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UNIVERSIDADE D
COIMBRA

Sara Maria Santos Soares Dias

Design, development and validation of construction elements made of composite wood waste

PhD thesis in Civil Engineering, Constructions, supervised by Professor António José Barreto Tadeu (University of Coimbra), Professor Jorge Manuel Caliço Lopes de Brito (Instituto Superior Técnico) and Doctor João António Soares Almeida (Itecons), and submitted to the Department of Civil Engineering of the Faculty of Sciences and Technology of the University of Coimbra.

July 2023

Faculty of Sciences and Technology of the University of Coimbra
Department of Civil Engineering

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Nomenclature

3DCP - 3D Concrete Printing

ACQ - Alkaline Copper Quaternary

ADP - Abiotic Depletion Potential

AP - Acidification Potential

ASR - Alkali-Silica Reaction

BAC - Bio-aggregate Concrete

bl - Bond length

CCA - Chromated Copper Arsenate

CDW - Construction and Demolition Waste

CLT - Cross-laminated Timber

EP - Eutrophication Potential

EPS - Expanded Polystyrene

EC2 – Eurocode 2

FRP - Fibre-reinforced Polymer

GWP - Global Warming Potential

HDPE - High-density Polyethylene

HoH - Heat of Hydration

LCA - Life Cycle Assessment

LCIA - Life Cycle Impact Assessment

LDPE - Low-density Polyethylene

LLDPE - Linear and Low-density Polyethylene

LOQ - Limits of Quantification

LVDTs - Linear Variable Differential Transformers

LVL - Laminated Veneer Lumber

MDF - Medium-density Fibreboard

NZEB - Nearly Zero Energy Building

ODP - Ozone Layer Depletion Potential

OPC - Ordinary Portland Cement

OSB - Oriented Strand Board

PET - Polyethylene Terephthalate

PLA - Polylactic Acid

POCP - Photochemical Oxidation Potential

PP - Polypropylene

PS - Polystyrene

PVC - Polyvinyl Chloride

RA - Recycled Aggregate

RAC - Recycled Aggregate Concrete

REF - Reference

RH - Rice Husks

RHA - Rice Husk Ash

SCMs - Supplementary Cementitious Materials

SD - Sawdust

SP - Superplasticiser

SEM - Scanning Electron Microscopy

TIC - Total Ionic Current

TCC - Timber-concrete Composites

UEPG - European Aggregates Association

WC - Wood Chips

WCB - Wood Cement Board

WCC - Wood-cement Concrete

WCP - Wood-cement Paste

WECP - Wood-extractive Cement Paste

WW – Wood Waste

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Abstract

Concrete, a widely utilized construction material, faces significant challenges due to its substantial carbon emissions and depletion of natural resources. To address these issues, various strategies have been explored, including the use of alternative aggregates.

This thesis starts by raising awareness of alternative aggregate' potential and limitations and promoting their widespread adoption in the construction industry. However, adopting alternative aggregates has been hindered by industry professionals' lack of awareness and knowledge regarding their availability and benefits. Concerns about these materials' quality and performance also contribute to the reluctance to adopt them. An essential factor to consider is the vital need to reduce waste generation and enhance the value of products and materials that are categorized as end-of-life or by-products, since incorporating them into concrete is emerging as a viable prospect.

The present study investigates the practical feasibility of utilizing end-of-life treated wood waste to produce lightweight cement and concrete composites. The proper management of this waste has become a pressing environmental concern within the wood industry, posing challenges for many companies. The research begins by characterizing wood waste from different sources to assess the presence of leaching substances and check the relevant physical and chemical properties for cement composite production. A comprehensive experimental study was then conducted to evaluate the feasibility of using concrete mixes containing wood chips and sawdust for structural and non-structural building applications. Several mixes with different types and amounts of wood were produced and evaluated for their durability, and mechanical and physical performance.

The study further investigates the feasibility of incorporating wood waste in structural applications by examining the steel-concrete bond of ordinary steel reinforcement bars and prestressed strands in wood-concrete composites. Full-scale structural elements were made and tested to assess the feasibility of using wood-concrete composites in structural applications. Bending and fatigue tests were performed under static and dynamic loads. The work also evaluated the environmental performance through a life cycle assessment (LCA) study.

In conclusion, this research studies the potential of wood waste as alternative aggregates for concrete and cement composites, addressing environmental concerns and advocating sustainable practices.

Keywords: Alternative aggregates for concrete; Wood waste; Forest by-products; Wood-cement compatibility; Wood-concrete composites; Sustainable materials.

Resumo

O betão, um material de construção amplamente utilizado, enfrenta desafios significativos devido às suas substanciais emissões de carbono e à exaustão de recursos naturais. Para enfrentar esses problemas, várias estratégias, incluindo o uso de agregados alternativos, têm sido exploradas.

Esta tese começa por sensibilizar o leitor para os agregados alternativos, potencial e limitações e promover a sua adoção generalizada na indústria da construção. No entanto, esta adoção tem sido dificultada pela falta de conhecimento e consciência entre os profissionais do setor sobre a sua disponibilidade e benefícios. Preocupações com a qualidade e desempenho desses materiais também contribuem para a relutância em adotá-los. Um fator essencial a considerar é a necessidade de reduzir a geração de resíduos e aumentar o valor de produtos e materiais categorizados como resíduos ou subprodutos, sendo a sua incorporação em betão uma possibilidade viável.

O presente estudo investiga a viabilidade prática da utilização de resíduos de madeira tratada em fim de vida para produzir compósitos de cimento e betão leves. A gestão adequada desses resíduos tornou-se uma preocupação ambiental urgente na indústria da madeira, representando desafios para muitas empresas. O trabalho de pesquisa começa pela caracterização dos resíduos de madeira de diferentes fontes para avaliar a presença de substâncias lixiviantes e investiga as propriedades físicas e químicas relevantes para a produção de compósitos de cimento. Um estudo experimental abrangente foi então realizado para avaliar a viabilidade do uso de misturas de betão contendo estilha de madeira e serradura para aplicações estruturais e não estruturais na construção. Várias misturas com diferentes tipos e quantidade de madeira foram produzidas e avaliadas quanto à sua durabilidade e ao seu desempenho e físico.

O estudo investiga ainda a viabilidade da incorporação de resíduos de madeira em aplicações estruturais, através da avaliação da aderência aço-betão de armaduras ordinárias e de cabos pré-esforçados em compósitos de madeira-betão. Elementos estruturais em escala real foram construídos e testados para avaliar a viabilidade do uso de compósitos de madeira-betão em aplicações estruturais. Foram realizados testes de flexão e fadiga sob cargas estáticas e dinâmicas. Neste trabalho, foi também avaliado o desempenho ambiental através de um estudo de avaliação de ciclo de vida (ACV).

Em conclusão, esta investigação estuda o potencial dos resíduos de madeira como agregados alternativos para betão e compósitos de cimento, abordando preocupações ambientais e defendendo práticas sustentáveis.

Palavras-chave: *Agregados alternativos para betão; Resíduos de madeira; Subprodutos florestais; Compatibilidade madeira-cimento; Compósitos de madeira betão; Materiais sustentáveis.*

CHAPTER 1

INTRODUCTION

1.1. Context and motivation

The projected increase in the global population, particularly in urban areas, will lead to a greater demand for new homes and infrastructure. Concrete, being a fundamental construction material, will be required in large quantities to meet these needs. However, the environmental impact of concrete production cannot be ignored, since Portland cement is a significant contributor to carbon dioxide emissions. Consequently, efforts have been made to develop greener strategies within the concrete industry.

In addition to carbon emissions, the use of natural aggregates in concrete poses further challenges. Quarrying for aggregates involves clearing large land areas, leading to habitat destruction and adverse effects on local wildlife and plants. It disrupts soil balance, causing increased erosion. Moreover, it results in water source contamination from sediment runoff and chemicals used in extraction. Air pollution arises from dust and particulate matter generated during extraction, while large energy consumption and greenhouse gas emissions are associated with the process. Furthermore, the use of aggregates like sand, gravel, and crushed stone depletes non-renewable resources, leading to significant environmental consequences. To address these concerns, alternative approaches that minimize environmental impacts and promote sustainability in concrete production are needed.

Another important aspect is the need to minimize waste production and add value to products and materials considered end-of-life or by-products. Multiple sources contribute to the availability of recycled materials for various purposes, namely as concrete aggregates. These sources comprehend recycled concrete aggregates, end-of-life products such as glass, plastic, and rubber, and agricultural and forest waste, like rice husk, hemp, and wood. Wood waste, which exists in significant volumes with varying degrees of contamination, has the potential to be diverted from incineration, thereby reducing pollution. It represents a valuable source of secondary raw materials. However, wood waste presents a significant challenge from a recycling perspective due to its diverse types, applications, and sources, resulting in a highly heterogeneous material. The disposal of end-of-life treated wood waste has emerged as an environmental predicament within the wood industry, with some companies struggling to find suitable solutions for its management. Recognizing this need, a Portuguese company, Toscca Wood & Solutions, has identified the importance of adding value to contaminated end-of-life wood, specifically to their commercialized wood posts for agricultural use (vineyards and orchards). In response to this demand, a research project called PROCK was initiated, ultimately leading to this thesis work's development. The project addressed the challenges associated with contaminated end-of-life wood posts and explored ways to enhance their value. By incorporating wood waste into concrete, it is possible to effectively divert it from traditional disposal methods and create a sustainable alternative that adds value to the wood waste and the concrete industry.

Prefabricated construction methods are particularly advantageous, as they offer faster construction, improved quality control, reduced resource and energy consumption, and decreased workplace accidents. Hence, it is crucial to promote construction systems that balance economic, social, and environmental aspects, contributing to sustainable development. Implementing prefabrication and industrialized processes in the construction industry is urgently needed, with a preference for more sustainable materials. By utilizing wood waste as aggregates, it is possible to reduce the overall weight of concrete and, thus, minimize the transmitted loads to the structure. However, it is essential to consider the trade-off between strength and density. Although using lighter aggregates, such as wood waste, can improve density and thermal behaviour, it may have implications on the strength and durability of concrete.

While wood waste is already utilized in cement materials, its application in structural contexts is not yet widespread. An additional research gap is the limited utilization of wood-cement composites derived from chemically treated end-of-life wood. Most existing studies primarily concentrate on utilizing raw materials obtained from sawmills. It is crucial to assess whether these composites, using treated end-of-life wood, exhibit comparable environmental performance to regular concrete. Although the life cycle assessment (LCA) does not explicitly consider that the wood waste is treated, it is imperative to examine this aspect. This study demonstrates that chemically treated end-of-life wood can be successfully employed as aggregates in wood-cement composites without compromising performance, both mechanical and environmental.

In summary, the primary objective of this research is to address environmental concerns related to concrete production by utilizing recycled end-of-life wood waste as aggregates. Developing new construction elements, particularly through prefabrication techniques, could offer promising solutions to enhance sustainability in the construction industry. By expanding the use of wood waste in structural applications and incorporating treated end-of-life wood, this research contributes to a more environmental-friendly and resource-efficient approach to concrete production.

1.2. Objectives

The primary objective of this thesis is to develop and study concrete using recycled wood wastes. It includes the composite materials' development and characterisation and the construction elements' design and study. The following specific objectives were set out for the research:

- Identify alternative aggregates for concrete and provide examples of their successful application in construction projects and products;
- Identify potential sources of wood wastes (such as sawmills and end-of-life treated wood) and characterise them physically and chemically;
- Formulate compositions for new cementitious composites by investigating the inhibitory effect of water-soluble wood extractives on cement hydration, setting, and hardening;
- Assess the compatibility of wood wastes and cement by monitoring the curing process, measuring the heat of hydration, and assessing the compressive strength of the resulting composites;
- Develop concrete compositions with wood waste incorporation and characterise the properties, including their mechanical, physical, and durability characteristics;
- Assess the structural applicability of these composites by studying the adhesion between concrete and reinforcement;
- Assess the structural applicability by testing real-size structural elements such as reinforced beams and columns under static and dynamic load;

- Conduct a life cycle assessment (LCA) to evaluate the developed structural elements' environmental impacts and compare them to conventional alternatives.

By accomplishing these objectives, this thesis intends to contribute to advancing sustainable construction practices by utilizing recycled wood waste and developing innovative prefabricated construction solutions.

1.3. Thesis structure

This thesis is organized in a manuscript format where the main chapters are written as standalone articles between a general introduction (Chapter 1) and a conclusion (Chapter 7). Every chapter contains a self-contained introduction, a detailed description of materials, samples, and methodologies, an in-depth discussion of the results, conclusive findings, and comprehensive references. While some overlapping of information may occur, meticulous attention has been paid to emphasize each section's unique aspects and specificities.

Chapter 2 provides a literature review that establishes the context and motivation for the need to study alternative aggregates for concrete. The review examines three main groups of materials: construction and demolition waste (CDW), end-of-life industrial wastes, and forest/agricultural wastes. These materials were selected based on their potential to replace effectively natural aggregates in concrete production and their significant contribution to waste generation. By finding new applications for these materials, the environmental impact of concrete can be reduced, fostering circularity. The chapter also highlights various construction projects that have already incorporated alternative aggregates, demonstrating their ability to meet conventional concrete's requirements and offer better solutions for specific applications. This thesis focuses on one particular alternative aggregate, wood waste, to promote the widespread use of alternative aggregates. As identified in the review, wood waste is a relatively underutilized material, particularly in structural applications. The examples found included prefabricated solutions like blocks, material for 3D printing, and loose aggregate, mainly taking advantage only of their good thermal and acoustic performance.

The disposal of preservative-treated wood waste raises significant environmental concerns and serves as a driving force for researching new recycling strategies. Chapter 3 investigates the feasibility of using end-of-life treated wood for producing lightweight cement composites. To achieve this objective, wood waste samples from four different sources undergo characterization regarding relevant chemical and physical properties. Cement pastes containing either wood extractives or wood particles are then used to assess the compatibility of wood and cement based on hydration heat, and mechanical properties. Additional tests explore the potential benefits of extracting or chemically treating wood particles before incorporating them into the cement paste. Finally, a concrete mix incorporating selected wood particles is produced to preliminarily examine the impact of wood waste on the mechanical properties of a reference concrete.

The subsequent phase of the research investigates the mechanical, physical, and durability performance of wood concrete composites, including wood chips and sawdust. Chapter 4 presents several defined mixes produced and evaluated for their mechanical, physical, and durability characteristics. Following the mechanical characterization of all mixes, the optimized mixes for durability and hygrothermal performance tests are selected based on the following criteria: maximizing wood incorporation, minimizing density, and ensuring a compressive strength above a predefined value of 25 MPa. The second section of this chapter focuses on the experimental results and discussion, primarily emphasizing the mechanical performance crucial for building applications, the durability assessment important for evaluating potential premature aging caused by the presence of wood, and the hygrothermal behaviour to assess the additional benefits of the formulated compounds. It should be noted that while all mixes undergo mechanical assessment, only two optimized mixes are selected to proceed with hygrothermal and durability characterization. Further exploration of wood wastes included investigating their potential for acoustic applications. Specifically, two variations of cement mixes without mineral aggregates and two types of loose-laid materials were developed and tested as acoustical insulation layers for slabs with varying thicknesses.

