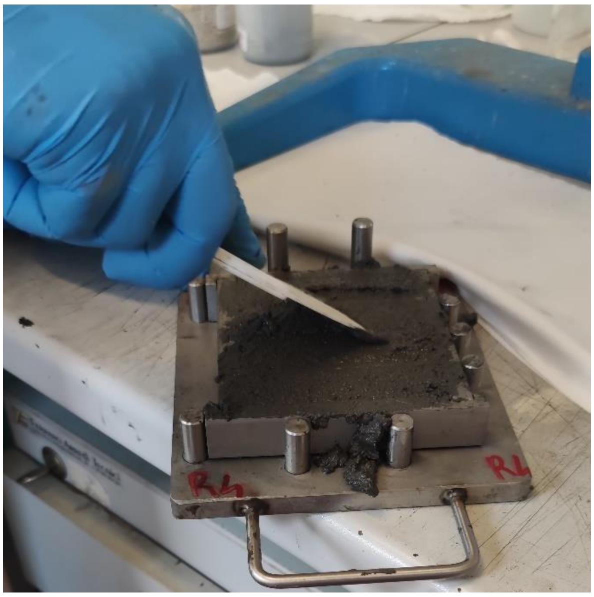


Figure 4. Precise zigzag movements with a plastic spatula.

3.2.2 Flexible and Compression Tests

After the completion of the initial seven-day curing period, the specimens were transferred to a dedicated testing facility for a comprehensive evaluation of their mechanical strength under varying flexural stress conditions.

Each of the four samples was meticulously positioned within a specialized flexural testing machine, ensuring precise alignment. Subsequently, the machine's proprietary software, Zwick/Roell (figure 5), was employed to conduct a thorough analysis of the specimens. This analysis provided valuable insights into how each specimen withstood the applied load, with the resulting coordinate diagram offering a clear visual representation of their tolerance.

The diagram featured both horizontal (representing deformation in %) and vertical (indicating force in MPa) measurements. Notably, several specimens demonstrated outstanding performance, achieving vertical values within the range of 6 to 7 MPa. Impressively, those specimens subjected to loads exceeding 8 MPa displayed particularly promising resilience and structural integrity.

Figure 5. Zwick/Roell mechanical for flexural (left) and compression (Right)strength.

3.3 Experimental Process on Recycled Wood and Wood Chips

3.3.1 Taguchi Method

Taguchi design, developed by Japanese engineer and statistician Genichi Taguchi (Genichi Taguchi and Wu, 1980), is a robust optimization technique that has found applications across various fields, including engineering, manufacturing, and quality control. This method holds particular value when addressing complex processes or systems characterized by multiple variables or factors that influence performance outcomes. (Mori & Tsai, 2011)

Taguchi Method, also known as an orthogonal array, is an experimental method that aims to enhance the consistency of product or process performance in varying conditions. Developed by Taguchi, it identifies controllable factors (control factors) to minimize the impact of uncontrollable factors (noise factors) on variability. (Taguchi Designs, n.d.)

Historically, Genichi Taguchi conceived this methodology to enhance product and process quality while concurrently minimizing variation and defects. Over time, the Taguchi method has evolved into a potent tool for optimizing a wide array of elements, ranging from product designs to manufacturing processes, leading to notable cost reductions and performance improvements in diverse industries.

In the context of the Taguchi method, it facilitates the generation of experimental configurations, allowing for the selection of setups based on the number of factors and their respective levels. This methodology culminates in the creation of a Taguchi experimental plan, which serves as a platform for conducting detailed analyses aimed at identifying control factor parameters capable of effectively minimizing response variation.

One of the notable advantages of the Taguchi method lies in its capacity to streamline experimentation, thereby significantly reducing time and cost expenditures. Furthermore, it bolsters the robustness of designs and processes, ultimately translating into superior product quality and performance. This versatility makes the Taguchi method an invaluable asset for researchers, engineers, and professionals grappling with optimization challenges in multifactorial settings.

In essence, the systematic approach of the Taguchi method extends its utility to anyone confronted with the intricacies of optimizing multifactorial processes or systems. Within the context of this thesis, the Taguchi method assumes a pivotal role in optimizing a multifaceted process integral to sustainable architecture and environmental resilience. The Taguchi method provides a structured framework for comprehensively assessing the impact of various factors on architectural performance and environmental resilience, thereby contributing to the development of more robust and sustainable architectural solutions.

The utilization of the Taguchi method in this thesis underscores its adaptability and applicability across diverse domains. The structured experimentation and data-driven approach intrinsic to this method align seamlessly with the research objectives, where the pursuit of precise and optimal solutions is paramount in the context of sustainable architecture and environmental resilience. (Mori & Tsai, 2011)

3.3.2 Mixing Cement and Biochar of Recycled Wood and Wood Chips

In this phase, following the principles of the Taguchi method, biochar was incorporated into the cement matrix. For the biochar component, we utilized recycled wood and wood chips, both of which were classified into three distinct categories based on their independent variable measurements: 50 (small size), 100 (medium size), and 200 (large size) μm. These measurements closely mirrored the particle dimensions of the biochar material.

The initial stage involved the preparation of nineteen bottles. Nine of these containers contained mixtures of recycled wood and cement, while another nine incorporated wood chips and cement. The remaining bottle was dedicated exclusively to cement. Transitioning to the subsequent stage, we employed data obtained through the Taguchi method to guide our actions in Excel. This data facilitated precise measurements of biochar and cement, aligning with the values specified in tables 2 and 3. This meticulous approach enabled us to validate the accuracy of our calculations and ensure the actual measurements closely matched the anticipated outcomes.

Upon the thorough preparation of materials, the components were thoughtfully within a ceramic container. Subsequently, these materials underwent a rigorous mixing process, exposed to 24 hours of continuous rotation within a specialized rotary device. This step was meticulously designed to ensure the thorough blending of all constituents, fostering homogeneity and the creation of a well-integrated composite material.

Following 24 hours of continuous rotation, the biochar of recycled wood and wood chips was primed for the next phase. The formulation of mortar mirrored the earlier process employed for cement integration.

In this mortar formulation, an additional step was introduced. We meticulously added superplasticizer into the water, adhering to the prescribed percentages outlined in tables 2 and 3, corresponding to the specific composition of the mixture.

This deliberate inclusion of superplasticizer aimed to enhance the mortar's fluidity and workability, facilitating precise testing procedures.

Upon completing the mortar mixture, a further 24-hour waiting period ensued, allowing the material to set and stabilize. Subsequently, the samples were carefully cut from their molds and submerged in water at ambient temperature, initiating the curing process. For 28 days, the samples underwent gradual curing, culminating in enhanced structural maturity.

The ultimate evaluation of the mortar's performance hinged on two critical tests: flexural and compressive strength. Employing the Zwick/Roell (figure 5), testing machine, these tests were conducted with precision, providing valuable insights into the material's mechanical properties and suitability for architectural applications.

Recycled Wood:

Table 2. Values of the 3 independent variables considered for the 19 tests identified by the Taguchi experimental design and for the 9 blank tests of recycled wood.

Experiment	Weighed cement (g)	Particle size (µm)	Weighed biochar (g)	SP (g)	Sand (g)	H_2O (g)
R1	60.55	50	10.69	0.71	213.72	35.62
R2	67.68	100	3.57	0.71	213.72	35.62
R3	64.12	200	7.13	0.71	213.72	35.62
R4	67.69	50	3.55	1.42	213.72	35.62
R5	64.13	100	7.12	1.42	213.72	35.62
R6	60.56	200	10.69	1.42	213.72	35.62
R7	64.12	50	7.12	2.14	213.72	35.62
R8	60.55	100	10.7	2.14	213.72	35.62
R9	67.68	200	3.56	2.14	213.72	35.62

Wood Chips:

Table 3. Values of the 3 independent variables considered for the 19 tests identified by the Taguchi experimental design and for the 9 blank tests of wood chips.

Experiment	Weighed cement (g)	Particle size (μm)	Weighed biochar (g)	SP (g)	Sand (g)	H_2O (g)
W1	60.55	50	10.70	0.71	213.72	35.62
W2	67.69	100	3.56	0.71	213.72	35.62
W3	64.12	200	7.12	0.71	213.72	35.62
W4	67.67	50	3.57	1.42	213.72	35.62
W5	64.11	100	7.12	1.42	213.72	35.62
W6	60.55	200	10.70	1.42	213.72	35.62
W7	64.13	50	7.13	2.14	213.72	35.62
W8	60.55	100	10.69	2.14	213.72	35.62
W9	67.68	200	3.56	2.14	213.72	35.62

3.4 Experimental Process on Superplasticizer Impact Wood Biochar

In the investigation of recycled wood biochar, particular attention was directed towards particles sizing at 100 µm within cementitious compositions, exploring their behaviour under the influence of different superplasticizer concentrations.

This phase of experimentation into the relationship between superplasticizers and the resulting flexural and compressive strengths aims to elucidate the optimal conditions for harnessing the full potential of recycled wood biochar as a sustainable and effective substitute for traditional cementitious materials.

In this experiment (table 4), five distinct trials were conducted, each featuring varying proportions of superplasticizer. The objective was to examine the influence of these diverse superplasticizer concentrations on the attributes of recycled wood biochar.

Recycled Wood:

Table 4. Impact of different percentages of superplasticizers on the mechanical properties of recycled wood.

Experiment	SP (g)	Particle size (µm)	Weighed biochar (g)	Weighed cement (g)	H_2O (g)	Sand (g)
Rsp1	-0-	50.00	7.12	64.12	35.62	213.72
Rsp2	0.21	50.00	7.12	64.12	35.62	213.72
Rsp3	0.43	50.00	7.12	64.12	35.62	213.72
Rsp4	0.64	50.00	7.12	64.12	35.62	213.72
Rsp5	0.85	50.00	7.12	64.12	35.62	213.72

3.5 Experimental Process of Substitution

3.5.1 Substitutions: Pine Pellets, Recycled Wood, and Walnut shells with Superplasticizer

In the third experiment, the investigation expanded to explore various combinations of biochar, including pine pellets, recycled wood, and wood chips incorporated into cement. The study was conducted in three parts:

1. First Set of Tests: Pine Pellets (PP)

- Exclusively examined the effects of incorporating pine pellets into the cement mixture. The aim was to understand how the pine pellets, without the influence of other biochar types, interacted with the cement and how the overall mechanical properties were affected.

2. Second Set of Tests: Two Types of Biochar - Pine Pellets in Cement and Recycled Wood in Sand (PP+RW)

- This set involved a dual approach where two types of biochar were simultaneously introduced into the experimental design.

- Pine pellets in cement: Investigated the impact of pine pellets when substituted directly into the cement mixture, assessing how this combination influenced the mechanical properties of the resulting composite.

- Recycled wood in the sand: Explored the effects of substituting sand with recycled wood biochar, focusing on the interaction between recycled wood and the sand component.

- In this experimental setup, two distinct types of biochar were employed: pine pellets integrated into cement and recycled wood mixed with sand (PP+RW). The pine pellet biochar was subjected to sieving, resulting in a particle size distribution of 200 μm, while the recycled wood biochar remained unsieved, with a particle size of 500 μm.

3. Third Set of Tests: Pine Pellets in Cement and Walnut Shells in Sand (PP+WS)

- Mirrored the second set but with a variation in the type of biochar used in the sand substitution.

- Pine pellets in cement: Similar to the second set, the influence of pine pellets on cement properties was examined.

- Walnut shells in sand: Explored the substitution of sand with walnut shells biochar, specifically investigating how wood chips interacted with the sand and the resultant impact on mechanical strength.

4. Fourth Set of Tests: Walnut Shells in Cement (200 μm) and Pine Pellets in Sand (WS200+PP)

- Introduced walnut shells with a particle size of 200 μm into the cement mixture, examining their effects on cement properties.

Pine pellets in the sand: Investigated the influence of pine pellets when substituted into the sand component.

5. Fifth Set of Tests: Walnut Shells in Cement (500 Micrometers) and Pine Pellets in Sand (WS500+PP)

- Examined the effects of walnut shells with a particle size of 500 μm when incorporated into the cement mixture.

Pine pellets in the sand: Similar to the previous set, the impact of pine pellets on the sand component.

Superplasticizer Usage:

Throughout all sets of experiments, a consistent percentage of superplasticizers was maintained. This allowed the isolation of the effects of the biochar types (table 5) and their interactions with cement and sand from variations in superplasticizer concentration and also enabled a direct comparison of the effects of different biochar types on the cement's flexural and compression strengths under similar conditions.

Table 5. Exploring the influence of biochar substitutions on sand and cement mixtures with superplasticizer and water.

Experiment	Biochar Cement (g)	Biochar Sand (g)	Cement (g)	SP (g)	Sand (g)	H_2O (g)
PP	7.12	-0-	64.11	1.42	213.72	35.62
PP+RW	7.12	10.66	64.11	1.42	203.03	35.63
PP+WS	7.12	10.66	64.11	1.42	203.03	35.62

3.6 Experimental Process on Particle Size Analysis Using Matersizer 3000

The particle size analysis of biochar involved the utilization of the Mastersizer 3000 (Figure 6), an advanced particle size analyzer manufactured by Malvern Panalytical. Operating on laser diffraction technology, the instrument emitted a coherent light beam from a laser source, interacting with individual particles within the dispersed biochar sample. When the laser encountered a particle, it induced diffraction or deviation of light, with the extent and angle of diffraction contingent upon the particle's size. A specialized detector captured the angle and intensity of the scattered light from each biochar particle. The collected data, encompassing particle sizes and scattered light intensity details, underwent processing by the Mastersizer 3000 software. The final step involved the software generating a comprehensive report, offering intricate insights into the particle sizes present in the biochar sample, including specifics such as particle size distribution and standard deviation. The Mastersizer 3000, with its laser diffraction technology, stands as a valuable tool in various industries, providing precise measurements essential for research, quality control, and development.

Figure 6. Granulometric analysis with Mastersizer 3000.