Chapter 5 contributes to the widespread application of these wood-waste concrete in structural applications by investigating the steel-concrete bond of ordinary steel reinforcement bars and prestressed strands. The chapter evaluates the bond strength through pull-out tests, which depend largely on the bond length and the adhesion between this particular type of concrete (with wood waste) and the steel bars and strands. The study determines the bond strength of ordinary reinforcement steel bars (ϕ6 and ϕ10) and two-wire strands (ϕ4.5) by employing different bond lengths: 5 d (based on EN 10080:2005) and the stranding pitch of 400 mm (based on ASTM A1081M-21). Another significant consideration is the potential for excessive cracking caused by the creep phenomenon. Creep effects are particularly relevant for prestressed structures due to their slenderness and high flexibility. Creep tests are also performed for strands, measuring the displacement continuously for 120 hours under a constant applied force to determine the influence of wood addition on concrete creep. Full-scale structural elements, including bar-reinforced beams (ϕ6 and ϕ10) and prestressed columns (ϕ4.5), are constructed and tested to assess the feasibility of using these composites in real applications such as ordinary cast-in-situ elements and prefabricated linear elements used in houses, small buildings/constructions, fences, and other agricultural facilities. Bending tests are employed to examine the behaviour of the beams and columns under static bending load. In addition to these static tests to failure, dynamic bending tests are also conducted.

Chapter 6 explores the feasibility of using the developed composites in structural applications by studying their environmental performance. A life cycle assessment (LCA) study incorporating data from prototypes and relevant bibliographic sources is presented. The primary objective of the LCA study is to quantitatively evaluate the environmental performance of the wood-concrete composite posts investigated in the previous chapter and compare them with two reference scenarios, a concrete and a wood post. The life cycle model for assessment focuses on the stages of raw material extraction, processing, transport to the factory, and production, following a cradle-to-gate approach.

CHAPTER 2

LITERATURE REVIEW

2.1. Introduction

Concrete is an important material for constructing buildings and infrastructures and is sometimes irreplaceable. It is the most consumed material after water and the most consumed man-made material in the world [1], with a consumption rate of 14 billion m^3 in 2020 [2]. Its consumption is not likely to decrease in the coming years; on the contrary, with the population's predicted to increase and the consequent need for infrastructure, the demand for concrete is expected to increase yearly.

There are concerns about the environmental impact of concrete production, particularly in terms of natural resource depletion and high carbon dioxide emissions [3]. Portland cement is the concrete constituent that contributes the most to carbon dioxide emission, and that is why it is the focus of strategies for creating a greener concrete industry [4]. Nevertheless, natural aggregates are not renewable and their exploitation causes significant environmental impacts [5]. Removal of land for quarrying has been associated with biodiversity reduction, noise pollution and health problems mainly due to soil erosion and release of dust into the air and water [6].

According to the European Aggregates Association (UEPG) [7], the tendency in the last years has been to increase the share of recycled and re-use aggregates, although it is still a small fraction.

In 2021, Europe's share of recycled and re-use aggregates was 9.3%, while crushed rock, sand, and gravel was 46.9% and 39.7%, respectively [8]. The Global Aggregates Information Network (GAIN), a coalition of aggregates associations worldwide, accounted for global aggregates production of 44 billion tonnes in 2019 [9]. China is responsible for 50% of the worldwide output. Continued population and economic growth, particularly in Asia, will likely drive global demand for aggregates to 50-55 billion tonnes by 2030 [9]. This increasing demand forces the replacement of natural aggregates with alternative ones. Since the aggregate deficit coincides with increasing waste production, using waste materials and by-products as aggregates is a possible solution to minimize the environmental impact of the concrete industry [5]. In view of this, research has been developed to study the use of waste and recycled materials in concrete mixes, but these approaches have not been implemented at a large scale.

This chapter examines three groups of alternative aggregates (construction and demolition waste (CDW), end-of-life manufactured materials wastes, and forest/agricultural wastes), highlighting their potential benefits and providing examples of their successful application in construction projects and products. The selection of materials for this review was based on several aspects. Firstly, there is strong evidence in the literature that they can effectively replace natural aggregates in concrete production. Secondly, they are substantial in terms of waste stream, and their use in concrete applications could make a noteworthy contribution to the circularity economy. Finally, these waste materials are often not used in the production of more valuable products.

By exploring the use of these alternative aggregates, the aim of this work is to present an analysis of their properties and potential applications, contributing to a broader implementation of sustainable construction practices. While a wider range of materials from each group was considered, only those with more published research and applications were investigated deeply. Some projects that have already been constructed are also presented to emphasize the feasibility of using these alternative aggregates in specific concrete applications.

2.2. Alternative aggregates for concrete

Aggregates are usually divided into coarse and fine aggregates, with the latter having a diameter of less than 4 mm. The different sizes and qualities of aggregates determine the concrete performance since they affect workability, mechanical performance, and durability. It is also known that aggregates play an important role in defining concrete's compressive strength, one of the most important features of structural concrete.

The following subsections will introduce the three groups of materials selected for this review (CDW, end-of-life manufactured materials wastes, and forest/agricultural wastes), highlighting the advantages and limitations of different waste materials within each one, and identifying, when relevant, the need for further study. Note that a number of other alternative aggregates could have been selected, e.g. from marine sources [10–13], metallurgical waste [14–18], ceramic waste [19–23], and artificial aggregates [24–27], but those are beyond the scope of this work. A final subsection discusses and compares the mechanical and physical features of the composites.

2.2.1.Construction and demolition waste

Construction and demolition waste materials are essentially anything produced during the construction, renovation, or demolition process that is no longer viable for use [28] (Figure 2.1).

Figure 2.1: CDW sample.

According to 2018 data [29], China was the country that produced the largest absolute amount of CDW in (million tonnes) in the world (2360), followed by the United States of America (600) and India (530). However, if the analysis takes into account the population size (tonne/capita), which for some purposes is a more realistic comparison, the European countries lead the ranking, with the Netherlands (5.9), Austria (5.5), and France (3.6) as the largest producers. The United States of America (1.8) and China (1.7) are the first non-European countries in the ranking. With the population increasing, this problem tends to aggravate.

Some authors report that approximately 35% of the global CDW was landfilled [30–33], although this percentage could be higher, since large countries like China have very low recycling ratios (about 5%) [34]. Until 2010, some European Union countries had a recovery ratio of CDW below 10% [35]; as a consequence, the European Commission identified CDW as a priority waste stream [35]. According to the European Commission [35], the European Union countries presented a recovery ratio of CDW of 89% in 2020, achieving the target of 70% of reuse and recycling set for 2020. However, the recovery data of the mineral CDW considers not only re-use and recycling but also backfilling operations, which could be misleading. In fact, this milestone was achieved mainly by backfilling and low-value recovery applications, reducing the potential to move towards genuinely circular waste management [36]. For instance, Portugal's low recycling ratio and heavy reliance on landfills for dealing with CDW have resulted in a negative waste hierarchy index of 39%. This disqualifies Portugal from being classified as a country that effectively implements the waste hierarchy [37].

The EU Directives enforced the use of coarse recycled aggregates from CDW in the production of concrete, but this practice is still quite limited. Marinho et al. [37] summarized some factors that hinder the reuse and recycling of CDW. For instance, these include lower quality of products with recycled content, cultural resistance to products or projects that include CDW, lack of encouragement and support from government regarding CDW reuse and recycling, and lack of balance between demand and supply in the reuse and recycling market, among others. The relevance of each reason can differ from region to region, but it is necessary to discuss measures to overcome those causes. Pacheco and de Brito [38] state that legislation and project requirements will follow the need for circularity, and coarse recycled aggregates will be part of the concrete industry in the future. CDW plants must be prepared to respond to this need [38]. The market of recycled aggregate concrete (RAC) depends on the assurance of a continuous supply of RAC to the concrete industry and the fulfilment of the quality requirements. Several authors [38–43] have presented approaches to improve the quality of RAC and mitigate their heterogeneity. However, little development has been observed in existing standards and specifications concerning the effect of recycled aggregates (RA) on the properties of concrete [44].

The first standards presenting methodologies regarding RAC appeared in the late 1970s in Japan, the USA, and a few European countries [45]. Nowadays, Japanese standards class RAC for concrete into three levels based on the intended use [46–48]: Class L (low-quality, used for low requirements of strength and durability), Class M (medium-quality, mainly used where drying shrinkage and freezing and thawing action are not relevant), and Class H (high-quality, obtained by advanced treatments, without restriction on its use). RILEM [49] also classes RAC into three levels (types 1, 2 ,and 3): RAC obtained from masonry waste, RAC acquired from concrete waste, and a combination of RAC and natural aggregates (NA), respectively. De Brito et al. [44] believe that the correct method for using RA is to class and incorporate them using a performance-based approach, i.e. by imposing limits on physical properties and limiting their incorporation [50].

According to bibliometric research (from a total of 1465 works) by Sandanayake et al. [51], in the last ten years, fly ash and recycled aggregate used in concrete production were the two main waste materials that were extensively researched. Despite this huge amount of knowledge gathered over the years, there is still work to be done. Some authors [29,38,52,53] have recently pointed out topics of future research, such as the development of methodologies for the expedited estimation of the environmental impacts, the development of greener treatment methods, the use of nanoparticles and nano-modified compositions to improve specific properties, approaches for controlling alkali–silica reactions and leaching of substances, and innovative crushing processes capable of preventing the release of contaminants into the air and water.

In conclusion, if backfilling is no longer possible, high levels of segregation and advanced plants will be needed to increase the recycling ratio of CDW. The future lies in the concrete industry, especially concrete plants, progressing and investing on quality RAC production.

2.2.2.End-of life manufactured materials

The environmental problem demands new end-of-life materials applications to contribute to a more circular economy. According to Ferdous et al. [54], 75% of tyres, 55% of plastics, and 75% of glass wastes are currently disposed of in landfills around the world, contributing to a substantial environmental burden. The use of these end-of-life materials in new construction products, integrated specifically into concrete and other cement composites, has been investigated. Figure 2.2 shows samples of these wastes.

a) b) c)

Figure 2.2: Samples of end-of-life manufactured materials with potential as alternative materials for natural aggregates: a) Tyre rubber; b) Glass; c) Plastic.

Tyres rubber

Waste tyres are not biodegradable. Globally, an estimated 1.5 billion are generated annually [55]. Four huge environmental concerns are linked to the accumulation of this waste: severe tyre fires with heavily toxic smoke, leachates containing harmful and toxic chemical compounds, breeding grounds for pest species, and land use [55]. Considering the abundance of rubber waste generated and the risks related to stockpiling, incorporating this waste in concrete has proved to be a feasible option. Tyre rubber aggregates (Figure 2.2a)) are obtained from two technologies, one being mechanical grinding at ambient temperature to produce chipped rubber (to replace coarse aggregates), and the other being cryogenic grinding at a temperature below the glass transition temperature, yielding rubber crumbs (to replace fine aggregate) [56]. The mixes with rubber crumbs are much more common.

Literature shows that using rubber instead of natural aggregates could cause a decrease in workability [57], which is probably related to the higher water absorption of rubber compared to mineral aggregates [58], and a reduction of mechanical properties with emphasis on compressive strength. Girskas and Nagrockiene [59] show that substituting 20 wt. % of fine aggregate with crumb rubber causes the compressive strength to drop 68%. Other studies corroborate this conclusion, showing that using rubber in the mix significantly reduces the compressive strength [60–63]. However, this reduction can be overcome with pre-treatments [63–66]. For instance, Onuaguluchi and Panesar [66] found significant improvement in compressive and tensile strengths in mixes containing coated crumb rubber and silica fume. These mixes outperform the reference mix at 5% and 10% fine aggregate replacement due to the interaction between the limestone powder of the coating and the silica fume. Other studies highlight the increase in drying shrinkage and water absorption chloride ion penetration depth [58,60,67,68].

Nevertheless, at the same time, the use of rubber as a natural aggregate substitute can also show superior properties to those of conventional concrete. Those advantages are expected to emerge on applications that benefit from lower matrix density [69], higher ductility and toughness [70,71], higher damping ratio [72], improved impact load resistance [73], higher thermal and sound insulation [74,75], increased strain capacity and improved energy absorption [58,76].

In spite of all the research, the practical use of rubber concrete in real constructions seems too little. Youssf et al. [76] consider the understanding of the performance of these composites in real-world structures to be essential. These researchers replicated a real-world situation, studying two large-scale reinforced concrete residential footing slabs of 4 m × 8 m each, one made of crumb rubber concrete and the other of conventional concrete. The mixes were provided by a commercial ready-mix company that did not report any batching, delivery, or mixing concerns. The construction was undertaken by an experienced contractor who noticed no difference concerning pumping, screeding, or finishing of the concrete surface using a power trowel. This work was important to prove that rubber concrete is potentially viable and a promising alternative to conventional concrete in the concrete residential market as well as in other applications. More recently, other concrete construction elements with rubber incorporated, developed under laboratory conditions, have been further studied [77–81].

This gap between research and the market reveals certain barriers that limit the application of rubberized concrete in the construction industry. Kara De Maeijer et al. [82] identified the four major obstacles to applying these composites in the concrete industry: the cost of crumb rubber recycling, the recyclability of rubberized concrete, poorer mechanical properties, and insufficient research about leaching criteria and ecotoxicological risks. Regarding this last topic, Mohajerani et al. [83] warned about the fact that products on the market that incorporate waste tyre rubber have not been subjected to any form of testing. They recommended practical procedures and guidelines to be developed to enable the incorporation of waste tyre rubber materials in construction on an industrial scale.

Glass

Another problematic waste is glass. According to Ferdous et al. [54], 130 million tonnes of glass waste are generated every year around the world. However, the glass is 100% recyclable and can be recycled indefinitely. Apparently, only 1/5 of it is recycled. Crushed glass (Figure 2.2b)) is being used in concrete to replace natural coarse and fine aggregates [84,85], and also as a binder [86,87]. The process to obtain the aggregates includes grinding and crushing to the proper size, which is a significantly less energy-consuming process than recycling glass to obtain new glass [88]. Also, waste glass as aggregates in concrete could be an alternative for mixed colour glass. Note that coloured glass can only be recycled into glass of the original colour [84].