The use of Mastersizer 3000 in granulometry analysis aims to assess the particle size distribution of biochar samples. This analysis is crucial for evaluating the alignment between the provided biochar dimensions (50, 100, and 200 microns) and the actual particle size distribution. The observed discrepancy between specified dimensions and actual distribution emphasizes the vital role of precise granulometry analysis in characterizing biochar properties.

This process focuses on sieving recycled wood biochar to assess its particle size distribution. This involved utilizing a sequence of sieves with diverse mesh sizes, spanning from coarse to fine, to segregate particles according to their dimensions. Subsequently, the biochar samples obtained from the sieving process were carefully gathered and subjected to analysis to ascertain the distribution of particle sizes within the sample. Particular emphasis was placed on ensuring uniformity in particle sizes, given its substantial influence on the material's properties and overall performance.

3.7 Experimental Process on Grounded Recycled Wood

3.7.1 Ground Recycled Wood 200 µm at 2h, 4h, 8h, and 12h

In the experiment involving biochar from recycled wood with a particle size of 200 µm, a Grinding Shaker Mixer was employed for the grinding process. The procedure consisted of placing the biochar in a container, accompanied by three stainless steel balls. The Grinding Shaker Mixer was utilized to impart agitation to the entire setup. This mixer employs a tumbling or shaking motion to ensure thorough blending and grinding of the biochar. The addition of stainless-steel balls aids in the grinding process by facilitating the breakdown of larger particles. The experiment involved varying durations of grinding, specifically at 2 hours, 4 hours, 8 hours, and 12 hours. The goal was to observe and quantify the changes in particle size distribution over these time intervals, providing insights into how the grinding process affects the biochar's characteristics and ensuring a controlled and consistent approach to particle size reduction.

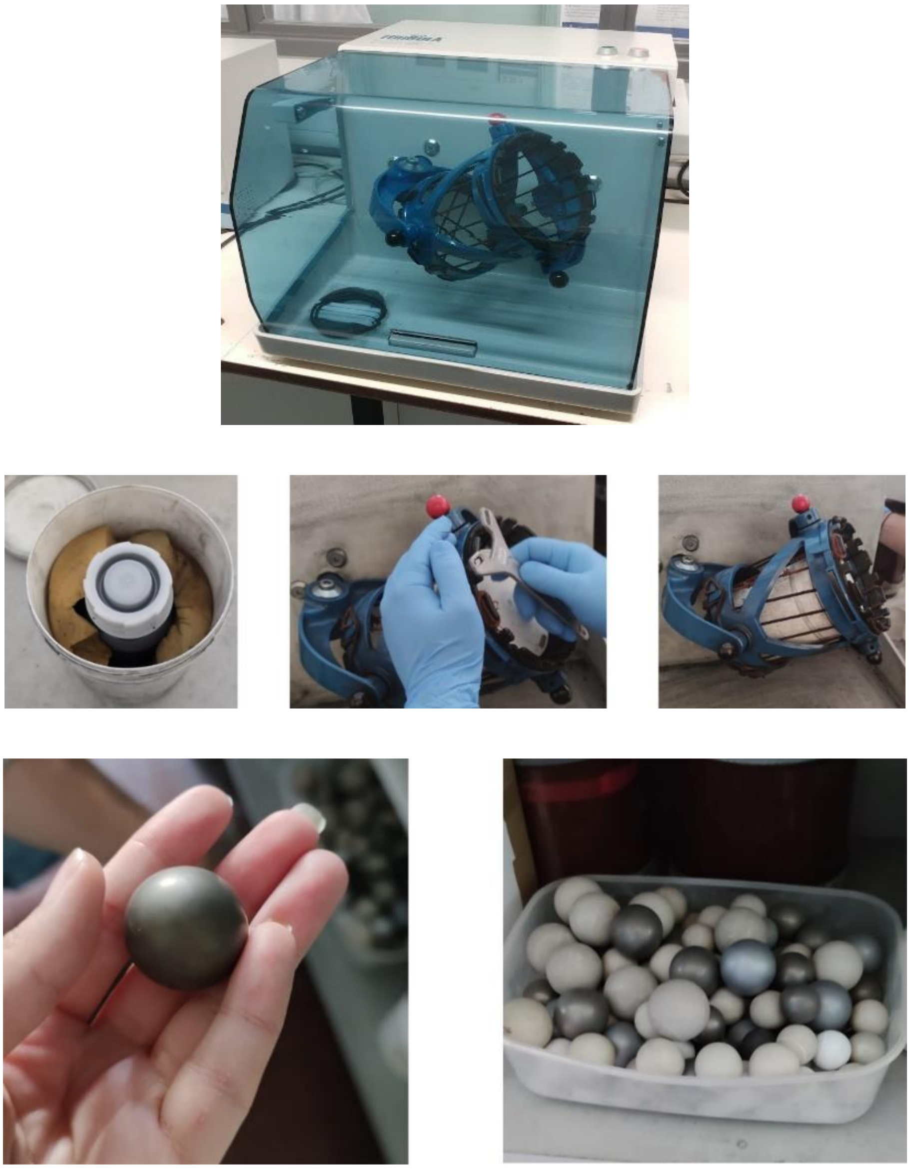


Figure 7. Grinding shaker mixer type T2F with stainless steel balls.

The experiment involved grinding recycled wood biochar for varying durations (table 6), including 2, 4, 8, and 12 hours, with a focus on observing changes in particle size distribution and their impact on compression strength. After assessing the results, it was decided to concentrate on the 12-hour interval for the final test, considering the progressive nature of grinding observed over the durations.

However, despite the extended grinding time, the compression strength of the recycled wood biochar did not improve; instead, it decreased. This outcome suggests that the reduction in particle size distribution did not positively influence the material's compression strength. Consequently, it was concluded that this grinding methodology for recycled wood biochar was ineffective in enhancing the material's properties.

Table 6. The particle size distribution data for recycled wood biochar after 12 hours of grinding.

Sample	Average flexural strength (MPa)	Average compression strength (MPa)
RGW 12h	3.01	10.60
Standard deviation (Mpa)	0.32	1.44

Chapter 4

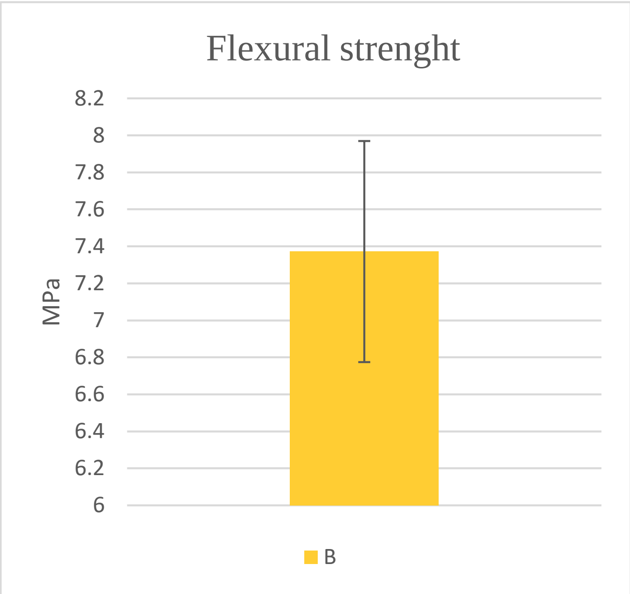
Results

4.1 Experimental Results on Blank

4.1.1 Mortar Specimens

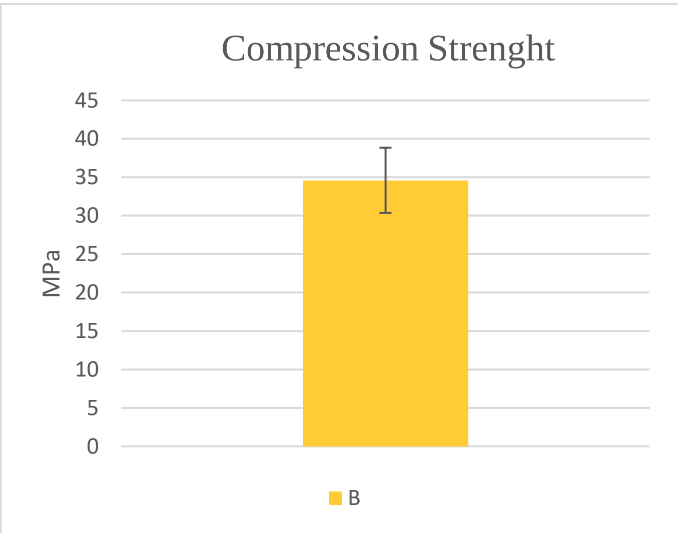
In mortar specimens without biochar, flexural strength refers to the maximum stress endured by the material before it fractures or bends. This property is crucial in assessing the material's ability to withstand bending or tensile forces, which are commonly encountered in construction and structural applications. Additionally, the compression strength measures the material's ability to withstand axial loads or forces pushing inward, providing insights into its structural integrity and load-bearing capacity. These mechanical properties play vital roles in determining the overall performance and durability of the mortar, especially in structural applications where resistance to bending and compression is essential for long-term stability and safety.

In the context of the experiment, "B" (figures 8 and 9) refers to the control or the **baseline condition**, commonly known as "**Blank**." This condition represents the normal state without the incorporation of biochar in the cement mixture. Essentially, it serves as the reference point against which the effects and variations induced by the presence of biochar and superplasticizers can be measured.



Sample	Average flexural strength (MPa)	Standard deviation (MPa)
Blank	7.37	0.59

Figure 8. The flexural strength of the mortar specimen.



Sample	Average Compression strength (MPa)	Standard deviation (MPa)
Blank	34.59	4.23

Figure 9. The compression strength of the mortar specimen.

4.2 Experimental Results on Recycled Wood and Wood Chips

4.2.1 Taguchi Method

In the Taguchi-based study exploring the flexural and compressive strength of mortar samples with recycled wood and wood chips biochars. Tests were conducted and results were categorized into four sections, comprising two flexural and two compressive tests. The compression test findings, presented in separate tables for recycled wood and wood chips, illuminate material behaviour under compressive stress, providing crucial insights into the effects of superplasticizers, particle size, and cement replacement. The initial set of experiments involved nine trials for both recycled wood and wood chips, applying Taguchi methodology to examine user interaction with superplasticizers, dimensions, and percentage of substitution. This set, focusing on a 10% substitution rate and varied particle dimensions, was subsequently optimized using Taguchi (R1 to 9 and W1 to 9).

4.2.2 Flexural Test Results for Recycled Wood

The flexural tests for recycled wood involved the examination of nine samples under various conditions, including alterations in three distinct percentages of superplasticizer. Additionally, the particle size of the biochar, used as a substitute for cement, varied within the range of 50, 100, and 200 micrometers.

Table 7 provides a comprehensive overview of the test results, elucidating how the flexible properties of recycled wood were influenced by these different variables, offering valuable insights into the material's behaviour under varying conditions.

Table 7. Displays measurements from R1 to R9 of recycled wood, providing insights into flexural strength.

Sample	SP [%]	Particle size (µm)	Cement replacement [%]	Flexural strength (MPa)
R1	1	50	15	5.37
R2	1	100	5	6.42
R3	1	200	10	5.20
R4	2	50	5	5.08
R5	2	100	10	4.30
R6	2	200	15	4.09
R7	3	50	10	4.20
R8	3	100	15	3.84
R9	3	200	5	4.30

In the following section, three graphs are presented to enhance the accessibility of the results at hand. These graphical representations serve as effective tools for conveying key findings related to the material properties and their responses to varying experimental parameters, including the impact of superplasticizer percentages, dimension of particle size distribution, and cement replacement. These graphs provide a deeper insight into the material's behaviour under different conditions.

The first graph (Figure 10) illustrates the impact of various superplasticizer percentages, a critical variable in the study. The experiment considered three percentages: 1, 2, and 3%. The graph clearly shows that lower superplasticizer percentages result in better outcomes. Adding just 1% of superplasticizer is notably more effective than using 2% or 3%. The vertical axis represents the compressive strength in MPa, with testing beginning at 1% of superplasticizer, progressing to 2, and then 3%. The trend demonstrates that lower superplasticizer percentages lead to higher compressive strengths, indicating improved material performance.

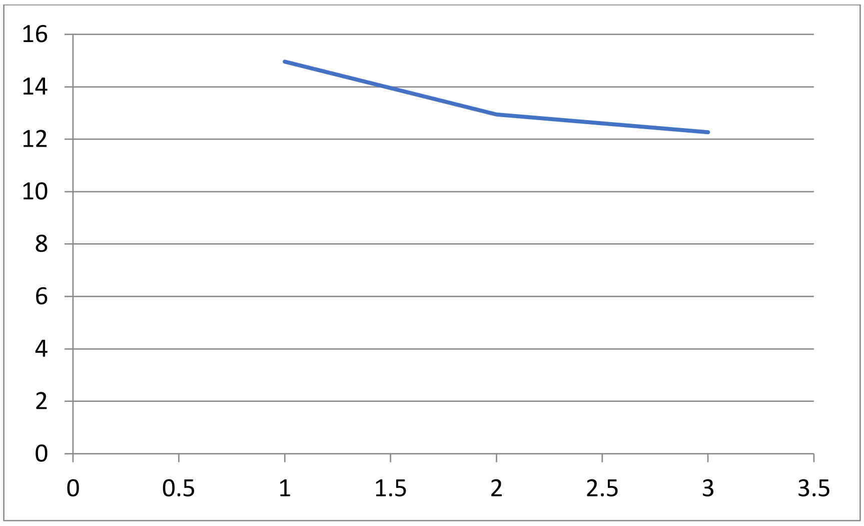


Figure 10. Effect of superplasticizer percentages on material performance in flexural tests.

The second graph (Figure 11) illustrates the impact of different particle sizes measured in micrometres: 50, 100, and 200 µm. Notably, a smaller particle size, such as 50 µm, results in significantly better outcomes, with higher compressive strength indicating superior material strength.

Furthermore, it is observed that as the particle size increases, the material exhibits reduced mechanical properties. This phenomenon can be explained by the fact that smaller particle sizes may fill in the voids within the cement paste (capillary pores) while bigger particles will create defects because of their low mechanical properties, leading to a decline in mechanical properties. This emphasizes the importance of carefully balancing particle size to achieve the best outcomes in terms of material strength and resilience.

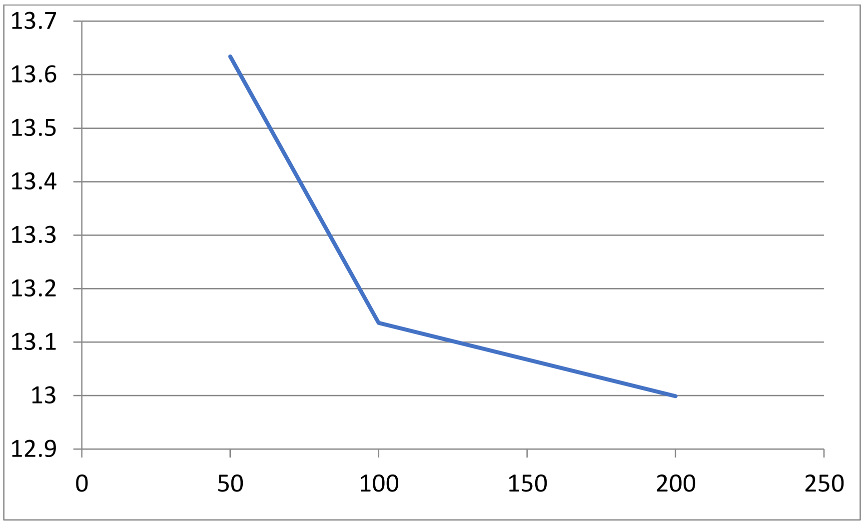


Figure 11. Influence of particle size (µm) on material performance in flexural tests.

The third graph (Figure 12) illustrates the effect of the percentage of substitution of recycled wood in cement, with three different percentages of cement replacement: 5%, 10%, and 15%. The notably higher strength values observed with a 5% substitution of recycled wood can be attributed to the optimal composition at this level. At 5% substitution, the material strikes a balance where the recycled wood effectively replaces a portion of the cement without compromising the overall structural integrity. This optimal composition enhances the material's mechanical properties, resulting in significantly higher strength values.

In contrast, as the substitution percentage increases to 10% and 15%, the material's mechanical properties are affected, resulting in lower mechanical properties.

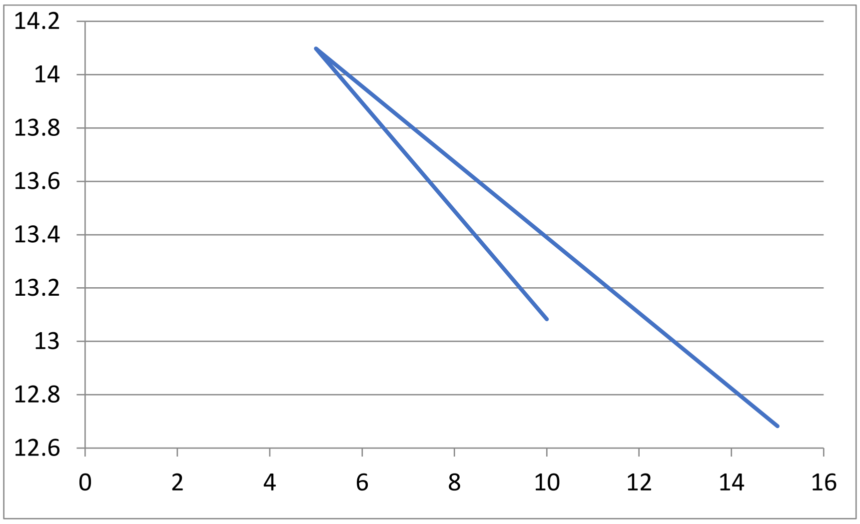


Figure 12. Influence of recycled wood substitution on material performance in flexural tests.

In the examination of flexural strength across the nine experiments (figure 13) involving recycled wood, R2 emerged as the most optimal point. This finding suggests that among the tested parameters or conditions, R2 demonstrated the highest degree of resistance to bending or fracturing, signifying superior structural integrity. Further analysis revealed that the composition or configuration associated with R2 exhibited a notable enhancement in flexural strength compared to other experimental setups. This underscores the significance of the specific variables or factors manipulated within the R2 formulation, shedding light on potential strategies for optimizing flexural strength in mortar specimens containing recycled wood biochar.

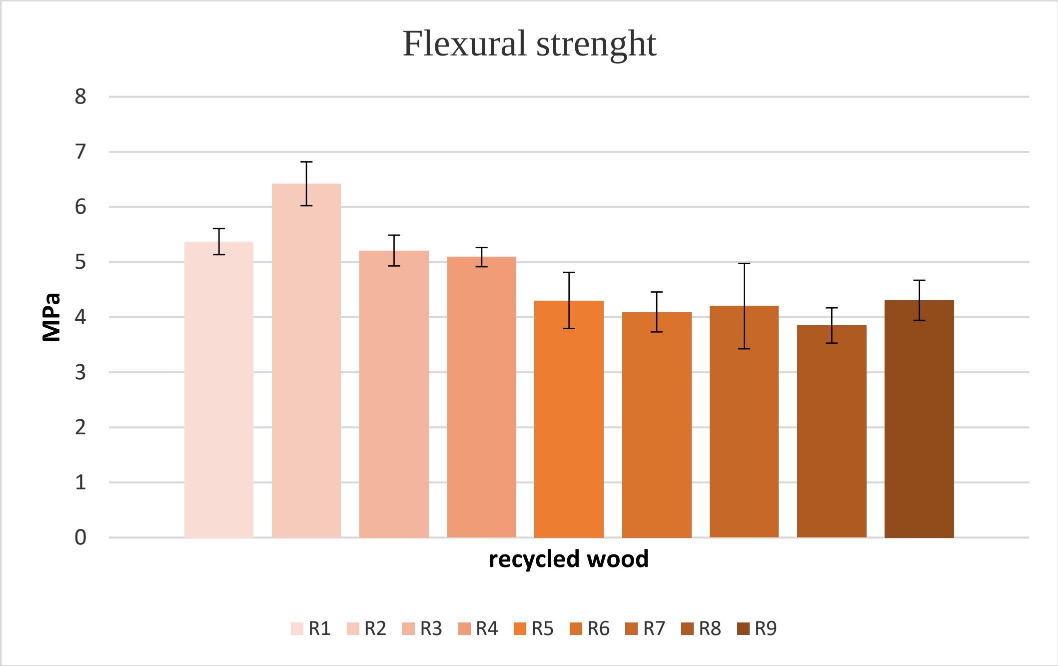


Figure 13. Displays measurements from R1 to R9 of recycled wood substitution on material performance in flexural tests.

Sample	Average flexural strength (MPa)	Standard deviation (MPa)
R1	5.37	0.24
R2	6.42	0.40
R3	5.21	0.28
R4	5.09	0.17
R5	4.30	0.51
R6	4.09	0.36
R7	4.20	0.77
R8	3.85	0.32
R9	4.31	0.36

4.2.3 Compression Test Results for Recycled Wood

Table 8 displays the measurements from the mechanical compression test specifically for recycled wood. Notably, these measurements align with those in the previous flexural test. The consistency in values highlights the material's performance in both flexural and compressive tests, providing a comprehensive view of its mechanical properties.

Table 8. Displays measurements from R1 to R9 of recycled wood, providing insights into compression strength.

Sample	SP [%]	Particle size (µm)	Cement replacement [%]	Compression strength (MPa)
R1	1	50	15	25.95
R2	1	100	5	27.50
R3	1	200	10	20.96
R4	2	50	5	17.06
R5	2	100	10	13.72
R6	2	200	15	12.24
R7	3	50	10	11.88
R8	3	100	15	15.86
R9	3	200	5	15.61

In the compression test, the primary objective is to measure the material's capacity to withstand applied force until it fractures. The first graph (Figure 14) illustrates the influence of varying superplasticizer percentages, a pivotal factor in this study. The experiment encompasses three percentage levels: 1, 2, and 3%. The graph distinctly shows that lower superplasticizer percentages consistently result in better outcomes. Remarkably, the addition of only 1% of superplasticizer proves significantly more effective compared to 2 or 3%.

The vertical axis represents the material's performance, and testing begins at 1% of the superplasticizer, advances to 2, and concludes at 3%. This trend underscores that lower superplasticizer percentages consistently lead to higher material performance values, highlighting the material's enhanced, particularly in the compression test where its ability to endure applied force is assessed.

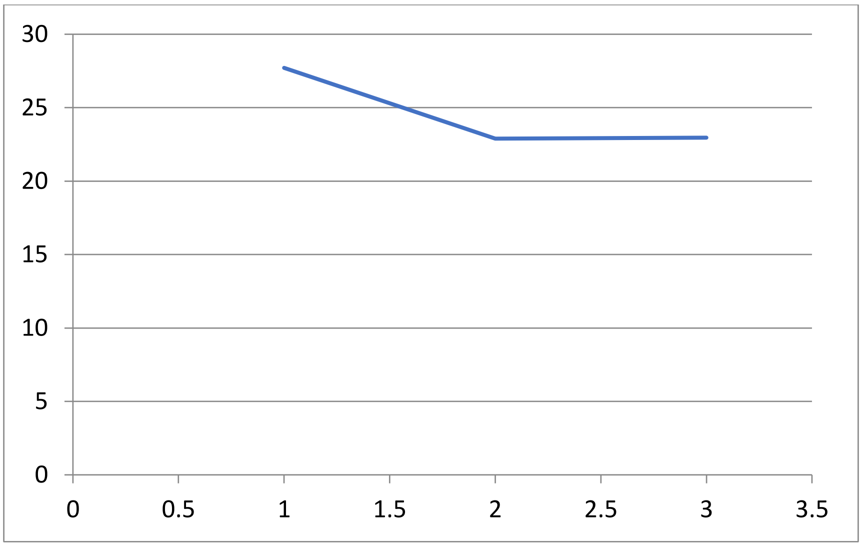


Figure 14. Effect of superplasticizer percentages on material performance in compression tests.

The second graph (figure 15) in the compression test illustrates the influence of various independent variable particle sizes measured in micrometres: 50, 100, and 200. Significantly, it is evident that a medium particle size, particularly 100 µm, outperforms both 200 µm and 50 µm. This finding highlights 100 µm as the most favourable particle size for achieving superior material performance in compression tests.

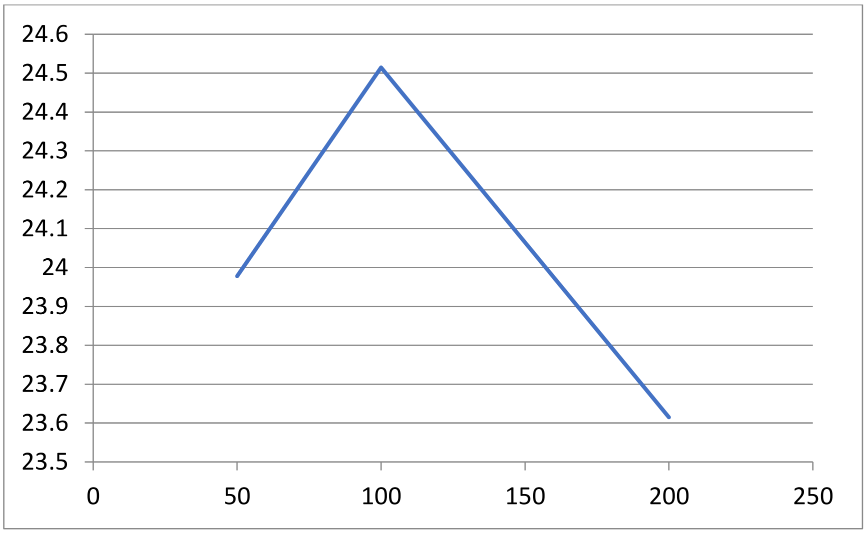


Figure 15. Influence of particle sizes (µm) on material performance in compression tests.

Figure 16 portrays the impact of substituting recycled wood for cement at varying percentages 5%, 10%, and 15%. The notably superior compression strength observed with a 5% substitution of recycled wood can be ascribed to the ideal composition achieved at this level. At a 5% substitution rate, the material attains a harmonious blend where recycled wood effectively replaces a portion of the cement without compromising the overall structural integrity. This balanced composition enhances the material's mechanical properties, resulting in significantly increased compression strength.

Conversely, with higher substitution percentages of 10% and 15%, the material experiences a reduction in its mechanical properties, leading to diminished compression strength.

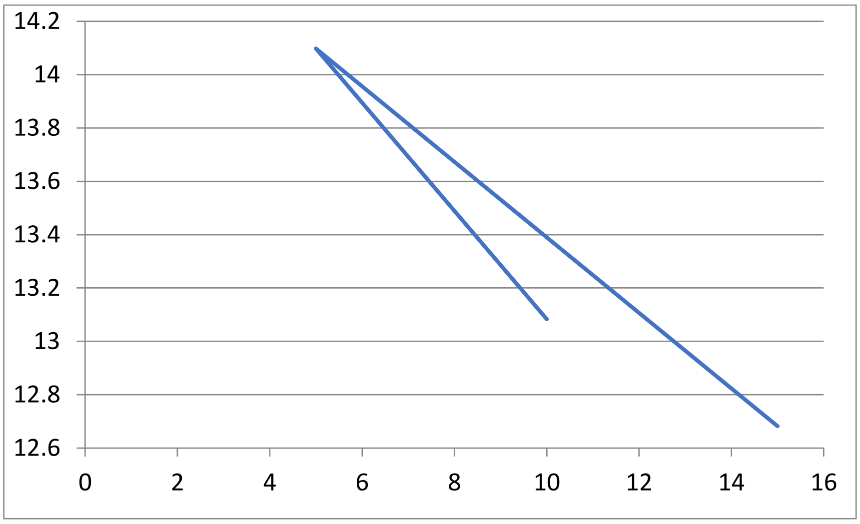


Figure 16. Effect of recycled wood substitution on material performance in compression tests.