Glass with a lower density than natural sand tends to reduce slump, while high-density glass increases slump [54]. In addition, the density of concrete will be reduced with increased glass content if the density is lower than natural sand. Lower fresh and dry densities were found with the increasing replacement ratios of waste glass [84]. Ting et al. [89–91] investigated the possibility of using recycled glass as fine aggregate for 3D concrete printing applications (3DCP). The authors [89] found that the flow properties of the mixes with glass waste are better than those of sand concrete. The improved flow properties (lower plastic viscosity and lower dynamic yield stress) of recycled glass mixes compared to river sand ones were attributed to several possible factors: the reduced water absorption capacity of glass leading to excess water in the mix, the smoothness of the glass surface particles, and the lower presence of fines in glass (higher fines content corresponds to a larger specific surface area). Further studies [90] were conducted and show that the dynamic yield stress and plastic viscosity increase as the recycled glass content increases, primarily due to the angular shape of the recycled glass particles, possibly impeding flow. It has been observed that material pump ability also decreases as the dynamic yield stress of the mixes increases with higher recycled glass content. As an alternative to sand, several studies show different conclusions about the effect of the incorporation of waste glass on mechanical properties. Some studies claim that sand substitution improves compressive strength [92–94]. A higher strength is generally explained by the higher aluminium and silica dissolution resulting in an efficient pozzolanic reaction and curing age [95]. Some studies report the opposite [96,97]. In this case, the reduction in bonding strength between the waste glass and the cement paste is justified by the high smoothness of the waste glass, which results in cracks and poor adherence between waste glass and cement matrix [84,98].

Qaidi et al. [98] report that, as the content of waste glass increases, the proportion of cracks and voids increases in the concrete's matrix. Proportions exceeding 30% of substitution were found to adversely affect the compressive strength [94]. Du and Tan [99], meanwhile, found that concrete containing up to 100% glass sand achieved similar compressive strength to that of the control, and at 90 days, the compressive strength had even increased. The optimal replacement level of natural sand by the glass is not consensual either. Ferdous et al. [54] claim that the optimal replacement was 45%, but others have reported up to 15% [100], about 20% [85,98] and 30% [94]. According to Ismail and Al-Hashmi, [85], the best 28-day compressive strength value was obtained from a concrete mix made with 20% waste glass fine aggregate, which led to an increase in compressive strength compared to the control reference.

Regarding other mechanical properties, lack of consensus remains. Some studies report that using waste glass aggregates reduced flexural strength [97,101]. Other investigations show the opposite, namely that substitution of fine aggregates improves flexural strength [85,102,103]. Concerning durability, Kim et al. [97] found that, as the mixing ratio of waste glass increased, chloride ion penetration resistance, sulphate attack resistance, and freezing and thawing resistance were all better in the concrete containing waste glass than in normal concrete. Bisht and Ramana [102] observed that water absorption and water permeability increases with the increment of waste glass in concrete. Abdallah and Fan [103] also noticed a clear decrease in water absorption with an increased waste glass aggregate ratio.

Regardless of the inconsistency found in the literature, the only significant limitation of concrete containing glass aggregates is the vulnerability to alkali-silica reaction (ASR) [88]. The reaction between the alkali from cement and the silica from glass creates a gel that swells and causes hydrostatic pressure when exposed to moisture, consequently leading to cracking [54,104,105]. Research has shown that glass colour and size profoundly influence ASR expansion [106,107]. Topçu et al. [107] analysed white, green, and brown bottle wastes in terms of ASR. They concluded that white glass aggregate causes the greatest expansion and also that the expansion rate by ASR increases with the higher content of the waste glass. Possibilities to mitigate ASR in concrete with glass have been investigated [108], like the incorporation of a suitable pozzolanic material [107,109,110], the reduction of alkali-silica agents and an increase in the water cement ratio [88]. However, some authors [111] say that in-depth research is required to understand the risks and to develop mitigating strategies to prevent an alkali-silica reaction in concrete containing glass waste, including long-term testing or/and numerical methods [112].

Waste glass has the potential to be utilized in concrete [84], but more research needs to be undertaken in the mix design to minimize the likelihood of the alkali-silica reaction from occurring while optimizing the pozzolanic activity produced from the glass.

Plastic

Plastic is the other waste considered an important alternative for mineral aggregate in concrete. The environmental problem of plastic is relatively well-known. Most plastics are not biodegradable and are chemically unreactive in the natural environment; hence, such polymeric products persist for decades, even for centuries [113]. In the last two decades, the production of plastics worldwide doubled. In 2020, the production of plastic in the world was about 367 million tonnes (not including recycled plastics production) [114]. Asia is the largest producer of plastics (more than half), but Europe has an important slice too (about 16 %) [114]. Gu and Ozbakkaloglu [113] presented data regarding the treatment of post-consumer plastics in 2012 by EU-27+2. At that time, 38% was sent to landfill, 36% was used for energy recovery, and only 26% was recycled. The data for 2020 [114] show a positive change. About 23% was sent to landfill, 42% was used for energy recovery, and 35% was recycled. The need to increase the last percentage creates the opportunity for using plastic materials in concrete production. A large number of studies reporting the behaviour of concrete containing plastic waste have been published [113,115,116]. Researchers studied waste plastics as aggregates in concrete (to replace natural aggregates) [117,118] and as fibres (as reinforcement) [119,120]. However, fibres are not within the scope of this work.

Plastics are a broad group of polymeric materials with very different properties according to the type of polymer. The literature reports a variety of types and origins of plastics used as aggregates in concrete - polyethylene terephthalate (PET), high-density polyethylene (HDPE), expanded polystyrene (EPS), polyvinyl chloride (PVC), low-density polyethylene/linear and low-density polyethylene (LDPE/LLDPE), polylactic acid (PLA), polypropylene (PP), polystyrene (PS), etc. The recycling methods also vary and usually involve direct mechanical recycling or melting. The former is an efficient and economical way to obtain recycled plastic aggregates and fibres, yielding materials with a more uniform size and properties [113]. The bulk density of plastic aggregates also differs based on the recycling method. The direct mechanical recycling method typically leads to a relatively low bulk density, whereas the melting process leads to a higher bulk density [113].

Most of the research agrees that concrete's fresh and hardened properties are mainly negatively affected by the incorporation of plastic aggregates. Saikia and de Brito [121] drew some conclusions in a review paper about how incorporating plastic aggregate diminishes concrete's various strength properties. The insufficient binding strength between the surface of plastic particles and cement paste is the fundamental reason for the performance's decrement. The authors pointed out that the variations found in the compressive strength values were mainly because of the differences in the type of plastic waste used, its size, and shape.

Tota-Maharaj et al. [122] investigated the use of a plastic (polymethyl methacrylate) as a fine aggregate replacement. The results show that increasing the ratios used (5, 10, and 15 wt. %) reduces workability and compressive strength (from 8% to 15%). This work also comprises steel-concrete bond assessment, an important feature for reinforced concrete applications. The results show that bond strength decreased by 8% to 32%.

The possibility of integrating electrical and electronic plastic waste in concrete materials has recently been investigated [123–127]. The also called E-plastic is defined, according to [128], as waste derived from electrical and electronic equipment, consumer electronics, and small and large household appliances. This kind of waste is heterogeneous and difficult to recycle [127]. Nwaubani and Parsons [127] present the results of an experimental study to assess the properties, durability, and microstructure of concrete incorporating different types of electrical and electronic plastic waste as partial replacement of fine and coarse natural aggregates. The results show lower mechanical and durability performance of concrete with E-plastic. Other studies [129,130] presented the same conclusions regarding E-plastic incorporation in concrete. Needhidasan and Sai [125] used fly ash as an addition and E-waste as partial replacement of coarse aggregate, and the results showed higher strength of concrete compared with the conventional product. They concluded that 20% of E-plastic waste could be used as coarse aggregate substitution without compromising performance.

Future studies, such as the long-term behaviour of plastic materials in concrete, environmental consequences of recycling concrete containing plastics after its service cycle, and financial benefits of these recovered plastic aggregates, are identified as needed research topics by some authors [113], [131]. The need for guidelines or restrictions for using plastic waste in construction materials is also a scientific concern.

2.2.3. Forest and agricultural waste

Agricultural waste is very difficult to estimate and, in some cases, the low price of such waste materials means that their economic value is less than the cost of gathering, transporting, and processing them for advantageous use [132]. Some agricultural waste that is characterised as having low inorganics and high carbon is incinerated for energy production, and the ashes are used to produce excellent materials for construction and industry. Although ashes are not the only way to add value to this type of waste, substituting the mineral aggregates in concrete is a viable option too [5,133,134].

In the last decade, increasing efforts have been made to explore the possibility of using agricultural wastes (crop-based aggregates) as an aggregate substitute in concrete or cement-based materials and bio-aggregate concrete (BAC) [135]. Such waste materials, include coconut shell [133,136–139], oil palm shell [140–145], corncob [146–148], straw [149–151], bamboo [152,153], and cork [154–157], among others. Some forest and agricultural wastes or by-products have been studied more than others in terms of integration in cement-based materials, partly depending on the abundance and predictable compatibility. Based on this, the present review selected rice husk, hemp, and wood (Figure 2.3). It is known that the mechanical properties of these plant-based concrete mixes could be considered the main weak point. However, integrating these materials into concrete could improve several physical properties, particularly those related to acoustic and thermal behaviour.

a) b) c)

Figure 2.3: Samples of agricultural waste with potential as alternative materials for natural aggregates: a) Rice husk; b) Wood; c) Hemp.

Rice husk

In 2020, rice production residues reached 497.2 million tonnes globally [158], which is expected to increase yearly as the population grows. Around 90% of the world's rice is produced and consumed in Asia [159]. Rice husks (RH), also called rice hulls, are coats of seeds or grains of rice. Each kg of milled white rice results in roughly 0.28 kg of rice husk as a by-product [160]. Rice husk does not have nutritional purposes and is composed of cellulose, lignin, inorganic matter, and high levels of silica [161]. Due to the large amount generated, different possibilities for using it have been studied [162–164].

Nevertheless, the typical endpoint destination of this material is composting or energy generation in industrial boilers [158]. Burning rice husks generates another residue product, rice husk ash (RHA). This ash is a pozzolanic material with more than 75 % of silica (by weight) [165] and it has been widely studied and used as cement substitute [161]. Although RHA is much more common in concrete as a cement alternative, RH has also been investigated as aggregate for concrete and cement composites. Some studies even combine both uses [158].

The presence of RH diminishes the mechanical performance of cementitious composites [159,166–168]. Among the factors that influence RH concrete's mechanical performance is the bio-aggregate's low specific weight [158]. Furthermore, roughness, size, and shape can potentially interfere with the stiffness of this bio-concrete [158,169]. Marques et al. [168] highlighted the fact that previously soaking the husks significantly influences the performance of cement-based composites. Chabannes et al. [170] developed concrete using RH for the same application as hemp concrete. When compared with hemp concrete, RH concrete showed lower mechanical performance but better thermal insulation, with a thermal conductivity ranging from about 0.10 to 0.14 W/mK. The authors claim that RH concrete is suitable for use as an eco-friendly insulating material for filling walls. Marques et al. [171] evaluated the performance of cement-based composites made with RH intended to be used in acoustic barriers and as thermal insulating material in multilayer systems. Their study confirmed the suitability and effectiveness of these composites for the intended applications.

Besides mechanical and physical performance, durability is an important aspect, especially given the organic nature of the aggregate. Pachla et al. [172] ascertained that axial compressive strength increases due to the curing time and wetting-and-drying cycles, Nonetheless, the three-point bending strength was reduced by approximately 52 % after the wetting-and-drying cycles. Sisman et al. [166] found that using RH as an aggregate replacement slightly increased the water absorption (about 3 % without RH and about 5.5 % for 30 % RH). However, the RH concrete developed was considered resistant to freezing, since the difference in compressive strength was as little as 10.9 %. In the authors' opinion, structural and insulating concrete can be produced using RH to meet the required strength resistance and thermal insulation. They suggest that these composites can be used in agricultural buildings. Yuzer et al. [167] state that RH reduces vapour pressure within concrete, thus preventing spalling and releasing less harmful gases than polypropylene fibres. They concluded that using RH in concrete will help lower the number of casualties in the event of fire when it is used as a coating, making it an interesting application for tunnels.

Concrete or other cement composites containing bio-aggregates from rice cultivation are generally proposed to be used in sandwich panels [173,174], masonry components, and façade elements [175,176]. Given the potential for reducing environmental impacts [158], weight [173], and costs [177], the use of rice residues should be studied more carefully and their behaviour better disseminated. Several authors [171] highlighted the need to study, in particular, RH concrete's durability and long-term behaviour.

Hemp shiv

Hemp is genetically close to THC-producing plants (the chemical responsible for the psychoactive properties in marijuana), so the production is tightly controlled under existing European laws [178]. In most European countries, the upper legal limit for cultivating industrial hemp for fibre is 0.2% of THC [179].

Hemp is considered a low-cost, ecological, and sustainable plant that can be used in different forms (fibres, powders, felts, seeds, and shives) for many varied applications, such as textiles, paper, energy production, cosmetics, medicine, and construction materials [178,180]. According to United Nations data [181], there are currently about 40 countries producing raw/semi-processed industrial hemp. In 2020, the biggest producers of hemp fibre were Canada, France, and China, and most of the rest were European Countries, like the Netherlands, Poland, Lithuania, Austria, and Italy [181].

Hemp shiv is a by-product of hemp fibre production and consists of the woody core of the hemp stalk obtained through defibration by a mechanical breaking process [182]. Hemp shives and hurds were first mixed with water and a mineral binder (which can be itself a mixture of different binders, [175]) in France in the 1990s, creating hempcrete [183]. This new material was used as an alternative to wattle and daub for the restoration of the historic building but now is widely used both for reconstruction and for new construction.

Binders commonly used for hempcrete are Portland cement or lime-based. Portland cement as a hempcrete binder has a significant role in providing strength to the concrete compared to only lime-based binder [184]. The main disadvantage of hemp concrete using lime as a binder is the time required to cure when casting on-site [175]. But lime-based binders have a carbon footprint much more favourable [185,186]. The carbon sequestration of hemp-lime is an enormous benefit of the material and, because of that, lime is used more with hemp than Portland cement.

The hempcrete can be cast in situ, as filling in wood-structure walls, or prefabricated as in masonry blocks, for example. Precast blocks allow optimal curing conditions, accelerating the hardening and improving the early age strength, representing an advantage. Casting in situ is done using a formwork, usually made of wood. The contribution of hempcrete to the racking strength of walls has not been examined [175,187], and that contribution should be further studied since it constitutes a gain. More knowledge about the shear behaviour of plant-based concrete is needed to optimize the structural design. Mukherjee and MacDougall [188] found that high-density hempcrete prevents weak-axis buckling of columns and carries some direct load. Low-density hempcrete was also found to avoid weak-axis buckling of the infilled walls. Other experimental studies [189] show that hempcrete has ductility when in compression and enables large deformations. Another situation that should be better studied, especially for prefabricated hempcrete, is the improvement of mechanical characteristics by applying compression during casting [190]. On the other hand, this compaction leads to an increase in density and, consequently, a rise in thermal conductivity, which constitutes inferior thermal performance [190,191]. The increasing adoption of hempcrete in construction is a promising indication of the growing recognition of its numerous advantages [192,193], including its positive impact on the environment, and its potential to enhance energy efficiency, along with the comfort and health of building occupants.

Wood

Wood, and forest resources, are finite but possibly renewable. With the increasing demand for wood-based products, it is crucial to consider using post-consumer wood as a raw material, which can reduce the pressure on virgin wood resources [194]. Wood waste from industry is relatively well-defined and clean, making it easier to recycle and use to produce items such as particleboard panels, oriented strand board (OSB), and medium-density fibreboard (MDF). Wood waste from other sources, like those generated by households and collected through municipal collection systems, construction and demolition wastes, or end-of-life wood products is certainly more challenging [195]. Contamination levels in wood waste from these sources can limit their adoption in a circular economy, namely for sequential recycling loops [196].

There are several studies [197–202] where mineral aggregates (fine, coarse, or both) are replaced by wood particles in different percentages. Wood incorporation generally reduces mechanical properties, including compressive strength, although thermal properties improve [203–207]. When waste aggregate is incorporated at high ratios in concrete, thermal conductivity decreases, making it an ideal solution for non-structural walls with better insulation capacity than regular concrete walls. In such cases, wood chips are typically the only aggregate used, resulting in a non-structural composite that closely resembles hempcrete. This material is often referred to as “woodcrete” or, in some cases (depending on the application) as “wood cement board” (WCB) and is commonly used for ceilings or walls [208].

In spite of the decrease of compressive strength, several authors [209–211] considered that some of these composites (for low waste ratio incorporation) can be used as a structural material, such as self-sustained walls. For instance, Smith [212] considers that concrete that uses wood chips as aggregate can be a solution to add stiffness and to solve the acoustic and vibration issues that affect pure timber construction structures, not increasing excessively the mass as it happens in regular concrete-timber structures. Another suggested application for these composites is as a replacement for masonry ceramic blocks with a solution that uses concrete blocks with wood chips. Pescari et al. [213] analysed four types of walls. The two proposed solutions of concrete blocks with wood chips had the best force–displacement relationship results.

According to Maier [214], the second most common use of wood waste after particleboards is its incorporation in concrete or mortar mixes for building materials. This option can be a solution for contaminated wood, although further research should be carried out to demonstrate the feasibility [205]. Contaminated wood can contain physical impurities in the form of foreign materials, including plastics, metals, glass, textiles, soil, and inert waste [215,216]. Chemical impurities are likely to be present too, as a result of treatments to improve durability [217–219]. The presence of these chemicals depends on the source of wood waste and can be hazardous and require special handling to avoid adverse environmental and health effects [218].

2.2.4.Discussion

This section discusses and compares the physical and mechanical features of the materials selected in this study. This macro analysis will provide a comprehensive perspective on the possible ranges of properties that can be achieved with different degrees of aggregate substitution. Furthermore, it will facilitate a direct comparison between different types of aggregates. The data are organised according to the proportion of aggregate substitution: [0] represents the reference without aggregate substitution;]0-30] represents substitution up to 30%;]30-100[represents substitution above 30% and below 100%; and [100] represents total substitution of natural aggregates. These percentages are in volume and include the substitution of fine, coarse, or both aggregates. When there is no mineral aggregate, some studies present the aggregate as a percentage of the binder (e.g. for hemp mixes), and those data were assigned to 100%. Some values considered in the analysis are approximations because data were extracted from graphic representations. Not every aggregate type fulfils all the substitution ranges for every property. The supplementary material provides the data references for each feature and aggregate type. The aggregate short description and source (when provided) are also included, as are the water/binder ratio (w/b) and binder content range.

The features presented are the most relevant to characterise concrete mixes, including density, compressive strength, modulus of elasticity, flexural strength, and thermal conductivity. Note that density is a physical property closely related to all the other properties. The resulting density typically decreases when mineral aggregates are replaced (Figure 2.4). This happens because natural aggregates are generally denser than the other options. The large range of results shown by the box plots presented in Figure 2.4 can be explained by different w/b ratios, which strongly affect the density and compressive strength.

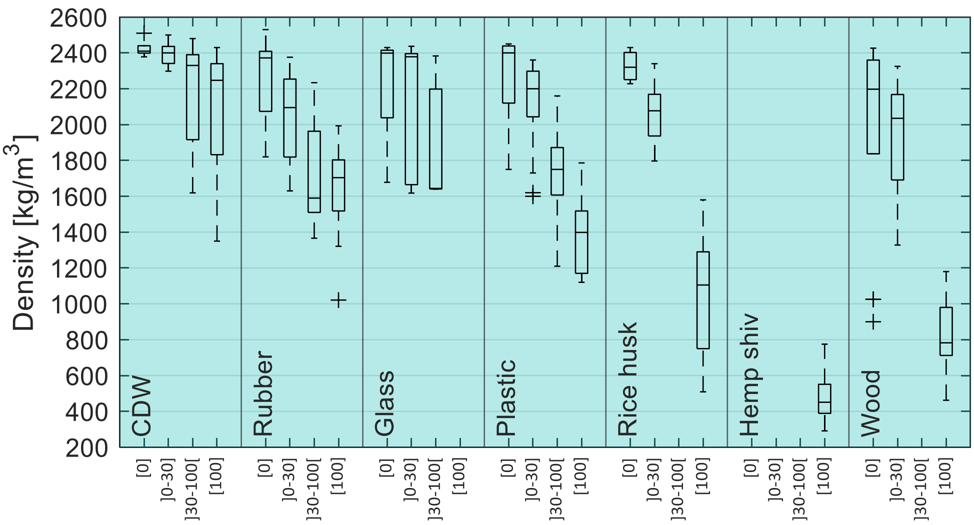


Figure 2.4: Box plots depicting density values found in the literature for the alternative aggregates under study and for different substitution ranges.

According to the EC2 code [220], lightweight concrete has a density below 2200 kg/m^3, whereas ACI 318-08 [221] suggests a range of approximately 1442-1842 kg/m^3 (90-115 bt/ft^3). The median density values of the CDW mixes studied are above 2200 kg/m^3. As expected, CDW has the smallest reduction (median values) in density compared with the reference, since its nature is quite similar to that of natural aggregates. Glass concrete also has high median densities. Again, this is because the density of glass is similar to that of the original mineral aggregates. In the case of polymeric (rubber and plastic) and organic (rice husk, hemp shiv and wood) aggregates, the decrease in density is significant, particularly for the organic aggregates and when the replacement of natural aggregates is total. Hemp is relatively unexplored as a partial substitute for concrete and has only been used and studied in mixes as the only aggregate. Also, compared with the other total organic composites (rice and wood), hemp is by far the lightest. In this case, the production method (vibrated, compacted, projected, precast, pre-soaked, or wet) influences the density more than the aggregate's density.

The compressive strength data (all cubic test specimen results) are presented in Figure 2.5. For CDW total incorporation, the range quantile falls between 30 and 50 MPa, which is compatible with most structural concrete requirements. Rubber and plastic concrete exhibits a clear tendency to lower the compressive strength with increasing ratio of aggregate substitution, with resistance bellow 20 MPa for total replacement. As previously referred, this reduction has been attributed to a loss of adhesion between the aggregate and the cement matrix, which becomes more evident as the ratio of substitution increases. On the other hand, glass does not seem to follow this behaviour, with a higher median than reference for low substitution ratios (bellow 30%). This corroborates the claims of various authors [85,94,98,100] that the optimal replacement ratio for glass is between 15% and 30%. As expected, organic aggregates presented lower mechanical performances, with a significant reduction in compressive strength that correlates with the density reduction. For instance, for mixes with no mineral aggregates, and usually with very high w/b relations, the compressive strength is between 5 and 10 MPa. Therefore, these composites are used as insulators rather than structural materials. It is important to emphasize that in some cases, for environmental reasons, Portland cement is not chosen as the binder of these composites, resulting in a resistance loss. Using these lightweight and less resistant composites for building envelopes can also help to reduce structural elements' dimensions by lowering the building's weight. For small substitution ratios (rice husk and wood), the reduction in strength is noticeable but generally remains above 20 MPa; in the case of wood, it is above 30 MPa.

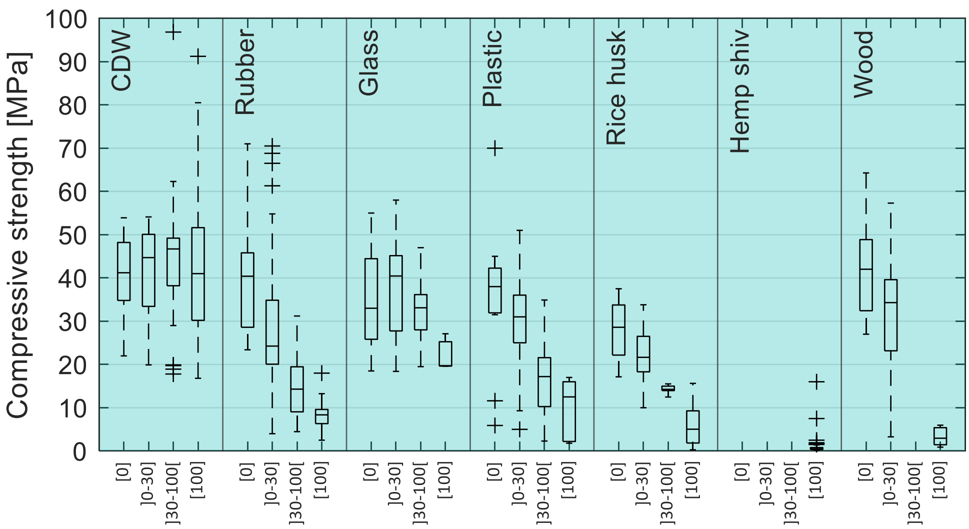


Figure 2.5: Box plots depicting compressive strength values found in the literature for the alternative aggregates under study and for different substitution ranges.

The experimentally determined values for modulus of elasticity are highly variable, differing by more than 1000 times (Figure 2.6). In some cases, the values are in the range of dozens of MPa, while in other studies they are in the range of dozens of GPa. To present this data consistently, the values are shown in GPa; which is why some bars begin almost at zero (Figure 2.6).

The modulus of elasticity depends to a considerable extent on the modulus of elasticity and the density of its components. Most alternative aggregates have a low modulus of elasticity compared with regular aggregates. However, this does not justify the large discrepancy in the literature results. Even concrete made with natural mineral aggregates only, ([0] aggregates substitution) present this high variability.

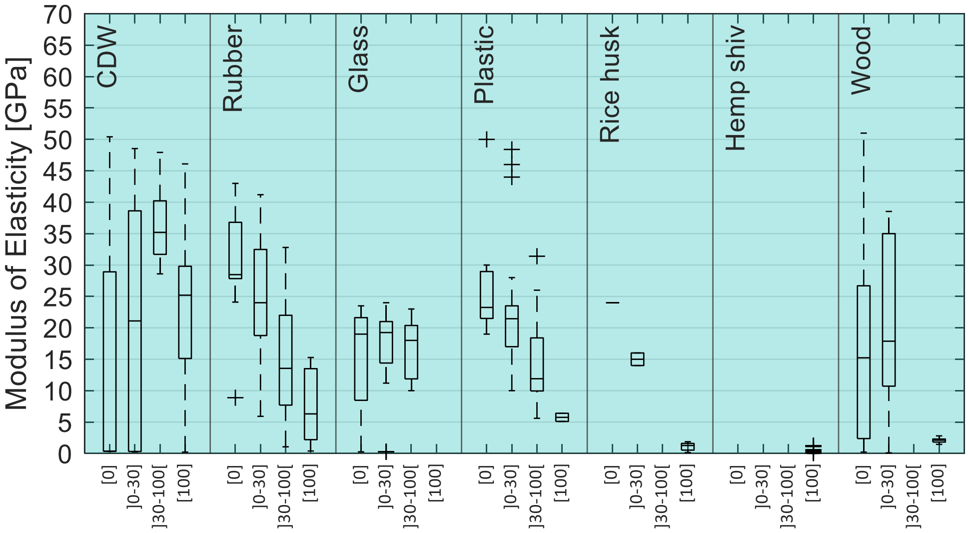


Figure 2.6: Box plots depicting modulus of elasticity values found in the literature for the alternative aggregates under study and for different substitution ranges.

This alerts for the necessity of checking the modulus of elasticity using different methods, perhaps using both static and dynamic approaches. Cross-referencing results with reference values in codes or guidelines could also help to validate a result. For example, for compressive strengths (cubes) below 30 MPa, EC2 [220] indicates reference values for modulus of elasticity between 27 and 30 GPa. In current practice, the modulus of elasticity is usually estimated rather than experimentally determined, which means there is a need to correlate density and/or compressive strength with modulus of elasticity for these new types of concrete/composites. These relations should be included in structural codes in the future just as they exist now for conventional concrete.

As happens with the compressive strength, so the modulus of elasticity of rubber and plastic concrete decreases with an increasing substitution ratio. The modulus of elasticity of glass concrete does not differ significantly from that of the reference concrete. In contrast, composites containing only organic aggregates have very low modulus of elasticity and density. These composites typically contain many voids, which deviate from the concept and properties of concrete. When the percentages of wood are small, the modulus of elasticity appears to have an extensive range of values, similar to that of concrete.

The flexural strength data are presented in Figure 2.7. Regarding the CDW and glass results, flexural strength does not seem to be much affected by the aggregate's substitution, since the interquartile is almost the same range. In some cases, the median is even higher than the reference median. With respect to rubber and plastic, the reduction in flexural strength is clear. The analysis of these mechanical features allows concluding that, when these wastes are incorporated in high percentages, they contribute to a general decrease in the material mechanical performance. Low flexural strength was also found for composite containing organic aggregates.

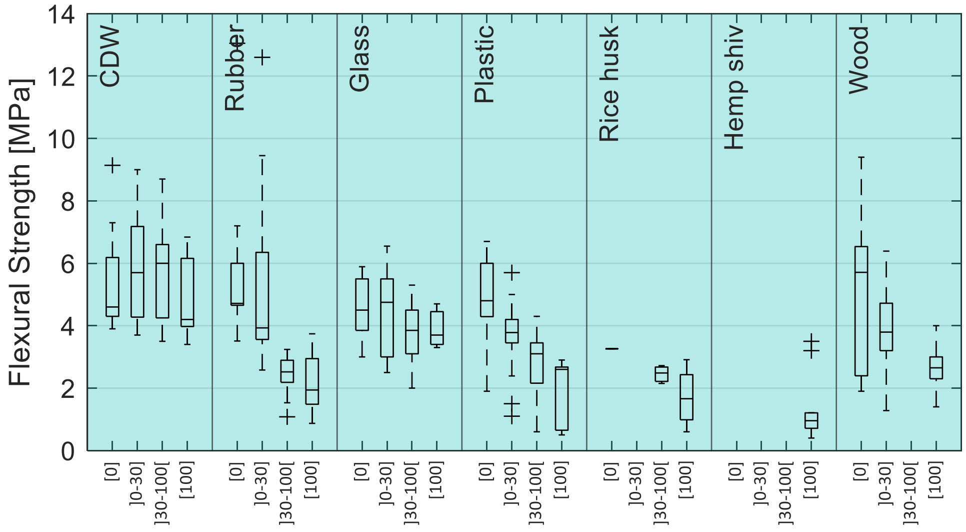


Figure 2.7: Box plots depicting flexural strength values found in the literature for the alternative aggregates under study and for different substitution ranges.