The compression strength of recycled wood biochar (figure 17) reveals a trend similar to that observed in the flexural strength results. While not identical numerically, certain compositions, possibly resembling conditions associated with R2, demonstrate enhanced structural integrity. This suggests that specific variables manipulated within the R2 formulation may contribute to improved compression strength.

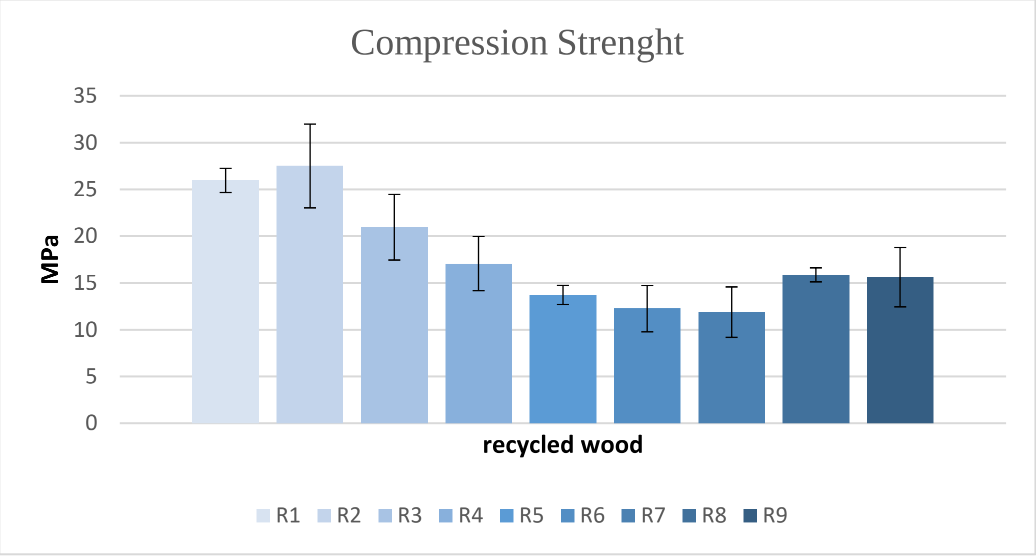


Figure 17. Displays measurements from R1 to R9 of recycled wood substitution on material performance in compression tests.

Sample	Average Compression strength (MPa)	Standard Deviation (MPa)
R1	25.95	1.29
R2	27.50	4.48
R3	20.96	3.51
R4	17.06	2.90
R5	13.72	1.02
R6	12.24	2.47
R7	11.88	2.69
R8	15.86	0.75
R9	15.61	3.17

4.2.4 Flexural Test Results for Wood Chips

The wood chips' flexural performance (table 10) was evaluated in experiments, encompassing nine samples. These experiments involved subjecting the wood chip samples to diverse conditions, including alterations in the percentage of superplasticizers. Additionally, the particle size of the biochar, employed as a substitute for cement, varied within the range of 50, 100, and 200 micrometres.

Table 9. Displays measurements from W1 to W9, providing insights into the material's performance.

Sample	SP [%]	Particle size (µm)	Cement replacement [%]	Flexural strength (MPa)
W1	1	50	15	4.75
W2	1	100	5	5.37
W3	1	200	10	4.97
W4	2	50	5	4.48
W5	2	100	10	3.26
W6	2	200	15	3.56
W7	3	50	10	3.79
W8	3	100	15	3.17
W9	3	200	5	3.97

Figure 18 shows the impact of different superplasticizer percentages, and notably, this trend aligns somewhat with the observations made in the recycled wood samples. The experiment involved three percentages: 1, 2, and 3%. The graph distinctly reveals that lower superplasticizer percentages yield superior results. Introducing merely a 1% superplasticizer content has a noticeably more beneficial effect than employing 2% or 3%. The vertical axis represents the compressive strength in MPa, with the examination commencing at 1% of superplasticizer content, advancing to 2%, and then 3%. The pattern indicates that lower superplasticizer percentages correlate with higher strength values, signifying enhanced material performance.

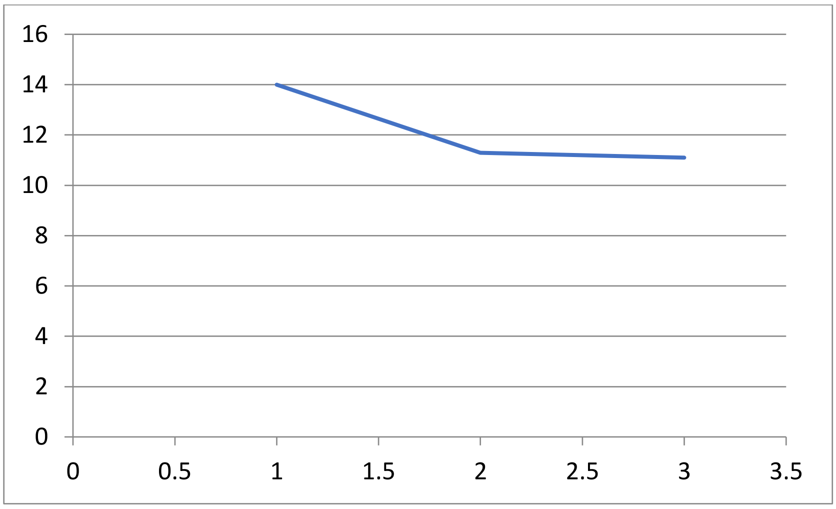


Figure 18. Effect of superplasticizer percentages on material performance in flexural tests.

These trends (figure 19) in particle size distribution align with observations made in the recycled wood samples, emphasizing consistency across different material variants. The influence of particle size on flexural strength is a critical aspect explored in both recycled wood and wood chips, providing valuable insights into how this variable affects the overall performance of the material. This parallel in findings reinforces the significance of particle size considerations in optimizing flexural strength across different types of biochar.

Additionally, in recycled wood, the flexural strength reaches up to 13 MPa, while in wood chips, all particle sizes exhibit flexural strength values below 13 MPa.

Comparatively, when examining mortar samples made with 200 µm of recycled wood, they displayed the lowest flexural strength values, whereas with wood chips, the values significantly increased, surpassing even the values observed with 100 µm.

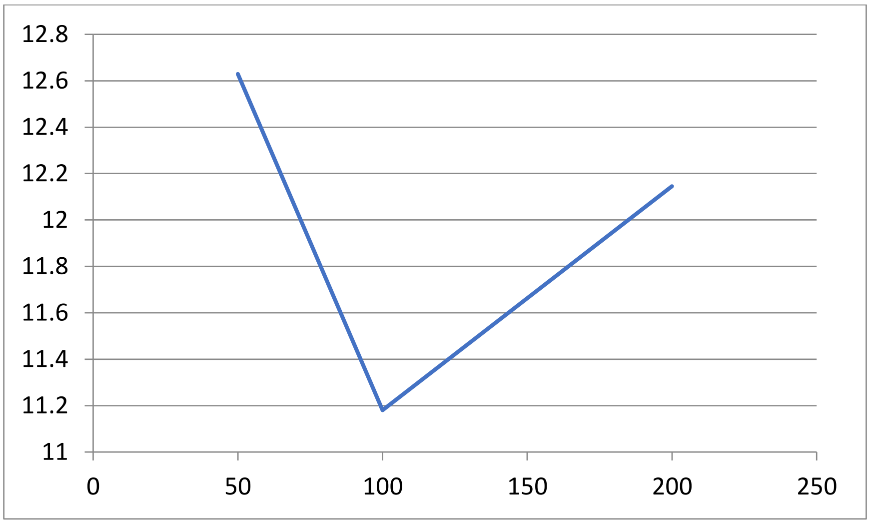


Figure 19. Influence of particle size (µm) on material performance in flexural tests.

This trend (figure 20) observed in both recycled wood and wood chips, highlights that a 5% substitution level is effective in improving flexural strength without compromising structural integrity. In contrast, as the substitution percentage increases to 10% and 15%, the material's mechanical properties are affected, resulting in lower strength values.

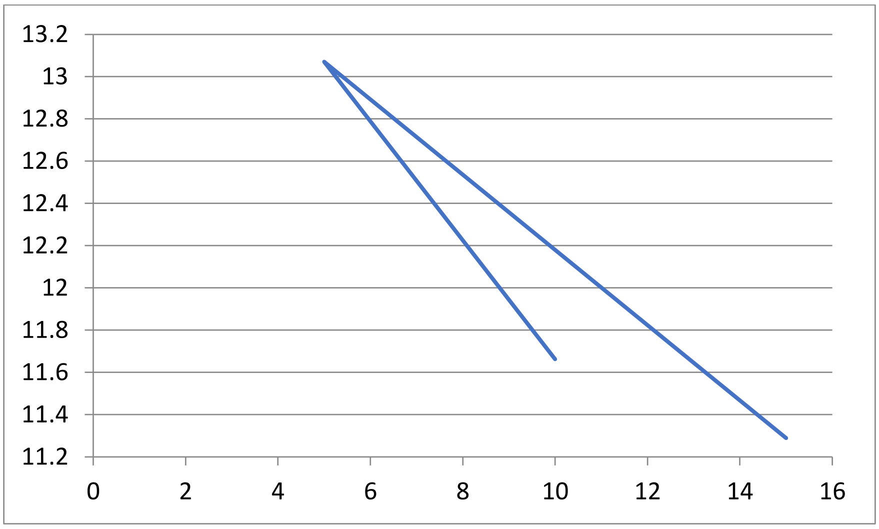


Figure 20. Influence of wood chips substitution on material performance in flexural tests.

In the investigation of flexural strength across nine experiments (figure 21) involving wood chips, W2 emerged as the most favorable point. This discovery indicates that among the various parameters or conditions tested, W2 exhibited the greatest resistance to bending or fracturing, indicating superior structural integrity. Further examination uncovered that the composition or setup linked with W2 showcased a significant improvement in flexural strength compared to other experimental configurations. This highlights the importance of the specific variables or factors manipulated within the W2 formulation, providing insights into potential approaches for enhancing flexural strength in mortar specimens containing wood chips biochar.

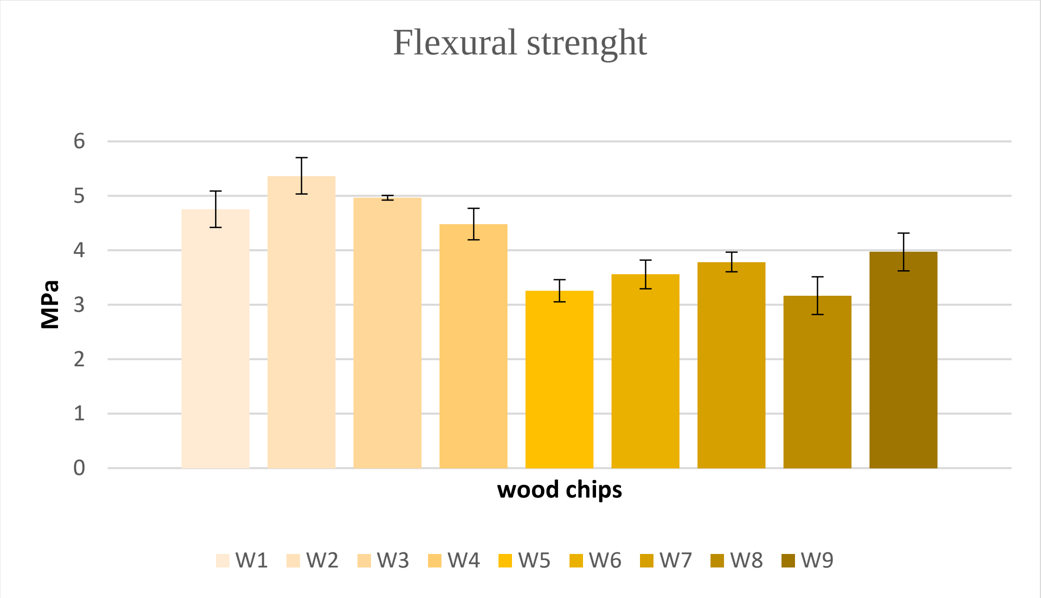


Figure 21. Displays measurements from W1 to W9 of wood chips substitution on material performance in flexural tests.

Sample	Average flexural strength (MPa)	Standard deviation (MPa)
W1	4.75	0.33
W2	5.37	0.33
W3	4.97	0.04
W4	4.48	0.29
W5	3.26	0.20
W6	3.56	0.26
W7	3.79	0.18
W8	3.17	0.35
W9	3.97	0.35

4.2.5 Compression Test Results for Wood Chips

In the comprehensive analysis of compression strength for wood chips, the investigation extended to various particle sizes (50, 100, and 200 μm) and three different percentages of superplasticizer. This multifaceted examination aimed to elucidate the interplay of particle size, superplasticizer content, and their combined influence on the compression strength of wood chips. Moreover, different substitution levels were explored to understand how the incorporation of wood chips as a cement replacement affects the material's ability to withstand compressive forces.

Encapsulating the varied dimensions and characteristics under examination, table 10 presents a comprehensive overview of the measurement scales applied across different aspects of the study. Including particle sizes, superplasticizer percentages, and substitution.

Table 10. Displays measurements from W11 to W9, providing insights into the material's performance under varying superplasticizer percentages, particle sizes, cement substitution, and results.

Sample	SP [%]	Particle size (µm)	Cement replacement [%]	Compression strength (MPa)
W1	1	50	15	19.26
W2	1	100	5	24.61
W3	1	200	10	18.28
W4	2	50	5	16.86
W5	2	100	10	9.82
W6	2	200	15	11.97
W7	3	50	10	13.08
W8	3	100	15	10.76
W9	3	200	5	12.90

The compression test for wood chips (figure 22) evaluated the material's resilience under applied force until failure across varying superplasticizer percentages (1% to 3%). Results showed that lower superplasticizer percentages consistently yielded superior outcomes, with 1% significantly outperforming 2% and 3%. This trend highlights the critical influence of lower superplasticizer levels in enhancing material performance, particularly evident in the compression test.

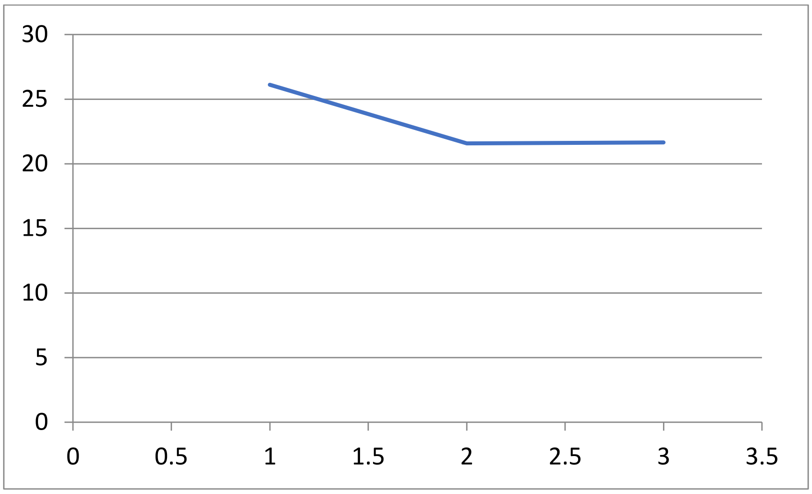


Figure 22. Effect of superplasticizer percentages on material performance in compression tests.

In the case of particle sizes (Figure 23), wood chips demonstrate varying performance based on their size distribution. Notably, wood chips with a particle size of 100 µm exhibit the highest value, indicating superior material performance in compression tests. Conversely, recycled wood, under the same conditions, showcases contrasting behaviour, with the highest value observed at a different particle size. This discrepancy underscores the nuanced influence of particle size on material performance and suggests the importance of optimizing particle characteristics for specific applications.

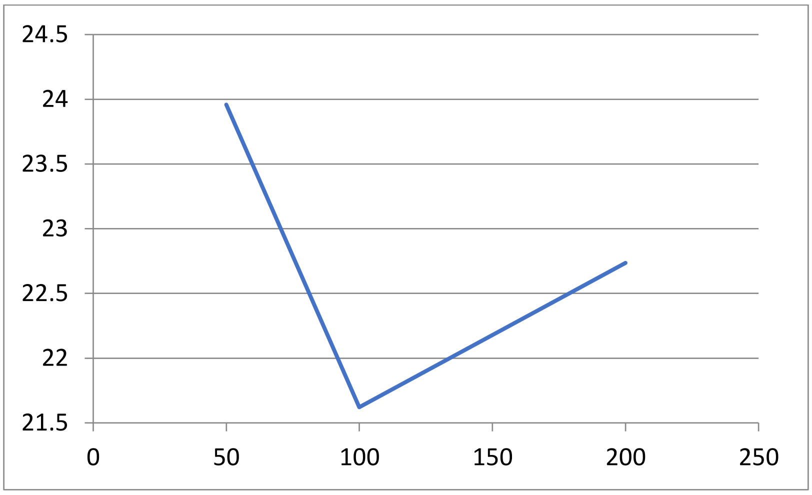


Figure 23. Influence of particle sizes (µm) on material performance in compression tests.

Figure 24 depicts the impact of substituting wood chips into the cement at different percentages (5%, 10%, and 15%). At a 5% substitution rate, wood chips contribute to enhanced compression strength, showcasing a balanced blend that maintains structural integrity while improving mechanical properties. However, as the substitution rate increases to 10% and 15%, compression strength diminishes.

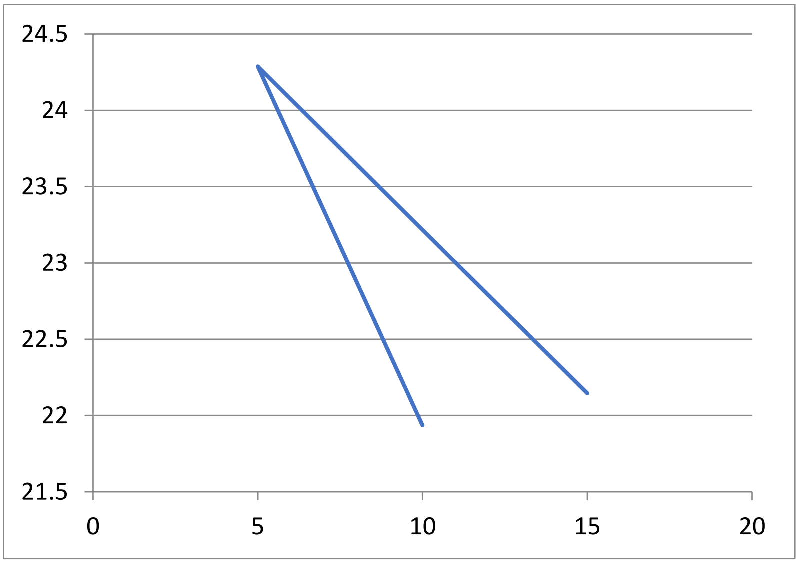


Figure 24. Effect of wood chips substitution on material performance in compression tests.

In the investigation of compression strength for wood chips biochar (figure 25), similar trends to those observed in the flexural strength results are apparent. While the numerical values may not align exactly, specific compositions exhibit notable improvements in structural integrity, mirroring conditions akin to those observed at the R2 point in the recycled wood biochar experiments. This suggests that particular variables manipulated within the formulations, which contributed to enhanced flexural strength, may also have a positive impact on compression strength.

A lower standard deviation indicates that the data points are closer to the mean, suggesting that there is less variability or dispersion within the dataset. In contrast, a higher standard deviation indicates that the data points are more spread out from the mean, indicating greater variability or dispersion within the dataset. Therefore, in general, a lower standard deviation is preferable as it signifies more consistency and reliability in the data.

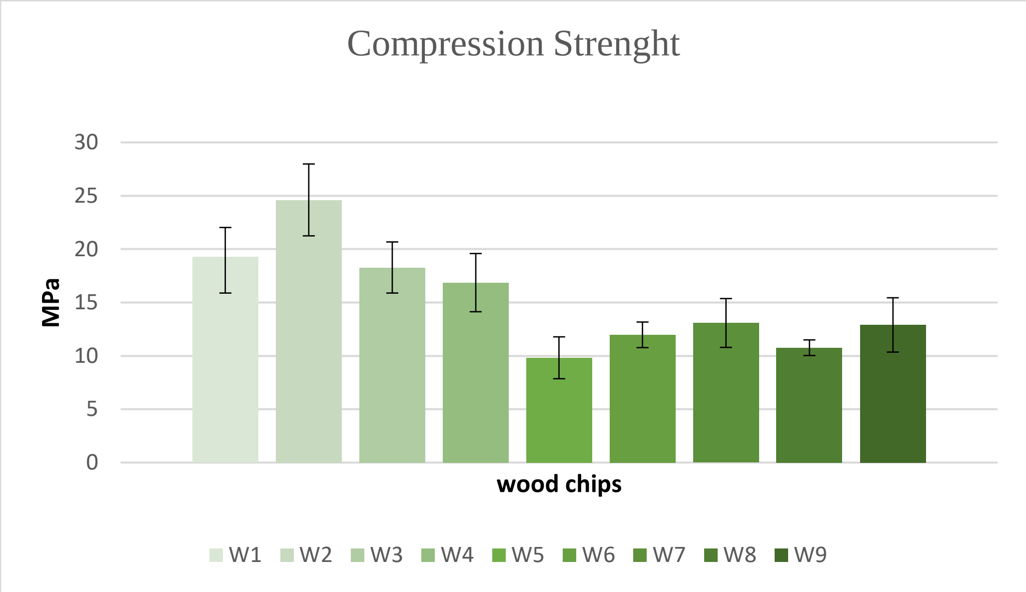


Figure 25. Displays measurements from W1 to W9 of wood chips substitution on material performance in compression tests.

Sample	Average flexural strength (MPa)	Standard deviation (MPa)
R1	25.95	1.29
R2	27.50	4.48
R3	20.96	3.51
R4	17.06	2.90
R5	13.72	1.02
R6	12.24	2.47
R7	11.88	2.69
R8	15.86	0.75
R9	15.61	3.17

4.3 Experimental Result on Superplasticizer Impact on Recycled Wood Biochar

In analyzing the results of the next experiment, a significant discovery of an anti-correlation between the concentration of superplasticizer and both flexural and compression strength was evidenced. This significant observation implies that as the superplasticizer content increases, there is a corresponding decrease in the flexural and compression strength of the recycled wood biochar.

When comparing the results of experiments involving recycled wood biochar with varying concentrations of superplasticizer to the Blank condition, a discernible pattern emerges. The anti-correlation between superplasticizer concentration and both flexural and compression strength becomes evident in the experimental groups, highlighting the substantial impact of superplasticizer on the mechanical properties of the biochar-cement composite. The Blank condition, devoid of biochar, serves as a baseline for assessing the influence of biochar and its interactions with superplasticizers on the overall performance of the composite material.

Analyzing the outcomes of this experiment reveals a notable trend regarding the effect of superplasticizers on recycled wood biochar. The results demonstrate an inverse relationship between the concentration of superplasticizer and both flexural and compression strength. In other words, as the amount of superplasticizer increases, there is a corresponding decrease in the mechanical strength of the recycled wood biochar composite. This indicates that adding more superplasticizers to the recycled wood biochar results in inferior performance, with the material exhibiting lower flexural and compression strength. Conversely, the findings suggest that utilizing recycled wood biochar without superplasticizer leads to better outcomes in terms of mechanical properties.

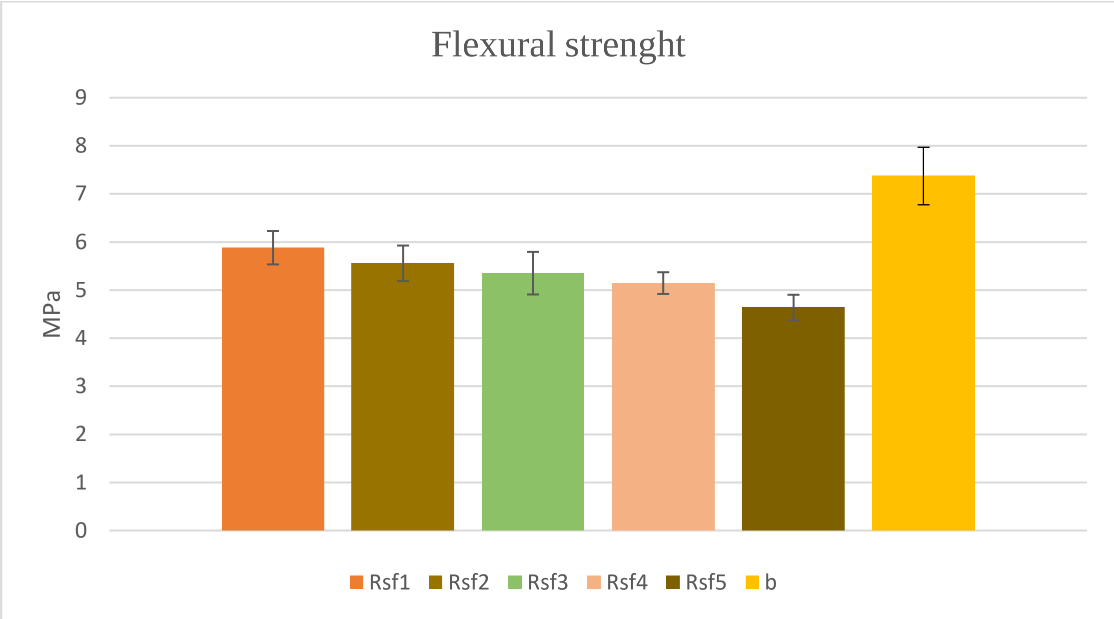


Figure 26. Displays measurements from Rsp1 to Rsp5 of recycled wood in flexural strength.

Sample	Average flexural strength (MPa)	Standard deviation (MPa)
Rsf1	5.88	0.35
Rsf2	5.56	0.37
Rsf3	5.35	0.44
Rsf4	5.15	0.23
Rsf5	4.64	0.27
B	7.37	0.60

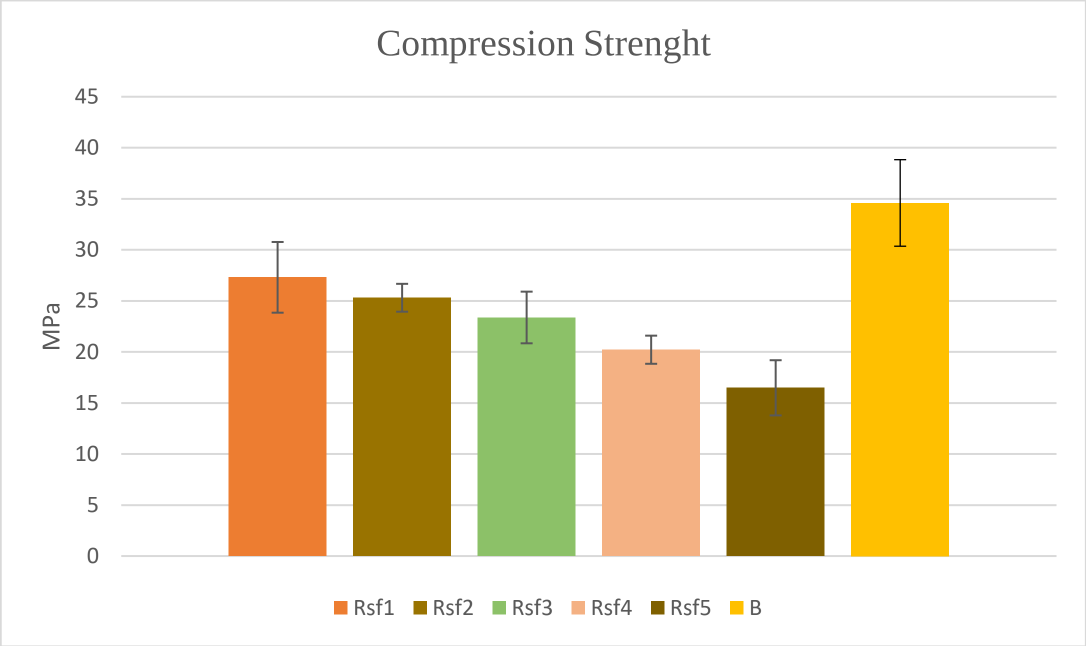


Figure 27. Displays measurements from Rsp1 to Rsp5 of recycled wood on material performance in compression tests.