These reductions in mechanical performance can offset an improvement in physical performance. Thermal conductivity is a property that is often not prioritized when studying concrete, because concrete is not typically used for insulation. However, this overlooks the potential benefits resulting from a small drop in thermal conductivity. Therefore, it is important to investigate the thermal conductivity of alternative aggregates in concrete (Figure 2.8).

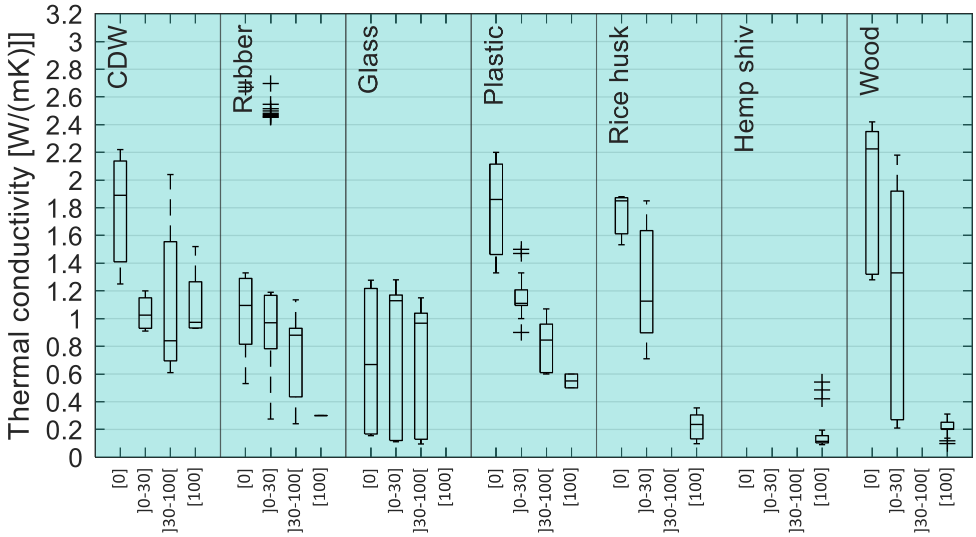


Figure 2.8: Box plots depicting thermal conductivity values found in the literature for the alternative aggregates under study and for different substitution ranges.

Organic aggregates are particularly noteworthy in this regard, especially in composites without mineral aggregates. As expected, the thermal performance only improves for aggregates that contribute to a decrease in density. Rice husk, hemp shiv, and wood composites have a very good thermal performances; nevertheless, only hemp is commonly used (in some countries) for housing envelopes. However, the integration of hemp in concrete mixes for structural purposes could offer a good compromise between strength, lightness, and thermal performance, which should be further explored.

2.3. Applications

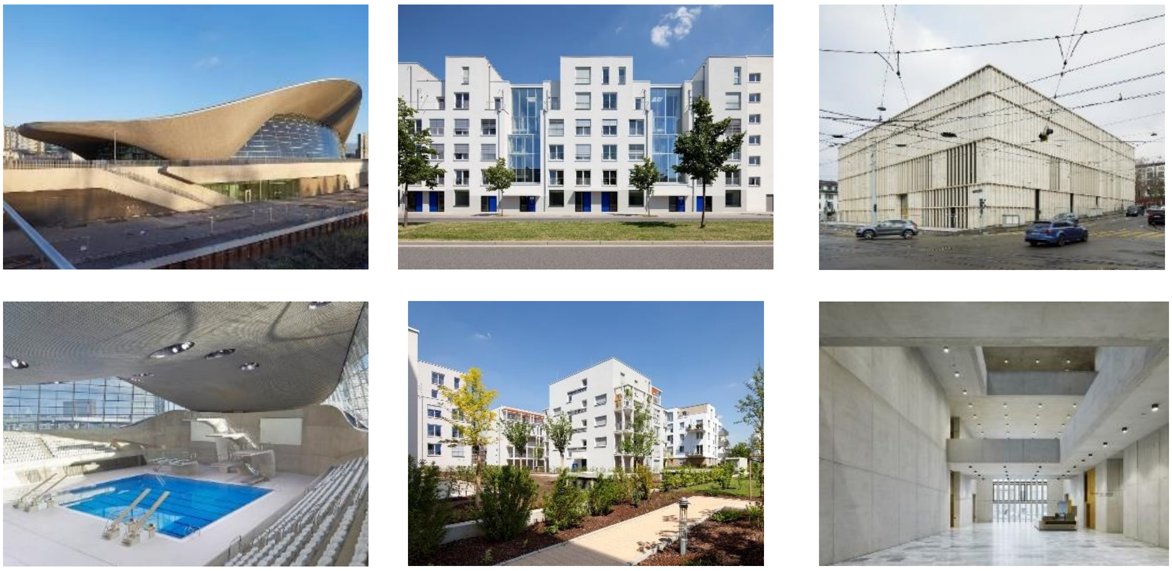
The use of alternative aggregates in a practical context helps to encourage further applications and should thus be better disseminated. The efforts made over the years by the scientific community to minimize the environmental impacts of concrete by replacing virgin aggregates with waste materials are well-known. The knowledge exists, and mixes have been developed and carefully studied. It is time to apply that knowledge in real projects.

There are excellent examples of recycling and waste integration in different applications worldwide. Unfortunately, these good examples are not yet common practice. General society is more than ever aware of climate change and environmental problem urgency. People want to contribute to a greener future, including green construction. However, there is a lack of information about the performance of these materials, and durability is always a concern. People still look at the words “recycled” or “alternative” in the construction sector with scepticism. That is because there is little research dissemination outside the scientific circle. Sometimes it is even scarce in the construction professional’s circle.

Having this in mind, and intending to contribute to further dissemination, examples of constructed projects related to the subjects discussed in this chapter are presented in this section. The examples are divided, as the chapter is, into: construction and demolition waste, end-of-life manufactured materials waste, and forest and agricultural waste.

2.3.1.Construction and demolition waste

CDW waste materials have been used since World War II [222]. Berlin's reconstruction after the war was partly aided by the reuse of demolition debris [223]. Although it is only in the last 20 years that CDW has been deeply studied, and then mainly used in road pavement layers, embankments, and earth-filling operations [222], the use of recycled concrete for buildings and structures has been potentiated by some countries with relatively small reserves of natural resources and/or with very restrictive environmental policies [222]. To exemplify the use of sustainable concrete with successful incorporation of CDW, three emblematic projects/constructions were selected (Figure 2.9): a big symbolic sports infrastructure in United Kingdom, an office/residential building in Germany, and a museum in Switzerland.



[224]

Name: London Olympics Aquatics Centre [227]

Designer/owner: Zaha Hadid Architects [227]

Location: London, United Kingdom

Construction year:2011[227]

Category: Sports infrastructure

[225]

Name: Zero emission area in Ludwigshafen [228]

Designer/owner: Seepe und Hund, Kaiserslautern, Jourdan Müller PAS, Frankfurt am Main [228]

Location: Ludwigshafen, Germany

Construction year:2010 [228]

Category: Office and residential complex

[226]

Name: Kunsthaus Zürich Museum Extension [226]

Designer/owner: David Chipperfield Architects [226]

Location: Zürich, Switzerland

Construction year: 2020 [226]

Category: Museums

Figure 2.9: Examples of emblematic construction projects using CDW as an alternative to natural mineral aggregates.

London Olympics Aquatics Centre

The London Olympics Aquatics Centre was designed by Zaha Hadid Architects for the Olympic Games in London in 2012. In this project, 11% of the concrete volume was reduced by a more optimized design saving 20,000 tonnes of embodied CO_2 and 120,000 tonnes of aggregate

[227]. Another approach used coarse aggregate substitution from the stent, glass sands, and recycled concrete aggregate. Concrete mixes with 76% coarse aggregate substitution were used, pushing beyond the 50% coarse aggregate substitution standard and reaching 169,000 tonnes of primary aggregate replacement [227,229]. Concerns were raised about the impact of coarse aggregate substitution on finishing quality. However, the Aquatics Centre's finishing demonstrated that coarse aggregate's substitution does not affect the achievable concrete finishing. Another strategy adopted was cement substitution with ground granulated blast-furnace slag (a by-product from the steel industry). To check compliance with standards for visible concrete, trials were conducted to determine the maximum blast-furnace slag content that could be used without compromising the requirements. It achieved the optimum percentage of 40%, and this work on cement substitution was recognized with a BREEAM innovation credit [227]. The Aquatic Centre is a success story since it surpassed many sustainability targets. It was a learning opportunity and a showcase for the other facilities of the Olympic Park, and more importantly, for the future.

Zero-emissions area in Ludwigshafen

In 2010, in Ludwigshafen, one building in a group of buildings was chosen as the first in Germany to be built with recycled concrete without increasing the cement content. It was built as a low-energy construction in a zero-carbon-emissions area [228]. The project was supported scientifically by the Institute of Energy and Environmental Research in Heidelberg and the Brandenburg University of Technology Cottbus. 30% by vol. of natural aggregates were replaced with reused aggregate made from recycled construction waste. Even fair-face concrete quality was achieved, and the demands made on the compressive strength with respect to the classification of concrete were fully met (C30/37). In addition, a higher resistance to carbon penetration than in normal concrete with the same strength was found. This project shows that recycled aggregates with properties very close to the raw ones can be produced. Besides the excellent workability of concrete, the quality of the fair-face concrete is also emphasized [228].

Kunsthaus Zürich Museum Extension and Zurich's green building practices

The Kunsthaus Zürich Museum Extension is a testament to Zurich's commitment to green building practices [230]. The city has been a pioneer in using recycled concrete in public buildings, with its first public building constructed with 80% recycled concrete being the "Im Birch" school in 2002 [231]. The success of this pilot project led Zurich to make it mandatory in 2005 for all public buildings to be constructed with recycled concrete, requiring concrete products to contain at least 25% recycled aggregates in total mass [232]. In 2013, Zurich went a step further by introducing an additional requirement that all concrete used in building construction works procured by the city meet the CEM III/B cement standard [232].

To address the concerns of architects and other stakeholders regarding the aesthetic quality of recycled CEM III/B concrete, Zurich built a "mock-up wall" [233]. This wall allows a direct comparison of the effects of various aggregate and cement types on the finished product. It also demonstrates that the impact of recycled aggregates on the end characteristics of concrete is limited. At the same time, the use of CEM III/B gives concrete a slightly lighter colour, which could be considered an additional aesthetic advantage by many architects. Also, recycled concrete is a cost-effective alternative to virgin concrete, as it is often around the same price or slightly cheaper [232].

Using recycled concrete has become a common practice in public building projects wherever it is technically feasible. Between 2005 and 2018, an average of 90% of concrete in public building projects was made from recycled aggregate. This commitment to green building practices is reflected in the buildings constructed over this period, such as the Werdwies housing complex (2006), Leutschenbach School (2009), Triemli city hospital (2015), Kronenwiese housing complex (2017), and more recently the Kunsthaus Art Museum (2022) [232].

Zurich has found that by mandating the use of recycled concrete in its public buildings, the market has responded with increased supply. Initially, only one supplier offered recycled concrete in the area, but eight to ten suppliers have since invested in production capabilities to meet the growing demand for sustainable building materials [232]. The tendency in the future will be to integrate small percentages of recycled aggregates but on a large industrial scale. This supply increase clearly shows that sustainable construction practices are becoming more accessible and viable for the industry.

2.3.2.End-of-life manufactured materials

Regarding industrial waste materials, it was challenging to find projects where this kind of waste was used in concrete. Maybe that information is less disclosed, or this type of waste is less often used.

It was evident during this research work that Australia is one of the countries where investment and effort to add value to glass, tyre rubber, and plastic wastes have been made more recently. The scientific papers published by different research groups and online news regarding concrete with these wastes show that interest. That could be related to the fact that Australia has banned the export of tyres, glass, and plastic waste since 2021/2022 [234]. This action, combined with high landfill levies, boosted waste recycling. These policies impact on the environment and the economy and are real incentives to increase the urgently needed circularity of solutions.

The examples chosen are not construction projects, but rather products or prototypes that integrate glass, rubber, or plastic, (Figure 2.10). The first example is a 3D-printed prototype using glass waste in the composition. Although not yet commercialized, it offers the potential for using glass in 3D-printed mixes. The second example is also a prototype of concrete road barriers that integrate rubber crumbs from end-of-life tyres. The third product is already commercialized and has been used in some projects in Hong Kong.

[235]

Name: 3D printable concrete

Designer/owner: Singapore Centre for 3D Printing - Nanyang Technological University, Singapore (NTU Singapore) [235]

Location: Singapore

Year: 2022 [235]

Category: Wall prototype

[236]

Name: Rubber T-Lok Barrier [236]

Designer/owner: Saferoads and researchers from the University of Melbourne's Advanced Protective Technologies of Engineering Structures (APTES) Research Group, with funding and support from Tyre Stewardship Australia (TSA) [236]

Location: Australia

Year: 2022 [236]

Category: Road barrier prototype

[237]

Name: "EcoBricks" [238]

Designer/owner: EcoBricks Limited [238]

Location: Hong Kong

Year: 2020 [238]

Category: Commercialized product

Figure 2.10: Examples of concrete products/prototypes using glass, rubber, or plastic as alternative aggregates.

3D printable concrete with glass waste

Researchers from Singapore University (NTU) have been working on developing a mix with recycled glass [89–91] to print a concrete bench [235], which passed strength tests and showed suitable buildability and extrudability [91]. This formula demonstrates for the first time that glass can indeed be used to 3D-print a bench with structural integrity. Since glass is less water absorbent, less water is required to create a concrete mix suitable for 3D printing. In collaboration with Singapore start-up company Soda Lemon, the researchers are looking at printing bigger structures with glass concrete [235].

Rubber T-Lok Barrier

The Rubber T-Lok product has been developed by Saferoads and researchers from the University of Melbourne's Advanced Protective Technologies of Engineering Structures Research Group, with funding and support from Tyre Stewardship Australia. This new product allows 115 tonnes of used tyres to be recovered for every 10 km of road safety barrier produced [236].

In 2022, a crash test was conducted at a speed of 100 km/h, and the findings indicated that the rubberized concrete road barriers, when designed appropriately, have the potential to lessen the impact force during collisions. This lowers the chances of sustaining severe injuries or being killed, and it is less damaging to the barrier itself. Including rubber enhances the flexibility and durability of concrete, and the product complies with the Australian and New Zealand standards for road safety barrier systems [236].