Sample	Average Compression strength (MPa)	Standard deviation (MPa)
Rsf1	27.31	3.46
Rsf2	25.30	1.37
Rsf3	23.37	2.53
Rsf4	20.22	1.38
Rsf5	16.48	2.70
B	34.59	4.23

4.4 Experimental Results on Biochar Modification of Cement Composites

4.4.1 The Impact of Pine Pellets, Recycled Wood, and Walnut Shells:

The fourth experiment investigates how the incorporation of these different biochars, along with the presence of superplasticizers, influences the mechanical properties and performance of the cement composites. Through systematic testing and analysis, the experiment aims to understand the synergistic effects of biochar and superplasticizers on the overall behaviour and characteristics of cement composites.

The results (figure 28) obtained from the flexural strength testing reveal intriguing insights into the performance of different biochar compositions within the cement composites. Interestingly, the flexural strength of the pine pellet biochar closely resembles that of the blank condition, indicating minimal deviation from the baseline material. This suggests that the incorporation of pine pellet biochar alone does not significantly alter the flexural properties of the cement composites.

Conversely, when pine pellet biochar is combined with walnut shells biochar, a notable decrease in flexural strength is observed. This finding suggests that the synergistic interaction between these two types of biochar may have a detrimental effect on the flexural performance of the cement composites. The decrease in flexural strength could be attributed to factors such as differences in particle size, surface characteristics, or chemical composition between the pine pellet and walnut shells biochar, leading to suboptimal reinforcement of the cement matrix.

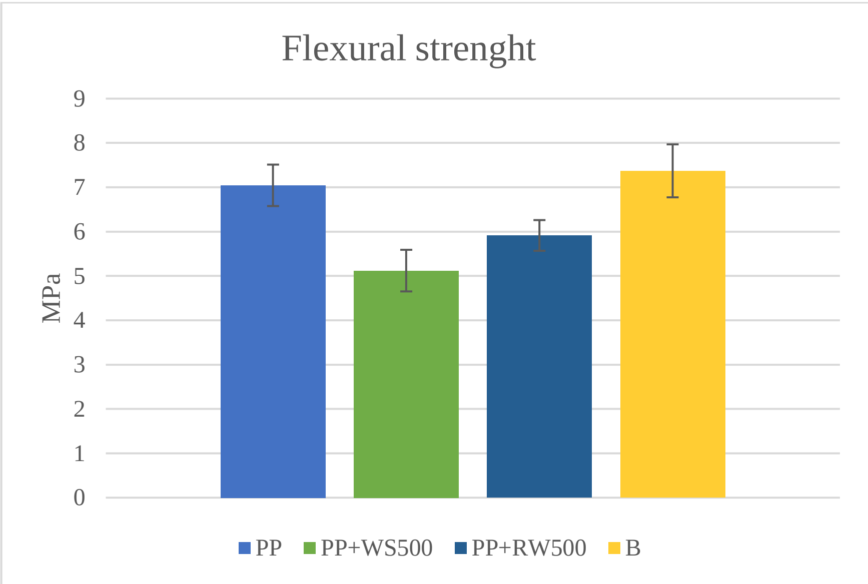


Figure 28. Displays measurements on material performance in flexural tests.

Sample	Average flexural strength (MPa)	Standard deviation (MPa)
PP	7.04	0.46
$PP+WS_{500}$	5.12	0.46
$PP+RW_{500}$	5.91	0.34
B	7.37	0.60

The compression strength test (figure 29) shows how different types of biochar affect the strength of cement composites. The pine pellet biochar was even stronger than the regular cement mix without any biochar. This means that adding pine pellet biochar made the cement stronger.

When we mixed pine pellet biochar with walnut shells biochar, the strength of the cement composite stayed higher than the blank, but it wasn't as strong as when we used just pine pellet biochar. This suggests that while adding walnut shells biochar helped, it didn't make the cement as strong as pine pellet biochar alone.

On the other hand, when we combined pine pellet biochar with recycled wood biochar, the strength of the cement composite decreased compared to the regular cement mix. This means that mixing these two types of biochar didn't make the cement stronger.

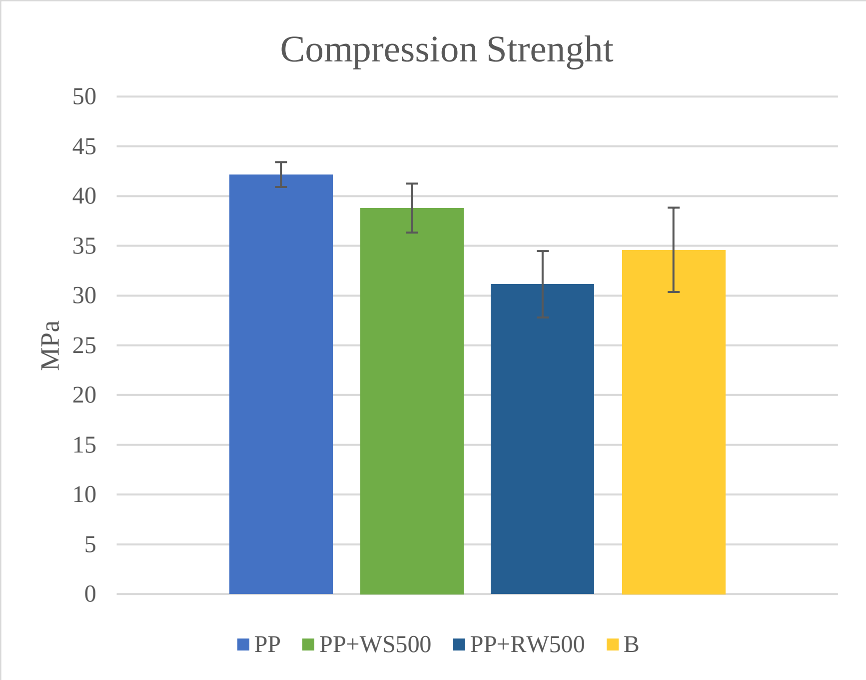


Figure 29. Displays measurements on material performance in compression tests.

Sample	Average compression strength (MPa)	Standard deviation (MPa)
PP	42.15	1.24
$PP+WS_{500}$	38.79	2.46
$PP+RW_{500}$	31.13	3.33
B	34.59	4.23

Overall, these results show that different types of biochar can have different effects on the strength of cement. Pine pellet biochar seems to be the most effective at making cement stronger while mixing it with other types of biochar might not always have the same positive effect. There's still more to learn about how biochar interacts with cement, but these findings are a good starting point for future research.

4.4.2 The Impact of Pine Pellets with Recycled Wood (500 µm), and Pine Pellets with Walnut Shells (200 µm) and (500 µm).

In addition to scrutinizing the preceding experiments, the inquiry extended its focus to the mechanical properties of the composite materials. This phase involved a detailed examination of the impact of integrating pine pellets biochar with walnut shells, taking into account two distinct particle size distributions: 200 µm and 500 µm. Furthermore, particular attention was directed towards understanding how the interplay between different biochar compositions and particle sizes influences the overall performance of the composite material. Additionally, the investigation involved sieving the recycled wood biochar to achieve a particle size distribution of 200 µm. This refined biochar was then carefully integrated with pine pellet biochar.

In the analysis of flexural strength, the integration of pine pellets biochar with walnut shells across two distinct particle size distributions, namely 200 µmand 500 µm, exhibited a decrease in strength compared to the blank mortar cement process without biochar. This observation underscores the impact of biochar composition and particle size on the flexural properties of the composite material. Furthermore, among the three types of biochar investigated, the combination of pine pellets with recycled wood biochar yielded significantly better results in terms of flexural strength.

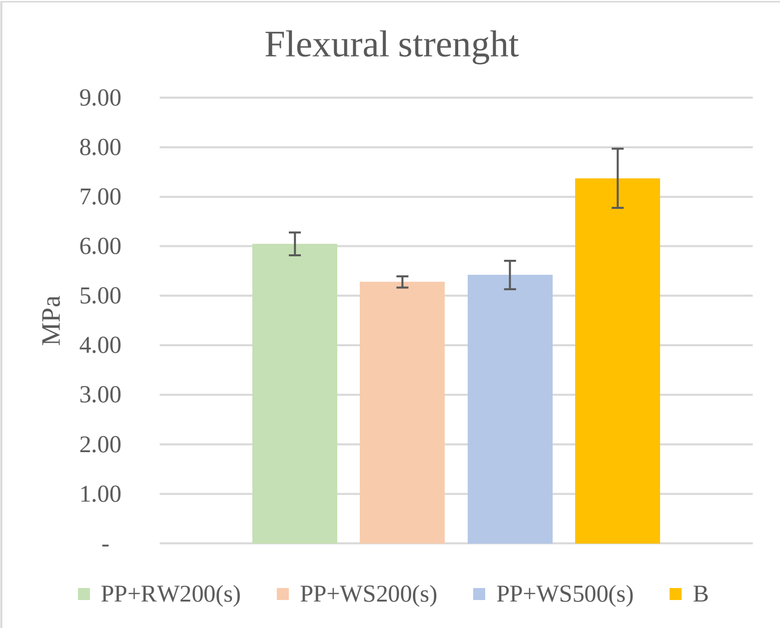


Figure 30. Displays measurements on material performance in flexural strength.

Sample	Average flexural strength (MPa)	Standard deviation (MPa)
PP+RW$_{200(s)}$	6.05	0.23
PP+WS$_{200(s)}$	5.28	0.11
PP+WS$_{500(s)}$	5.42	0.29
B	7.37	0.60

In the assessment of compression strength, the integration of pine pellets biochar with walnut shells at two different particle size distributions, 200 µm and 500 µm, demonstrated a reduction in strength relative to the blank mortar cement process devoid of biochar. Similar to the findings in flexural strength, the combination of pine pellets with recycled wood biochar exhibited superior compression strength compared to other biochar combinations.

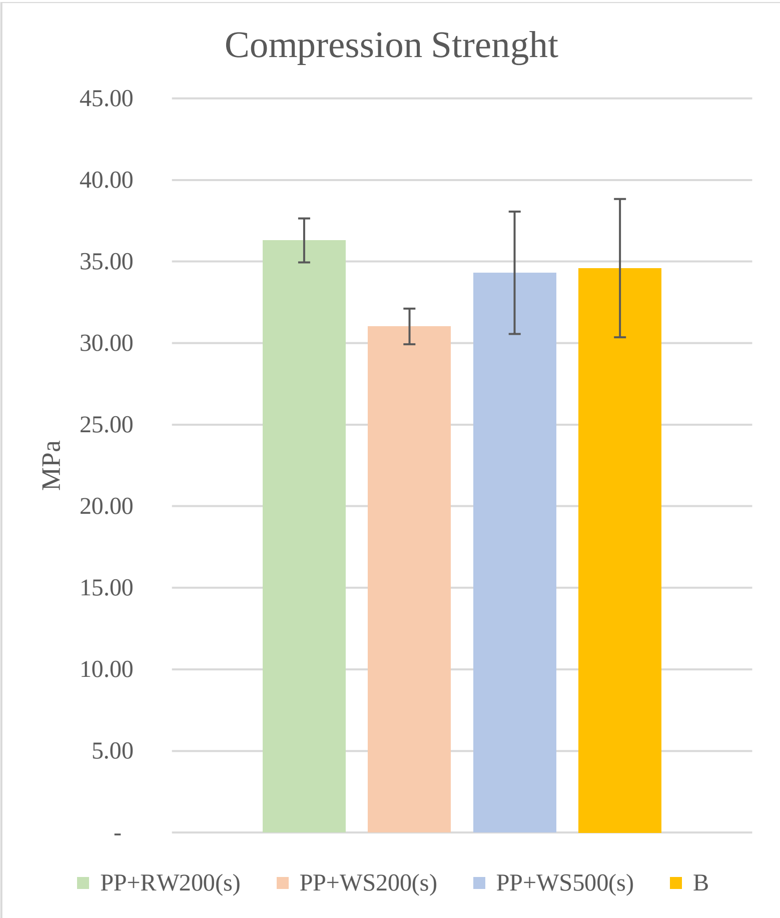


Figure 31. Displays measurements on Material Performance in Compression Tests.

Sample	Average compression strength (MPa)	Standard deviation (MPa)
$PP+RW_{200(s)}$	36.29	1.35
$PP+WS_{200(s)}$	31.02	1.09
$PP+WS_{500(s)}$	34.31	3.75
B	34.59	4.23

4.5 Experimental Result of Particle Size Analysis

The passage discusses the sieving of recycled wood and wood chips, emphasizing the importance of particle size distribution. Experiments were conducted using the granulometry master-sizer 3000 to analyze the particle size distribution of biochar. Discrepancies in the dimensions of received biochar samples were revealed after sieving, highlighting the need for accurate sieving and showing that it improved particle size distribution, ultimately enhancing performance.

However, upon conducting the analysis, discrepancies emerged between the expected and actual particle size distributions. Specifically, the biochar samples provided by the supplier, particularly those designated as 200 μm, did not entirely align with the anticipated size specifications. Despite the expectation that all particles would fall within the designated size range, the analysis revealed that the particle size distribution exceeded the specified threshold, indicating a broader range of particle sizes. This disparity underscores the importance of rigorous quality control measures and accurate sieving techniques to ensure consistent and precise particle size distribution. As a result, subsequent experiments focused on the fractions obtained through sieving, particularly targeting the 200 μm, 100 μm, and 50 μm fractions provided by the supplier.

4.5.1 Recycled Wood

The particle size distribution of recycled wood biochar (figure 30) with a size of 200 μm spans from 1 μm to 300 μm. Similarly, for recycled wood biochar with a size of 100 μm, the particle size distribution ranges from 90 nm to 200 μm, while for biochar with a size of 50 μm, the particle size distribution spans from 80 nm up to 100 μm. These values signify points in the distribution where a certain percentage of particles are either smaller or larger than a specific size. For instance, DX90 at 118 μm indicates that 90% of particles are below this size.

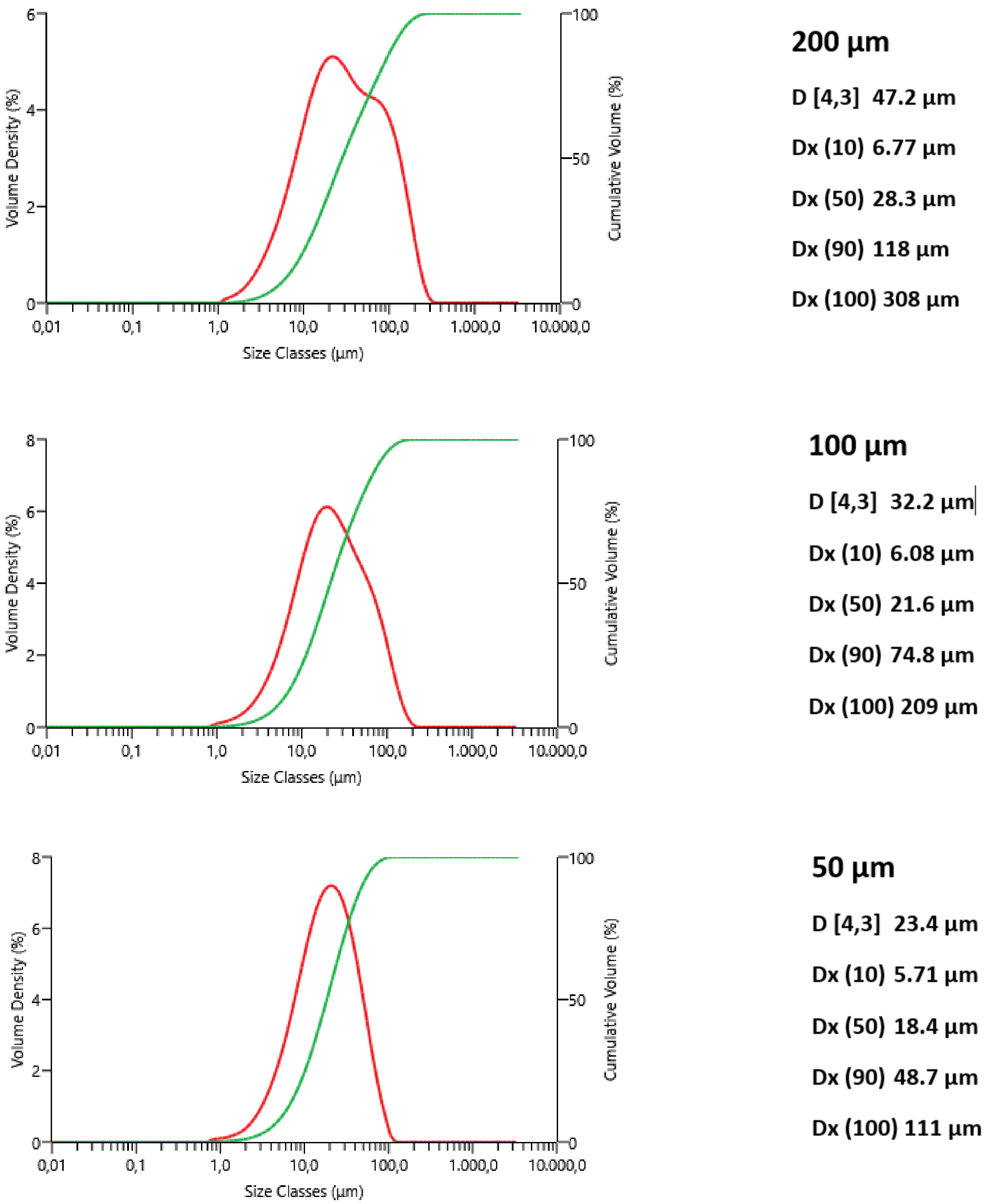
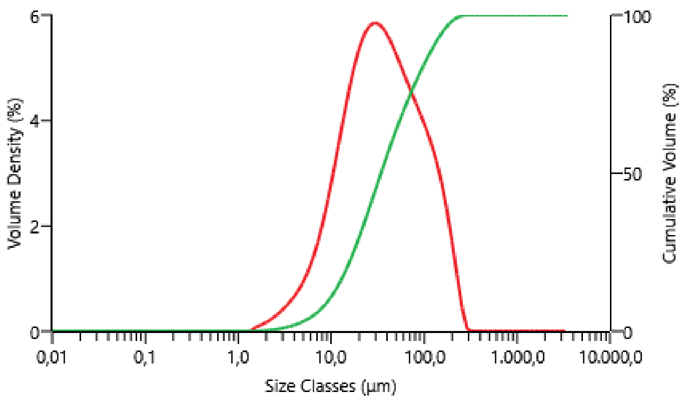


Figure 32. The particle size distributions of the three different samples of recycled wood biochar, specifically at 200 µm, 100 µm, and 50 µm, were analyzed.

4.5.2 Wood Chips

As evident from the curve graphs, the particle size distribution of wood chips at 200 µm spans from 1 µm to 300 µm. Additionally, for wood chips at 100 µm, the particle size distribution ranges from 1 µm to 200 µm, and for wood chips at 50 µm, the particle size distribution spans from 1 µm up to 100 µm. These observations offer insights into the diverse range of particle sizes within each variant of wood chips biochar.



200 µm

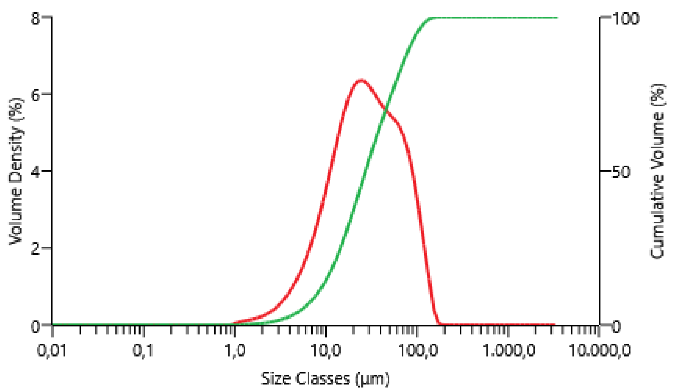
D [4,3] 52.3 µm

Dx (10) 9.48 µm

Dx (50) 34.2 µm

Dx (90) 125 µm

Dx (100) 272 µm



100 µm

D [4,3] 37.2 µm

Dx (10) 7.95 µm

Dx (50) 27.2 µm

Dx (90) 82.7 µm

Dx (100) 163 µm

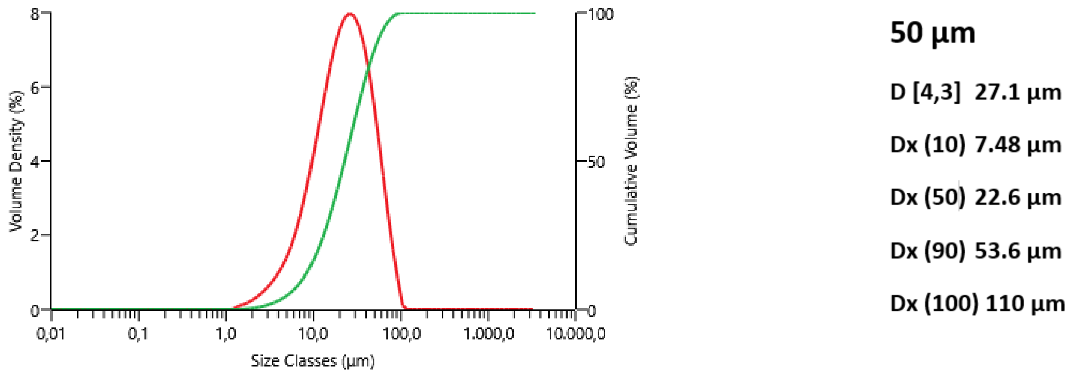


Figure 33. The Particle size distributions were analyzed for three distinct samples of biochar classified under the wood chips category, specifically focusing on sizes of 200 µm, 100 µm, and 50 µm.

4.5.3 Pine Pellet

In the analysis of the pine pellet biochar, the particle size distribution of the 100 µm sample was meticulously examined, corroborating previous analyses conducted in preceding months. The graph illustrates a discernible trend, showcasing a finer particle size distribution for the biochar derived from pine pellets when juxtaposed with recycled wood and wood chips. This distribution ranges from 20 nm to 100 µm, with a segment of the curve extending up to 200 µm.

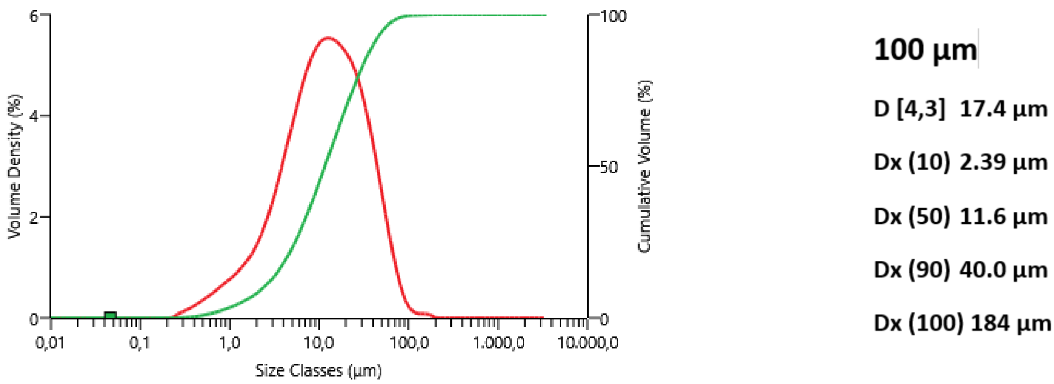


Figure 34. The particle size distributions were analyzed for the pine pellet focusing on a size of 100 µm.

4.6 Experimental Result on Optimizing Material Strength

4.6.1 Integration of Pine Pellet Biochar and Recycled Wood Sieving in Only Cement Substitution

In the final phase of our experimental investigations (figures 35 and 36), attention was directed towards the incorporation of recycled wood biochar and walnut shells, both subjected to meticulous sieving processes. Our analyses yielded compelling results, indicating a marked improvement in mechanical properties, notably flexural and compression strength, in comparison to the blank cement samples lacking biochar additives. Particularly noteworthy was the significant enhancement observed after the sieving of recycled wood biochar. This process has a substantial increase in mechanical strength, surpassing not only the blank but also pine pellet biochar.

In our comprehensive analysis comparing flexural and compression strength within the context of incorporating recycled wood and walnut shells biochar with sieving, distinct patterns emerged, delineating the significance of compression strength over flexural strength. In the realm of flexural strength, the integration of recycled wood and walnut shells biochar, following the sieving process, yielded outcomes lower than those observed for pine pellet biochar and the blank samples. The flexural strength of the biochar-infused specimens, particularly those derived from recycled wood and walnut shells, was notably diminished. Conversely, the scenario was markedly different concerning compression strength. Here, the sieved recycled wood biochar demonstrated the highest levels of strength, surpassing even the pine pellet biochar counterparts. Furthermore, the compression strength exhibited by the walnut shells biochar, although slightly lower than that of pine pellets, remained considerably robust. This dichotomy underscores the paramount importance of compression strength in assessing the efficacy of biochar integration within cementitious matrices, indicating its potential as a key determinant of material performance.

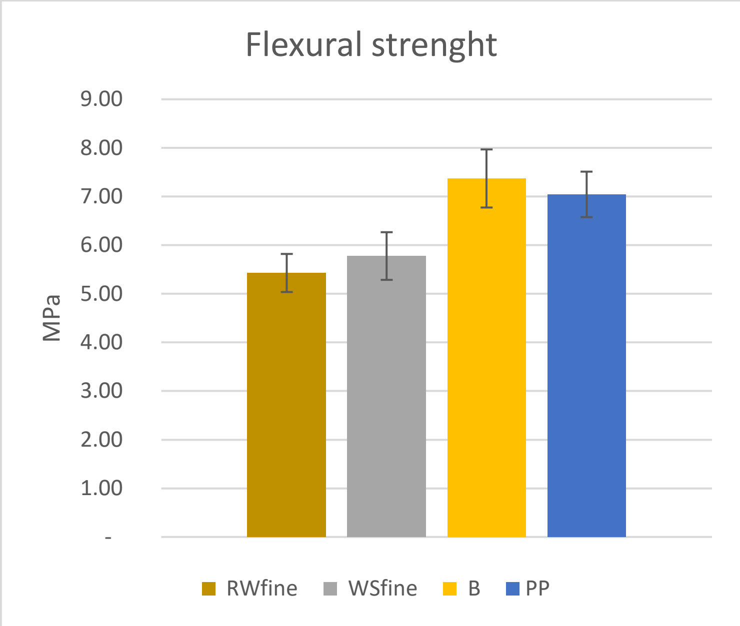


Figure 35. Displays measurements on material performance in flexural strength.