“Ecobrick”

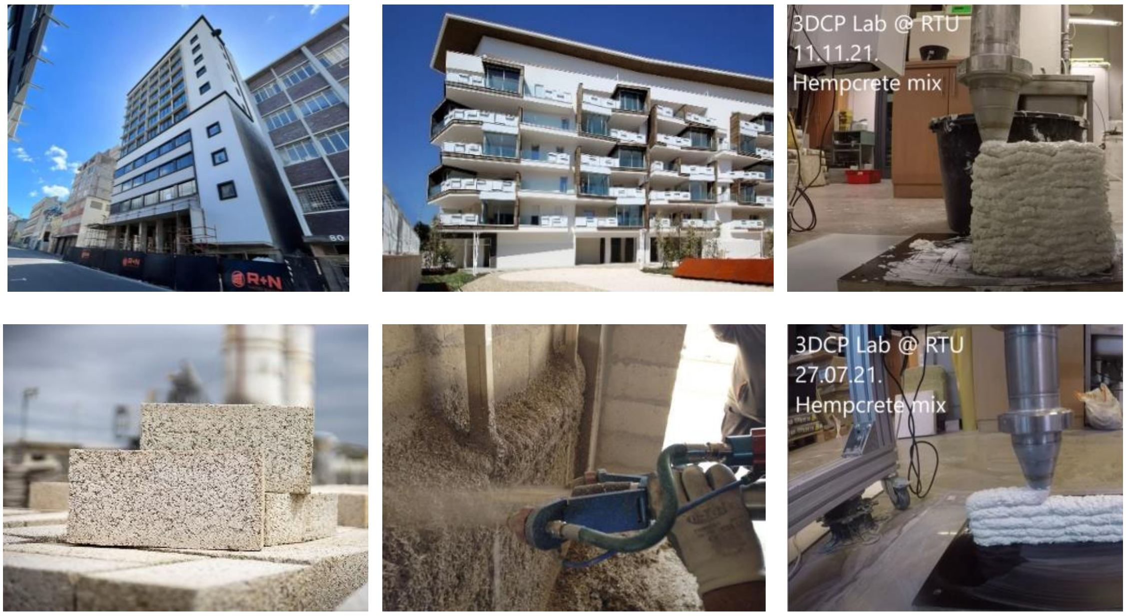
Hong Kong-based start-up EcoBricks has developed a product to upcycle plastic waste from old washing machines. According to the information provided by the company [238], EcoBricks can use any plastic waste, materials that are impossible to recycle. The process is 100% cold, with minimal processing contributing to lower embodied carbon. Another advantage mentioned is weight reduction without compromising performance. According to the founder of EcoBricks [237], the product can replace up to 50% of natural aggregates in concrete bricks with plastic waste. This means up to 2,000 kg of plastic waste could be diverted from landfills for every 100 m^2 of EcoBricks produced, which is equivalent to 200,000 plastic bottles [237]. One of the first uses of EcoBricks was at Gold Coast Piazza in Tuen Mun, Hong Kong.

2.3.3.Forest and agricultural waste

Of the three agricultural and forest waste products addressed in this study, hemp is the most widely used. Its use has been demonstrated worldwide [239,240], with some countries, such as France, leading the way in knowledge and application. A wealth of information on its properties design, and application guides is readily available [241–244]. In addition, there are various associations - the “Construire en Chanvre association” (France), International Hemp Building Association, US Building Association, among others, committed to advancing the use of hemp in sustainable building practices and promoting its benefits, which further contributes to its use and acceptance. The examples of constructions made with hemp are fortunately countless. The chosen cases emphasise innovation and difference: the tallest building made with hemp, collective housing rewarded for sustainability and innovation purposes, and research projects/work to collect the environmental benefits of hemp in the Construction 4.0 context by using 3D printing (Figure 2.11).

In contrast, the use of rice husk and wood in concrete construction is not as widespread. In the specific case of rice husk and wood, their use as ash for cement substitution has been studied and applied much more. The examples include prefabricated solutions like blocks, material for 3D printing, and loose aggregate (Figure 2.12). The two first examples align with the trend towards more industrialized construction, which is needed to address some countries' lack of construction workforce.

The incorporation of wood in concrete fulfils almost the same applications as hemp and rice husk, taking advantage of the good thermal and acoustic properties. The examples chosen in Figure 2.13 are a house constructed in 1948 to show how this material can be durable, even though it is from natural sources, and two prefabricated solutions, elements for homes, and barriers, which seem to be a solution well-received in the market.



[245,246]

Name: First hemp skyscraper [250]

Designer/owner: Hemporium and Afrimat Hemp and Wolf + Wolf Architects partnership [245]

Location: Cape Town, South Africa

Construction year: 2023 [246]

Category: Residential/Hotel

[247,248]

Name: Case di Luce [247][251]

Designer/owner PS Architecture [251]

Location: Bisceglie, Italy

Construction year: 2016 [251]

Category: Collective housing (21 dwelling) and commercial

Frames of a film [249]

Name: 3D printing with hemp

Designer/owner: N.A

Location: N.A

Construction year: N.A

Category: 3D printed house/elements

Figure 2.11: Examples of construction projects using hemp as alternative aggregate.

First hemp skyscraper

The world's "first hemp skyscraper" [250] is nearing completion in Cape Town, South Africa. According to the New York Times [250], the 12-storey building will be the tallest structure in the world to incorporate largely hemp construction. The building will feature around 50 apartments, and all its walls will be made from hemp blocks, although a traditional frame is still required due to load-bearing limitations. Using hemp blocks for the walls reduces the mass of the building, which in turn reduces the load on the foundations and the cost of the structural elements. The joint venture behind the project believes that this project is "setting the benchmark on how to build a safe, carbon-neutral, multistorey building using hemp blocks and hemp systems" [246]. The building is a pioneering project demonstrating the potential of hemp as a viable and sustainable building material. It may pave the way for future hemp-based construction projects of considerable dimensions.

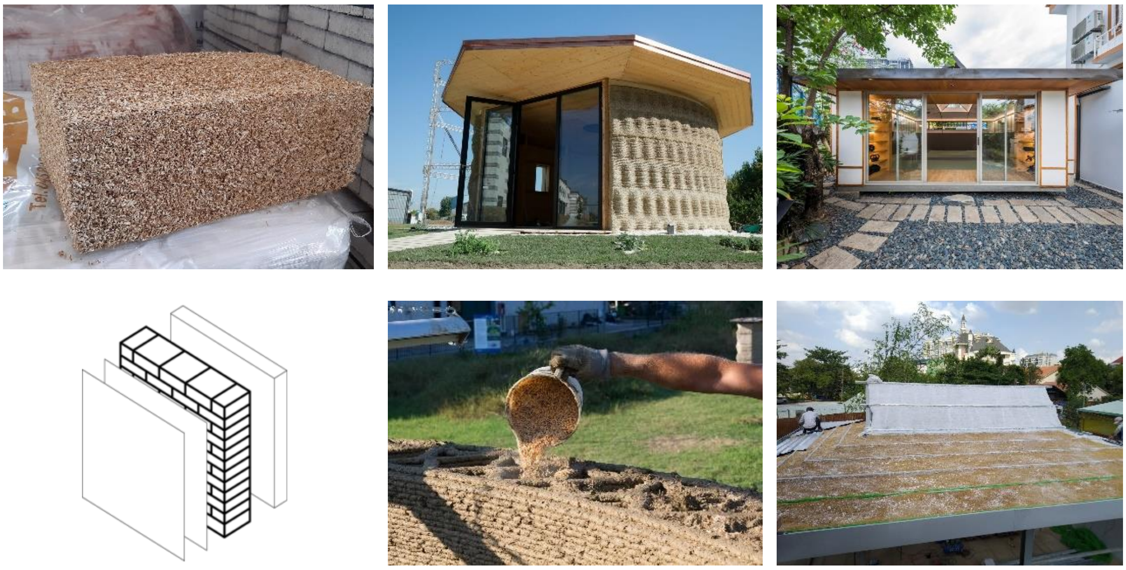
Case di Luce

Case di Luce is a building in Italy awarded the Green Building Award in 2016 for its innovation as a Nearly Zero Energy Building (NZEB) [251]. This building is constructed with a completely natural envelope, utilizing hemp and lime bio-composite building materials, e.g. Biomattone® (precast blocks of hemp and lime), making it one of the largest buildings in Europe built with these materials. It is also one of the first examples in Italy to meet the European Directive 2020 objectives due to its high CO_2 absorption and low energy consumption [252]. The building's envelope is made exclusively from natural materials, hemp blocks, and a constructive system of sprayed masonry in hemp and lime, which has earned LEED certification. According to Magwood [244], spraying hempcrete can reduce application time and drying periods and lower the installed material’s density, thus improving the insulation capacity. The infill walls comprise an inner layer of tuff, onto which a mixture of hemp and lime is sprayed, followed by a final spray of a hemp-lime mixture. This allows an external monolithic masonry to be created that fulfils both the casing and insulating functions with a single material.

The hemp blocks and the sprayed masonry in hemp and lime are the primary products utilized in constructing Case di Luce. The building's remarkable features include thermal, acoustic, and hygrometric comfort, with excellent insulation and low embodied energy during manufacturing. The building envelope is permeable to water vapour, resistant to fire, frost, insects, and rodents, and guaranteed to be free from toxic fumes in a fire.

3D printing with hemp

There are several ongoing research projects investigating applications for additive construction using hempcrete. The idea is to benefit from the new technology and material environmental benefits. For example, a team from Texas University [253] launched a project last year aimed at 3D printing resilient buildings using hempcrete. The objective is to develop an approach that can reduce the environmental impact of conventional construction methods and improve the availability and affordability of housing. Other research groups and companies are interested in hempcrete printables [254]. In preliminary experiments, Sinka et al. [255] from Riga Technical University demonstrated that hempcrete could be printed at a relatively low density of 660 kg/m^3 while achieving sufficient buildability and compressive strength for printing individual wall elements (Figure 2.11). Combining hempcrete with 3D printing technology offers numerous possibilities for expanding the use of this sustainable material while reducing the environmental impact of the construction industry.



[256]

Name: RH-B Prefabricated rice husk block (RiceHouse) [256]
Designer/owner: RiceHouse [256]
Location: N.A.
Construction Year: N.A.
Category: Construction Product

[257,258]

Name: Gaia [257,258]
Designer/owner: WASP collaboration with RiceHouse [257,258]
Location: Massa Lombarda, Italy
Construction Year: 2018 [257,258]
Category: Residential (3D printed house)

[259]

Name: Dojo in Saigon [259]
Designer/owner: Kanopea Architecture Studio/T3 Architects [259]
Location: Ho Chi Minh, Vietnam
Construction Year: 2020 [259]
Category: Sportive infrastructure

Figure 2.12: Examples of concrete products/projects using rice husk as alternative aggregate.

RH-B Prefabricated rice husk block

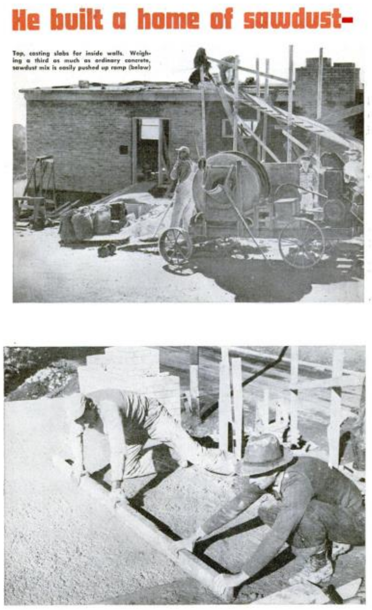
RH-B Prefabricated rice husk blocks with a density of 600 kg/m^3 are commonly used in traditional constructions for internal and external insulating masonry, combined with a load-bearing frame made of concrete, steel, or wood. These blocks provide excellent thermal insulation, with a thermal conductivity of 0.075 W/mK and specific heat of 1800 J/kg K [256]. When used in single or double layers with materials such as masonry, wood, or stone, they create massive structures with high thermal lag, thereby ensuring indoor comfort and health. Additionally, the blocks allow easy installation of plant engineering parts, making them ideal for constructing internal partitions or counter walls [256].

<u>Gaia 3D printed house</u>

The *Gaia* project is an innovative eco-sustainable architectural model built using a 3D printer and natural materials found nearby. The structure was made from a blend of clay and rice husk, which is entirely natural and promotes a healthy environment. The house is highly efficient from an energy consumption standpoint, and maintains a comfortable temperature [257,258]. The project emphasizes the importance of environmental sustainability and blends seamlessly into the surrounding landscape. The construction of the house only took ten days and cost was low due to the masonry's thickness, which is 45 cm. Italian 3D-printing technology built the house using natural materials, which were 25% soil, 25% rice husk, 40% chopped straw rice, and 10% hydraulic lime. The resulting product is entirely biodegradable, and if not maintained it will return to the soil. The walls were constructed with vertical holes that were subsequently filled with rice husks to provide insulation. The outer cavity in the wall remained empty to facilitate proper air circulation within the structure, and a bio-plaster made from rice husks coated the structure's internal walls and roof to provide additional insulation [257,258]. The project was completed within 100 hours, making it time and cost-efficient. WASP claims that agricultural waste could become a vital resource in the construction industry.

<u>Dojo in Saigon</u>

The Dojo, designed by Kanopea Architecture Studio/T3 Architects in Saigon, is an example of sustainable architecture incorporating locally sourced materials. The building roof is insulated with 20 cm of loose rice husk mixed with diatomaceous earth, which provides excellent insulation and energy efficiency while utilizing a readily available material that would otherwise be wasted [259].



[260]

Name: "Home of sawdust" [260]
Designer/owner: Walt Friberg [260]
Location: Moscow, Idaho, Unite States of America
Construction Year: 1948 [260]
Category: Residential

[261]

Name: Precast noise-barriers (AGRESLITH-AC®) [261]
Designer/owner: Agresta technologies [261]
Location: N.A.
Construction Year: N.A.
Category: Noise-barriers

[262]

Name: Woodcrete framework (LegnoBloc) [262]
Designer/owner: LegnoBloc [262]
Location: N.A.
Construction Year N.A.
Category: Precast elements for walls and slabs

Figure 2.13: Examples of concrete products/projects using wood as alternative aggregate.

Home of sawdust

In 1948, Walt Friberg constructed a house made of sawdust concrete in Idaho. At that time, the construction was featured in Popular Mechanics magazine [260]. Friberg used diatomaceous earth and added common clay to create lightweight, fire-resistant, and insulating concrete to improve insulation and reduce costs. Years later, the magazine Mother Earth News [263] revisited the house to see how it had fared. They found it was still standing and had withstood the cold Idaho winters remarkably well. The owners also reported that the house's excellent insulation had resulted in significant savings on heating bills. Walt Friberg's innovative approach to construction led him to build or assist in constructing 30 to 40 sawdust concrete buildings in the northern Idaho/eastern Washington area [263]. Although there is currently no information about the houses or the builder, this case study is an example of the long-term application and durability of sawdust-concrete construction, which is still relevant today.

Precast noise-barriers

Noise barriers made with wood aggregates are highly sound-absorbent, making them a popular application of concrete in reducing noise from highways, railways, and industrial sources. The porous surface of these barriers allows them to absorb sound and transmit it through cavities in the wall, forcing energy to follow a longer path over and around the barriers. Many companies claim these barriers are durable for at least 40 years and require minimal maintenance, resulting in low whole-life costs [261,264]. In addition to their sound-absorbing properties, these barriers offer several other advantages, including customizable profiles, colours, and sizes, lower shipping costs and facilitating fast construction. They are also resistant to fire and vandalism and are highly resistant to rot, fungal growth, vermin, and termites, thus reducing dead loads on the entire structure.