Sample	Average flexural strength (MPa)	Standard deviation (MPa)
RWfine	6.05	0.23
WSfine	5.28	0.11
PP	7.04	0.46
B	7.37	0.60

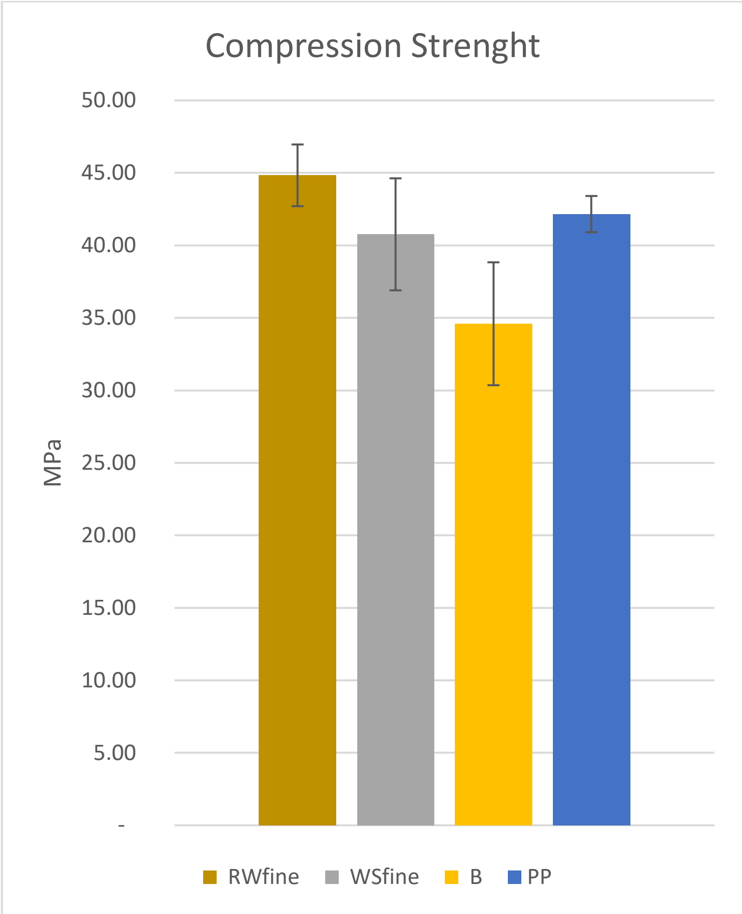


Figure 36. Displays measurements on material performance in compression tests.

Sample	Average compression strength (MPa)	Standard deviation (MPa)
RWfine	44.83	2.13
WSfine	40.76	3.86
PP	42.15	1.24
B	34.59	4.23

Chapter 5

Conclusion

5.1 Recommendation

The conclusion of the study aims to reduce CO_2 emissions in the cement industry without compromising the mechanical properties of mortar and concrete. Essentially, the goal is to find alternative materials to substitute cement in mortar, ensuring that the resulting material maintains its mechanical strength. While simply substituting cement with other materials can reduce CO_2 emissions, the real challenge lies in maintaining mechanical properties. The primary objective is to decrease CO_2 emissions by replacing cement with environmentally friendly alternatives like biochar. However, achieving this without sacrificing the mechanical integrity of the mortar is the most challenging aspect of the study. This means that the mortar should retain its structural integrity, durability, and other mechanical characteristics even after the substitution. Successfully meeting this goal would signify a significant advancement in sustainable construction practices, ensuring both environmental benefits and material performance.

It's crucial to emphasize the connection between increasing mechanical strength and reducing CO_2 emissions. Failure to address both aspects could result in reduced mechanical properties, limiting the application of such materials across various fields such as civilian engineering and architecture. Therefore, it's imperative to develop materials that excel in mechanical strength while minimizing CO_2 emissions. This dual objective is essential for sustainable construction practices, ensuring that buildings and structures not only contribute to environmental preservation but also meet safety, reliability, and longevity standards.

To all Research institutions subjected to the content of this thesis, or construction operational bodies that are required to implement EU directives on carbon neutrality and zero carbonised on the experimental findings and analysis, it is recommended to prioritize two crucial aspects when substituting biochar in cement or mortar which come as follow:

Firstly, careful attention should be paid to the particle size distribution (granulometry) of the biochar. Variations in particle size can significantly influence the mechanical properties and performance of the resulting cementitious materials. Therefore, selecting biochar with an appropriate particle size distribution tailored to the specific application is essential for achieving optimal results.

Secondly, the type of biochar chosen for substitution is equally important. Different types of biochar possess distinct chemical properties and levels of durability, which can impact the overall effectiveness and longevity of the cement or mortar. Therefore, selecting the most suitable type of biochar based on its chemical composition and durability characteristics is crucial for ensuring the desired performance and sustainability outcomes in cementitious materials. By prioritizing these two critical aspects, practitioners can effectively harness the potential of biochar as a sustainable alternative in cement and mortar applications while maximizing its beneficial impacts on both performance and environmental sustainability.

5.2 Future of Studies

In the final chapter of your thesis, discussing the future of studies related to biochar opens up exciting possibilities and areas for further exploration. As biochar continues to gain attention as a sustainable alternative to traditional cement in reducing CO_2 emissions, it's important to consider the potential avenues for future research and development, particularly in the realm of construction materials. As research progresses and our understanding of biochar's properties deepens, we can anticipate the development of production methodologies that are increasingly aligned with architectural and civil engineering requirements. This alignment could lead to the creation of biochar production processes tailored specifically for integration into mortar and concrete manufacturing facilities. By utilizing biochar in construction, we may have the potential to sequester carbon from the atmosphere, further mitigating the environmental impact of the concrete industry.

These future applications highlight the transformative potential of biochar in reducing CO_2 emissions and advancing sustainable practices within the construction sector. As biochar technology continues to evolve, it promises to play a significant role in addressing the environmental challenges associated with traditional construction materials, ultimately contributing to a more sustainable and resilient built environment.

there are some key factors considering of realm of this study which serve to be a turning point in Future that comes as follows: Firstly, expanding upon the current understanding of biochar's properties and its interaction with mortar and concrete materials could lead to optimized formulations and applications. Research could delve deeper into the mechanisms behind how biochar affects the mechanical properties, durability, and long-term performance of construction materials. This could involve conducting comprehensive studies on the chemical, physical, and structural characteristics of biochar and its impact on mortar and concrete at various scales, from microscopic to macroscopic levels.

Moreover, exploring the potential synergies between biochar and other supplementary cementitious materials (SCMs) could lead to novel composite materials with enhanced properties. Investigating the compatibility, reactivity, and performance of biochar when combined with SCMs such as fly ash, slag, or silica fume could unlock new avenues for sustainable construction materials with improved mechanical strength and reduced environmental footprint.

Additionally, considering the broader implications of integrating biochar-based materials into the construction industry is essential. Future studies could explore the life cycle assessment (LCA) of biochar-based construction materials to evaluate their overall environmental impact compared to conventional counterparts. This could involve assessing factors such as energy consumption, resource utilization, greenhouse gas emissions, and waste generation throughout the entire life cycle, from raw material extraction to end-of-life disposal or recycling.

Furthermore, exploring innovative manufacturing techniques for producing biochar-based construction materials could lead to scalable and cost-effective production methods. This could involve investigating advanced processing technologies, such as pyrolysis reactors or pelletization techniques, to optimize biochar production efficiency, quality, and consistency.

References

Alfattani, R., Shah, M. A., Siddiqui, M. I. H., Ali, M. A., & Alnaser, I. A. (2021). Bio-Char Characterization Produced from Walnut Shell Biomass through Slow Pyrolysis: Sustainable for Soil Amendment and an Alternate Bio-Fuel. Energies, 15(1), 1. https://doi.org/10.3390/en15010001

Barbhuiya, S., Bhusan Das, B., & Kanavaris, F. (2024). Biochar-concrete: A comprehensive review of properties, production and sustainability. Case Studies in Construction Materials, 20, e02859. https://doi.org/10.1016/j.cscm.2024.e02859

Bennetts, H., Radford, A., & Williamson, T. (2003). Understanding Sustainable Architecture (0 ed.). Taylor & Francis. https://doi.org/10.4324/9780203217290

Buss, W., Jansson, S., Wurzer, C., & Mašek, O. (2019). Synergies between BECCS and Biochar—Maximizing Carbon Sequestration Potential by Recycling Wood Ash. ACS Sustainable Chemistry & Engineering, 7(4), 4204–4209. https://doi.org/10.1021/acssuschemeng.8b05871

Daugėlaitė, A. (2023). Psychological Acceptance of Sustainable Architecture in Lithuania: A Qualitative Study. Journal of Sustainable Architecture and

Civil Engineering, 32(1), 41–57. https://doi.org/10.5755/j01.sace.32.1.33400

Dong, F., Dai, Q., Jiang, Z., Chen, X., Xu, R., Zhang, Q., An, D., Li, Q., Zhang, T., Andelka, P.-M., Capezzuoli, E., Li, B., & Mors, R. A. (2023). Travertine/tufa resource conservation and sustainable development call for a worldwide initiative. Applied Geochemistry, 148, 105505. https://doi.org/10.1016/j.apgeochem.2022.105505

Gupta, S., Kua, H. W., & Low, C. Y. (2018). Use of biochar as carbon sequestering additive in cement mortar. Cement and Concrete Composites, 87, 110–129. https://doi.org/10.1016/j.cemconcomp.2017.12.009

Hassan, W., Li, Y., Saba, T., Jabbi, F., Wang, B., Cai, A., & Wu, J. (2022). Improved and sustainable agroecosystem, food security and environmental resilience through zero tillage with emphasis on soils of temperate and subtropical climate regions: A review. International Soil and Water Conservation Research, 10(3), 530–545. https://doi.org/10.1016/j.iswcr.2022.01.005

Italian Biochar School—Ichar—Italian Biochar Association. (2023, August 1). https://ichar.org/index.php/scuola-italiana-biochar/

Joseph, P., & Tretsiakova-McNally, S. (2010). Sustainable Non-Metallic Building Materials. Sustainability, 2(2), 400–427. https://doi.org/10.3390/su2020400

Laboy, M., & Fannon, D. (2016). Resilience Theory and Praxis: A Critical Framework for Architecture. Enquiry The ARCC Journal for Architectural Research, 13(1). https://doi.org/10.17831/enq:arcc.v13i2.405

Mejía-Villa, Dr. A., Torres-Guevara, Dr. L. E., Prieto-Sandoval, Dr. V., Cabra, Dr. J., & Jaca, Dr. C. (2023). Training for sustainability through biomimicry and creative problem-solving processes. Thinking Skills and Creativity, 49, 101359. https://doi.org/10.1016/j.tsc.2023.101359

Mori, T., & Tsai, S.-C. (2011). Taguchi Methods: Benefits, Impacts, Mathematics, Statistics and Applications. ASME Press. https://doi.org/10.1115/1.859698

Pipíška, M., Krajčíková, E. K., Hvostik, M., Frišták, V., Ďuriška, L., Černičková, I., Kaňuchová, M., Conte, P., & Soja, G. (2022). Biochar from Wood Chips and Corn Cobs for Adsorption of Thioflavin T and Erythrosine B. Materials, 15(4), 1492. https://doi.org/10.3390/ma15041492

Reza, M. S., Afroze, S., Bakar, M. S. A., Saidur, R., Aslfattahi, N., Taweekun, J., & Azad, A. K. (2020). Biochar characterization of invasive Pennisetum purpureum grass: Effect of pyrolysis temperature. Biochar, 2(2), 239–251. https://doi.org/10.1007/s42773-020-00048-0

Santos, L. B., Striebeck, M. V., Crespi, M. S., Ribeiro, C. A., & De Julio, M. (2015). Characterization of biochar of pine pellet. Journal of Thermal Analysis and Calorimetry, 122(1), 21–32. https://doi.org/10.1007/s10973-015-4740-8

Senadheera, S. S., Gupta, S., Kua, H. W., Hou, D., Kim, S., Tsang, D. C. W., & Ok, Y. S. (2023). Application of biochar in concrete – A review. Cement and Concrete Composites, 143, 105204. https://doi.org/10.1016/j.cemconcomp.2023.105204

Szabados, M., Kakucs, R., Páldy, A., Kotlík, B., Kazmarová, H., Dongiovanni, A., Di Maggio, A., Kozajda, A., Jutraz, A., Kukec, A., Otorepec, P., & Szigeti, T. (2022). Association of parent-reported health symptoms with indoor air quality in primary school buildings – The InAirQ study. Building and Environment, 221, 109339. https://doi.org/10.1016/j.buildenv.2022.109339

Tagliaferro, P. A. (2020). Biochar. IOP Publishing Ltd. https://doi.org/10.1088/978-0-7503-2660-5

Taguchi designs. (n.d.). [Mtbconcept]. Retrieved January 25, 2024, from https://support.minitab.com/en-us/minitab/21/help-and-how-to/statistical-modeling/doe/supporting-topics/taguchi-designs/taguchi-designs/

Tariq, R., Bassam, A., Orozco-del-Castillo, M. G., Ricalde, L. J., & Carvente, O. (2023). Sustainability framework of intelligent social houses with a synergy of double-façade architecture and active air conditioning systems. Energy Conversion and Management, 288, 117120. https://doi.org/10.1016/j.enconman.2023.117120

Van Ellen, L. A., Bridgens, B. N., Burford, N., & Heidrich, O. (2021). Rhythmic Buildings- a framework for sustainable adaptable architecture. Building and Environment, 203, 108068. https://doi.org/10.1016/j.buildenv.2021.108068

Zhou, Y., Qin, S., Verma, S., Sar, T., Sarsaiya, S., Ravindran, B., Liu, T., Sindhu, R., Patel, A. K., Binod, P., Varjani, S., Rani Singhnia, R., Zhang, Z., & Awasthi, M. K. (2021). Production and beneficial impact of biochar for environmental application: A comprehensive review. Bioresource Technology, 337, 125451. https://doi.org/10.1016/j.biortech.2021.125451