Woodcrete framework

Woodcrete can produce eco-friendly blocks that are non-combustible, highly breathable, and offer superior thermal and acoustic insulation. These framework blocks made of wood-cement conglomerates provide eco-sustainable masonry options that offer excellent thermal and high acoustic insulation. They are also lightweight and easy to install, making them an economical and quick solution. Many of these blocks have obtained CE marking and other relevant certifications, ensuring compliance with current regulations and providing confidence to owners and stakeholders. While these products are typically made with virgin wood, there is potential for integrating end-of-life wood waste, further enhancing the circular economy.

2.4. Discussion

The literature highlights the growing interest in alternative aggregates for two main reasons: the need for greater circularity in waste reuse and the need to reduce the environmental impact of natural aggregate extraction. Despite significant research investment, there has been limited uptake in real applications and it is still far from being a common practice.

Regarding CDW, high levels of segregation and advanced industrial units would be necessary to increase the recycling rates of waste resulting from construction and demolition activities. The knowledge about RA and concrete integrating CDW is solid, and recycled concrete in construction is more widely accepted than substitution with other types of aggregate. The good performance and total feasibility of using RA in concrete (of course, with the right quality control) encourages wider application. Although it requires an effort from construction sector operatives, namely cooperation between stakeholders, owners, engineers, architects, the concrete industry, and constructors, it is desirable to use more CDW and this practice should result in more sustainable projects and constructions. In the examples presented, it was mentioned how cooperative work between parties contributed to achieving sustainable goals. Furthermore, public investment in construction with CDW, like the example of Zurich, also gives confidence in using recycled concrete. The future tendency will be for governments and municipalities to require the integration of RA in all concrete constructions, thus creating an efficient way to force the industry and economy to change.

Studying the addition of the end-of-life waste materials from rubber tyres, glass, and plastic into concrete applications showed that it is less prevalent in practice, and seems to be explored almost only in an academic context. However, specific precast solutions previously developed by scholars could be viable marketable products for use in less exacting structural/mechanical requirements with bigger waste content, or used for more demanding applications but in small percentages. Taking the example of concrete with rubber waste, the capacity to absorb energy and the possible gain in ductility should be better exploited for specific purposes, like when impact and dynamic loads are design requirements.

Finally, forest and agricultural wastes are important because their good thermal and acoustic behaviour, plus the environmental benefit, offer huge potential. But if there is still some mistrust regarding these materials, there is nonetheless a growing interest in natural and organic materials. This market trend will lead to the appearance of more specialized enterprises in this type of product and help to involve key construction players who are more experienced in and aware of sustainability issues. Hempcrete is already a trend in some countries, especially for housing envelopes. That influences the more widespread use of materials to educate engineers, architects, and contractors. The other two resources, rice husk and wood, still have very little relevance in the market, since they are only commercialized by a few companies speculating on sustainability. Still, their relevance is also likely to be noticed in the next few years.

2.5. Conclusions

This review set out to comprehensively analyses concrete and cement composites that incorporate different waste materials, including recycled concrete waste, end-of-life manufactured materials, and forest/agricultural waste. The impact of incorporating these waste aggregates on concrete performance was discussed, and their advantages and disadvantages examined. Based on the findings of this review, it becomes evident while alternative aggregates can offer benefits, such as reduced density and improved thermal performance, they often lead to a decrease in compressive strength, flexural strength, and modulus of elasticity. Understanding these commitments and establishing correlations between fundamental properties are, therefore, crucial for effectively utilizing these new concrete composites in various construction applications.

Among the aggregates under analysis, CDW and glass are those that exhibit the slightest reduction in density, as their nature is similar to that of natural aggregates. On the other hand, polymeric (rubber and plastic) and organic (rice husk, hemp shiv, and wood) aggregates result in significant density reductions, particularly for organic aggregates and when total replacement of natural aggregates is implemented. Regarding compressive strength, CDW exhibits a range of values between 30 and 50 MPa when fully incorporated, which is compatible with most structural concrete requirements. Rubber and plastic concrete show a clear tendency to decrease compressive strength with increasing ratios of aggregate substitution. This reduction is attributed to a loss of adhesion between the aggregate and the cement matrix, which becomes more pronounced as the substitution ratio increases. In contrast, glass does not exhibit a significant decrease in compressive strength, with median values higher than the reference for low substitution ratios (below 30%). Organic aggregates generally demonstrate lower mechanical performance, with a substantial reduction in compressive strength that correlates with the decrease in density. For mixes with no mineral aggregates and typically high water/binder ratios, the compressive strength ranges between 5 and 10 MPa, making these composites more used as insulation rather than structural applications. As far as the modulus of elasticity is concerned, alternative aggregates generally have lower values compared to regular aggregates.

Additionally, examples of construction projects, products and prototypes that integrated these alternative aggregates were provided and described, giving a sense of these materials' real-world applications and also promoting their use. It is evident in this case that despite the significant investment in research, the percentage of concrete or cement-based materials with waste integration currently being used is still relatively small. This review emphasizes that policies that favour better environmental choices, and even those that enforce the application of circular economy models, can play a crucial role in driving the adoption of these sustainable practices in the construction industry.

In summary, reusing waste materials as substitutes of natural mineral aggregates, leads to a reduction in the depletion of natural resources and is a positive measure towards increased circularity, which is urgent needed in today's world. Therefore, because sustainability is on the agenda, political and economic incentives should be used to promote these eco-friendly practices in the construction sector to enhance sustainability and reduce environmental impact.

Supplementary material

Table 2.1: References of the data discussed in section 2.2.4.

Material	Waste description and source	Water/binder ratio (w/b)	Binder content and type [kg/m^3]	Density of the composite [kg/m^3]	Compressive strength (28d) [MPa]	Flexural strength [MPa]	Modulus of elasticity (28d) [GPa]	Thermal conductivity [W/(mK)]
Construction and Demolition Waste	RA, 92.1% crushed concrete, 1.6% of ceramic aggregates and 5.3% of bituminous and 0.8% of others [265]; RA obtained from three different recycling plants – (Czech Republic) [266]; RA from medium-high strength (rejected specimens of a precast factory and from laboratory produced concrete [267]; RA from different sources (CW recycling plant and old concrete from laboratory) [268]; RA from 5 different sources (68% and 86% content of concrete and 1% and 29% of clay materials) – (Portugal) [269]; RA from concrete elements of an abandoned factory [270]; RAC from materials laboratory, civil engineering department CUET (Bangladesh) [271]; RAC was obtained by crushing previously tested concrete samples [272]; RAC from industrial brick waste produced at ceramic plant – (Portugal)[273]; RAC from a building structure built around 15 years ago in Harbin – (China) [274]; Recycled aggregate from concrete pavement demolishing spot [275]; RAC from concrete waste sourced from the demolition site of a water tank [276]; RA from RECYBETON Project – (France)[277]; Recycled aggregate thermal insulation concrete [278].	0.29-0.68	270-485 OPC	[265] (2007) [267] (2014) [270] (2015) [272] (2017) [273] (2018) [274] (2018) [275] (2020)	[265] (2007) [267] (2014) [268] (2014) [269] (2015) [271] (2015) [272] (2017) [276] (2018) [274] (2018) [273] (2018) [277] (2020) [275] (2020) [278] (2020)	[267] (2014) [273] (2018) [276] (2018) [275] (2020)	[265] (2007) [267] (2014) [268] (2014) [269] (2015) [276] (2018) [277] (2020)	[266] (2014) [270] (2015) [272] (2017) [274] (2018)

Material	Waste description and source	Water/binder ratio (w/b)	Binder content and type [kg/m³]	Density of the composite [kg/m³]	Compressive strength (28d) [MPa]	Flexural strength [MPa]	Modulus of elasticity (28d) [GPa]	Thermal conductivity [W/(mK)]
Tyres rubber	Waste tire particles (crumb rubber) obtained from an industrial unit (Jordan) [57]; Rubber aggregates used were obtained from the mechanical grinding of end-of-life tyres [279]; Chipped and crumbed tire rubber particles [280] (2008); Shredded tire chips, STC, obtained by mechanical grinding [281]; Crumb rubber, obtained from the recycle plant (Thailand) [75] (2009); Rubber shreds recovered by a shredding process of waste tyres [282] (2010); Crumb rubber from Ara Jaya Enterprise (Malaysia) [74] (2012); Pre-coated crumb rubber [66] (2014); Recycled rubber particles produced by mechanical shredding [283] (2015); Rubber particles were recovered through mechanical shredding at ambient temperature [284] (2016); Crumb rubber obtained from mechanical grinding of waste tires [59] (2017); Crumb rubber was obtained from a local industrial unit (Jordan) [272] (2017); Crumb rubber and Fibers fixed to crumb rubber [285] (2017); Crumb rubber was supplied by industry (India) [60] (2018); Crumb rubber from waste tires (Egipt) [286] (2019); Crumb rubber from scrap tyre industry [62] (2020); Crumb rubber from recycled tyres [61] (2021); Recycled rubber granules – Biosafe (Portugal)[171] (2021); Cutting leftover tyre rubber [287] (2022); Two different sizes of rubber particles collected from a recycling plant (Australia) [288] (2022); Waste crumb tire rubber – Saudi Rubber Products Co. (Saudi Arabia) [289] (2022); Two different sizes of rubber particles (Australia) [290] (2023).	0.35-0.60	Portland cement type I, Ordinary Portland Cement (OPC) Type I plus fly ash and silica fume; Portland Limestone Cement CEM II – 52.5 N CEM I 42,5 R 335-480	[279] (2008) [75] (2009) [282] (2010) [74] (2012) [66] (2014) [283] (2015) [59] (2017) [272] (2017) [285] (2017) [286] (2019) [171] (2021) [287] (2022) [288] (2022) [290] (2023)	[57] (2008) [279] (2008) [280] (2008) [281] (2008) [282] (2010) [66] (2014) [283] (2015) [284] (2016) [59] (2017) [272] (2017) [285] (2017) [60] (2018) [286] (2019) [291] (2019) [62] (2020) [292] (2020) [61] (2021) [171] (2021) [289] (2022) [287] (2022) [288] (2022) [290] (2023)	[282] (2010) [283] (2015) [285] (2017) [60] (2018) [286] (2019) [171] (2021) [289] (2022) [287] (2022) [288] (2022)	[279] (2008) [281] (2008) [293] (2008) [66] (2014) [283] (2015) [285] (2017) [60] (2018) [291] (2019) [287] (2022) [288] (2022)	[75] (2009) [74] (2012) [272] (2017) [285] (2017) [292] (2020) [171] (2021) [289] (2022) [287] (2022)

Material	Waste description and source	Water/binder ratio (w/b)	Binder content and type [kg/m³]	Density of the composite [kg/m³]	Compressive strength (28d) [MPa]	Flexural strength [MPa]	Modulus of elasticity (28d) [GPa]	Thermal conductivity [W/(mK)]
Glass	Collected waste glass includes containers (bottles, jars) and flat glass(windows from the State Company for Glass Industry in Al-Ramadi city and others in Baghdad city (Iraq) [85] (2009); Mixed colour beverage glass containers from the materials recovery facilities [101] (2009); Recycled glass [294] (2012); Waste glass of the used windows [103] (2014); Mixed colour post-consumer con-tainer glass from a glass recycling company in the Sydney region (Australia) [94] (2015); Recycled waste glass was used as a partial replacement for natural fine aggregate [295] (2015); Cathode ray tube (CRT) waste glass is an industrial waste [97] (2018); Mixed coloured soda-lime glass supplied by the Cairns Regional Council (Australia) [96] (2020) A Crushed glass of different types and colour from a local market in the Bangladesh (Bangladesh) [296] (2023).	0.35 – 0.67	Ordinary Portland Cement (OPC) (Type I) CEM I, 42.5 N Portland cement Portlan Cement and metakaolin 275-477	[85] (2009) [294] (2012) [94] (2015) [103] (2014)	[85] (2009) [294] (2012) [103] (2014) [94] (2015) [97] (2018) [96] (2020) [296] (2023)	[85] (2009) [101] (2009) [103] (2014) [97] (2018) [96] (2020)	[101] (2009) [294] (2012) [103] (2014)	[294] (2012) [296] (2023) [295] (2015)
Plastic	Waste PET bottles [297]; PVC granules from PVC pipes [298]; Virgin plastic waste – Central Institute of Plastic Engineering and Technology (India) [299]; PET-waste mostly PET-bottles – Plastic recycling plant (Portugal) [300]; PET bottles granules – SASA PET Bottles Plant (Turkey) [301]; PET particles [302]; Synthetic aggregate made by recycled plastic and filler [303]; Plastic waste: PE and RPA – Recycling plant (Saudi Arabia) [304]; Plastic waste: (PVC), (HDPE) and (PP) – ITP plant in Oran (Algeria) [305]; Thermoplastic shredded recycled plastic waste aggregates: PET, HDPE and PP – Recycling Plastic Australia PTY LTD (Australia) [306]; Polyethylene waste – collected from agricultural production (Marocco) [307]; HDPE particles – Alyaf company (Saudi Arabia) [289] PP wastes [308].	0.32-0.74	Ground granulated blast furnace slag (GGBS) and metakaolin (MK); OPC 327-589	[297] (2005) [298] (2009) [299] (2012) [300] (2013) [301] (2014) [302] (2016) [303] (2018) [304] (2020) [305] (2020) [307] (2022) [308] (2022)	[297] (2005) [298] (2009) [299] (2012) [300] (2013) [301] (2014) [302] (2016) [303] (2018) [305] (2020) [304] (2020) [306] (2021) [307] (2022) [289] (2022) [308] (2022)	[299] (2012) [300] (2013) [301] (2014) [302] (2016) [304] (2020) [306] (2021) [289] (2022) [308] (2022)	[297] (2005) [298] (2009) [302] (2016) [305] (2020) [304] (2020) [306] (2021) [308] (2022)	[305] (2020) [304] (2020) [307] (2022) [289] (2022)

Material	Waste description and source	Water/binder ratio (w/b)	Binder content and type [kg/m3]	Density of the composite [kg/m3]	Compressive strength (28d) [MPa]	Flexural strength [MPa]	Modulus of elasticity (28d) [GPa]	Thermal conductivity [W/(mK)]
Rice husk	Rice husk paddy waste – Thrace region [166] (2011); Raw rice husk[167] (2013); Rice husk from rice field – Bio-sud, Arles (France) [170] (2014); Rice husk (water soaked and not) [168] (2019); Rice husk (not treated) [309] (2020); Rice Husk from Mogi das Cruzes – São Paulo (Brazil) [169] (2020); Rice husk from Baixo Mondego, agricultural region (Portugal)[171] (2021); Rice residues (husk and straw)without treatment [172] (2021); Rice husk is from Hubei Province(China) [310] (2021); Rice husk [158] (2022).	0.25-0.78	Type I (PC 42.5) Portland cement; EM I 42.5 R; 50/50 wt% combination of natural hydrauliclime NHL3.5 and hydrated calcic lime CL90; sulfate-resistant Brazilian Portland Cement CPV-ARI RS; Portland cement with RHA CEMIIB-LL32.5R 258-775	[166] (2011) [167] (2013) [170] (2014) [168] (2019) [169] (2020) [309] (2020) [171] (2021) [172] (2021) [310] (2021) [158] (2022)	[166] (2011) [167] (2013) [170] (2014) [168] (2019) [169] (2020) [309] (2020) [171] (2021) [172] (2021) [158] (2022)	[168] (2019) [171] (2021) [172] (2021)	[170] (2014) [169] (2020) [310] (2021) [158] (2022)	[166] (2011) [167] (2013) [170] (2014) [168] (2019) [309] (2020) [171] (2021) [172] (2021) [158] (2022)
Hemp shiv	Hemp shives (BCBChanvribat) [311] (2008); Hemp shiv without fibre [190] (2010); Hemp shiv [312] (2010); Hemp shiv was collected from a farm in Grästorp (Sweden)[313] (2013); Commercial defibered and fibered hemp shiv, [191] (2014); Hemp shives, flax shives, and rape straw[314] (2016); fibred hemp shiv and hemp straw – (France) [315] (2017).	0.55-2.44	- Prompt Natural Cement (PNC) - Tradical PF70; Slaked lime and hydraulic lime plus fly ash; Hydrated lime CL90; Commercial binder (TH); Mixture of a lime-based binder hydrate lime, pozzolanic material and hydraulic binder	[311] (2008) [190] (2010) [313] (2013) [191] (2014) [314] (2016) [315] (2017)	[311] (2008) [190] (2010) [312] (2010)	[311] (2008) [312] (2010)	[311] (2008) [190] (2010) [312] (2010)	[311] (2008) [190] (2010) [313] (2013) [191] (2014) [314] (2016) [315] (2017)

Material	Waste description and source	Water/binder ratio (w/b)	Binder content and type [kg/m^3]	Density of the composite [kg/m^3]	Compressive strength (28d) [MPa]	Flexural strength [MPa]	Modulus of elasticity (28d) [GPa]	Thermal conductivity [W/(mK)]
Wood	Wood chipping of raw wood from sawing process [316] (2014); *Pterocarpus soyauxii* wood wastes from furniture industry (India) [211] (2016); Spruce specie wood shavings – VELOX Werk Ltd (France) [317] (2017); Sawdust of hardwood Cedrus Deodar from wooden factory (Pakistan) [204] (2018); Wood shavings from spruce [318] (2018); Wood shavings from spruce, pre-treated with sodium silicate from wood industry [319] (2019); Wood shavings and sawdust from coniferous trees are a by-product in sawmills [320] (2020); Wood chips [321] (2020); Wood aggregates treated with sodium silicate – Granuland (France) – [171] (2021); Wood shavings was used in saturated surface dry condition [199] (2021); *Shorea robusta* wood from wood industry (Bangladesh) [322] (2021); Wood residues in the form of chips from a sawmill – G Andersson Söner AB, Linneryd, (Sweden) [323] (2021); Wood chips and sawdust residues by products of industry – Toscca Wood & Solutions (Portugal) [202] (2022); Waste wood/sawdust, by-product from wood industry[206] (2022); Wood shavings with saturated surface [324] (2022); Raw wood mechanically processed and pre-treated with sodium silicate. [325] (2023); Iroko wood chip [326] (2023).	0.26-0.65	267-633 (Cem Type I, Type II 32.5 N and 42.5 N)	[316] (2014) [317] (2017) [204] (2018) [318] (2019) [320] (2020) [171] (2021) [199] (2021) [322] (2021) [323] (2021) [202] (2022) [206] (2022) [324] (2022) [325] (2023) [326] (2023)	[316] (2014) [211] (2016) [317] (2017) [204] (2018) [320] (2020) [321] (2020) [171] (2021) [199] (2021) [322] (2021) [202] (2022) [206] (2022) [324] (2022) [325] (2023) [326] (2023)	[316] (2014) [211] (2016) [317] (2017) [204] (2018) [321] (2020) [171] (2021) [199] (2021) [322] (2021) [323] (2021) [202] (2022) [325] (2023)	[316] (2014) [317] (2017) [204] (2018) [323] (2021) [202] (2022) [324] (2022)	[204] (2018) [318] (2019) [319] (2019) [320] (2020) [171] (2021) [323] (2021) [202] (2022) [206] (2022)

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CHAPTER 3

CEMENT COMPOSITES CONTAINING END-OF-LIFE TREATED WOOD

3.1. Introduction

According to EUROSTAT [1], in 2020, the EU28 countries generated every year more than 48 million tonnes of wood waste from multiple sources (e.g. construction, agriculture and railway). It turns out that a significant part of this waste is contaminated with hazardous substances used to protect wood from biological degradation and ageing. The seriousness of the ecological risk and the human hazard of wood preservatives have been highlighted in several studies in the last few years [2–6].

Although treated wood residues are mainly composed of cellulose, hemicellulose, and lignin, small amounts of several heavy metals and organic compounds can also be found in their composition, which limits the recycling options [7], [8]. Disposal in landfills or incineration remains thus the commonest way to deal with end-of-life treated wood. However, increasing awareness about the scarcity of resources and environmental concerns with the disposal of waste in landfill have motivated researchers to investigate innovative recycling strategies.

Several recycling approaches can be exploited to add value to end-of-life treated wood, namely the production of wood-based composites. However, many industries are reluctant to incorporate wood fibres containing chemical preservatives in new materials due to health and environmental concerns, and they most often opt to use non-treated wood. Mohajerani et al [8] claim that wood-based composites are not an ideal solution as they are simply deferring disposal rather than avoiding it. However, the same authors recognise that the reuse of treated wood in construction applications is a reasonable solution if the results of leaching tests (e.g.[9], [10]) comply with regulatory limits. Following this path, several studies have investigated the environmental risk of reusing treated wood [11]–[14]. For instance, Qi [14] performed leaching tests on wood particles of CCA-treated red pine and wood-cement boards consisting of ordinary Portland cement and the same wood particles, concluding that the copper and arsenic were fixed quite well in the board, as opposed to the situation with the wood particles.

Note, however, that the environmental and health risks are not the only topic of concern when incorporating wood particles in cement composites. Major compatibility issues have been reported between some wood species and cement binders. Wood extractives, in particular, have been shown to have an important role in disturbing the chemical processes of cement hardening [15]. However, the impact of this phenomenon on the mechanical performance of wood-cement composites is difficult to predict, as it depends not only on the extractive content, but also on the chemical composition of the extractives. Moreover, other physical characteristics of the wood particles (e.g. size and geometry distribution, surface area and water absorption capacity) and composition characteristics of the mix (e.g. cement type, wood-cement ratio and water-cement ratio) contribute to the final behaviour of the composite.

A very useful method to assess the chemical compatibility between wood and cement is to compare the heat release during the exothermic process of cement hydration of a wood-cement mix with that of a corresponding cement paste without any wood. Information on the hydration rate during the initial phase of cement hardening can also be used to complement this assessment. For this purpose, several test standards can be followed (e.g. EN 196-11:2018 [16], ASTM C1702-17 [17]). Fan et al. [18], for example, investigated the compatibility of ordinary Portland cement with 15 commercially available wood species by studying cement hydration and concluded that the heat release of wood-cement pastes varies considerably, depending on the wood species. The same authors showed that wood-cement compatibility can be significantly improved by pre-treating wood particles with a saturated lime ($Ca(OH)_2$) solution. Miller and Moslemi [19] also studied nine wood species from North America and concluded that hardwoods have a stronger negative effect on the hydration of cement and tensile strength of composites than softwoods do. They also found that heartwood (central wood of trees) is more prone to affect the hydration of cement pastes than sapwood, which is probably because of the different solubility in water of saccharides present in the respective natural fibres. Kochova et al. [20] studied the effect of different organic compounds present in lignocellulose fibres on the cement hydration reactions, demonstrating the major role of glucose, mannose and xylose in cement hydration. These compounds slowed the hydration down for up to two days. Na et al. [21] also reported a greater delaying effect of glucose and sucrose compared to other compounds.

Regarding end-of-life treated wood, additional hazardous substances may be extracted depending on the preservatives used. Creosote is one of the oldest wood preservatives; it became widely used to protect timber elements that require a very long service life (e.g. bridgework, railway sleepers, marine pilings and utility poles). In addition to toxicity to fungi, insects, and marine borers, it serves as a natural water repellent. This tar-based preservative, which contains a complex mixture of natural oils, aromatic hydrocarbons (e.g. PAH and BTEX) and phenolic compounds, was extensively used before its carcinogenic properties became known. Although creosote is mostly insoluble in water, lower molecular weight compounds may become water-soluble after longer weather exposure and leach into the environment. The rest of the insoluble chemicals remain in a tar-like form until the end-of-life of the wood. Creosote is considered a restricted-use pesticide [22].

Chromated copper arsenate (CCA) was introduced later and quickly became one of the most common preservatives used to protect timber elements intended for outdoor applications. In the CCA treatment, the chromium acts as a fixing agent by helping the other chemicals to bind to the timber, also providing ultraviolet (UV) resistance. The copper protects the wood against decay, fungi, and bacteria, while the arsenic is the main insecticidal agent, protecting wood from insect-attacking, including termites and marine borers. The European Union restricts the use of arsenic, including CCA wood treatment [23]. Accordingly, CCA treated wood cannot be used in residential or domestic constructions, rather in industrial and public works (e.g. bridges, highway safety fencing, electric power lines and telecommunications poles).

Alkaline copper quaternary (ACQ) is a preservative made of copper and a quaternary ammonium compound (quat) like didecyldimethylammonium chloride. Copper is the primary bactericide and fungicide agent, while the quaternary ammonium cation is added to prevent growth of copper-tolerant bacteria, fungus, and mould, acting as an insecticide. ACQ has come into wide use following international restrictions on CCA. Its use is governed by international standards, which determine the volume of preservative uptake required for a specific timber end use (e.g. EN 351-1:2007 [24], BS 8417:2011+A1:2014 [25]). The main drawback of ACQ is the significant amount of ammonia released from treatment plants and freshly treated wood in storage yards.

However, these chemicals do not necessarily represent a problem when embedded in cement pastes [26], [27]. Schmidt et al. [28] found stronger bendability of cement test pieces containing wood treated with chromated copper arsenate (CCA). The increased compatibility of CCA treated wood was attributed to the prior acid washing of water extractives from wood by CCA preservative. Huang and Cooper [29] also confirmed the good physical-mechanical properties of cement-bonded particleboards made from CCA-treated wood. More recently, the scientific community is getting more interested in exploring the potential of bio-based cementitious composites in construction by embedding non-conventional constituents in mortars and concrete [30]–[33]. Gloria et al. [30] proposed a method for designing mouldable bio-concrete, after studying cement composites containing three different vegetable residues (wood shaving, bamboo particles and rice husk). This procedure includes a physical and morphological characterization of the bio-aggregates, as well as the analysis of their compatibility with cement-based matrices. Other studies have also investigated the feasibility of using wood ashes as supplementary cementitious materials [34]–[36]. Such ashes are mainly composed of lime and silica, but are free of undesirable organic extracts. In addition, under given circumstances, they can show pozzolanic activity [37].

As previously mentioned, environmental concerns over the disposal of preservative-treated wood waste are the main driving forces of research into new recycling strategies. It is therefore necessary to look for innovative ways to treat wood waste. This work seeks to investigate the feasibility of using end-of-life treated wood for producing lightweight cement composites. For this purpose, wood waste samples from four different sources were characterized in terms of relevant chemical and physical properties. Cement pastes containing either wood extractives or wood particles were then used to assess the wood-cement compatibility based on hydration heat and mechanical properties. Further tests were carried out to screen the potential benefits of extracting or chemically treating wood particles before adding them to the cement paste. Finally, a concrete mix containing selected wood particles was produced for a preliminary examination of the effect of wood waste on the mechanical properties of a reference concrete.

Section 3.2 presents the materials and the wood-cement pastes, fully describing all the materials and wood-cement paste compositions. Test methods are described in section 3.3. The results are presented and discussed in Section 3.4, comparing hydration heat profiles and the mechanical performance of different wood-cement mixes. The main conclusions are summarised at the end (Section 3.5).

3.2. Materials

Wood waste samples from various origins were first chemically and physically characterised. Subsequently, to evaluate the wood-cement compatibility, two types of cement pastes were prepared: a Portland cement with wood waste extractives replacing the water; and a Portland cement with wood waste particles. Portland cement CEM II/B-L 32.5N was used. Variations were introduced in terms of wood type, wood content, wood particle size, and wood pre-treatment. The analysis was carried out in two stages. First, 16 mixes were subjected to an isothermal calorimeter to evaluate the influence of the wood waste on the heat of hydration and the setting time of the cement pastes and wood-cement pastes. Then, the mixes with the best performance were subjected to mechanical tests. In both stages, a Portland cement paste was used as reference. Finally, a concrete mix containing selected wood particles were produced to initially examine the effect of wood waste on the mechanical properties of a reference concrete.

3.2.1. Wood wastes

Four types of wood waste were supplied in the form of chips (size up to 20 mm) by Toscca Wood & Solutions, as illustrated in Figure 3.1.

WW1 WW2 WW3 WW4

Figure 3.1: Wood waste samples used in this work.

Information about the wood samples, including potential preservatives and estimated annual production, is summarised in Table 3.1. Note that the potential preservatives were identified based on the origin of the wood waste and decade of production. Given the nature and the amount of chemicals found in the eluate of WW4, it was decided not to proceed with this wood waste in the production of cement pastes and the remaining tests.

Table 3.1: Information about the wood samples

Sample reference	Wood source	Decade of production	Potential preservatives	Estimated annual production
WW1	Sawmills from untreated wood	2010-2020	---	1 500 m^3/year
WW2	Agriculture posts and fences	1990-2000	Alkaline copper quaternary (ACQ)	2 500 m^3/year
WW3	Agriculture posts and fences	1990-2000	Chromated copper arsenate (CCA)	10 000 m^3/year
WW4	Railway sleepers	1980-1990	Creosote	500 m3/year

3.2.2.Wood-cement pastes

To proceed with the investigation of end-of-life wood-cement composites, several cement pastes containing wood extractives and wood particles were prepared varying the type of wood (WW1, WW2 and WW3), the wood particles content (5 w%, 10 w% and 15 w%), the particle size (≤ 4 mm and ≤ 10 mm), and the pre-treatment of the wood (cold water extraction, hot water extraction, calcium hydroxide extraction and sodium silicate mineralization). A reference mix without wood was also prepared for comparison purposes. The experimental designs of the wood-cement pastes used in the hydration heat evaluation and mechanical tests are presented in Tables 3.2 and 3.3, respectively. For clarity's sake, wood-extractive cement paste (WECP) and wood-cement paste (WCP) samples were identified as WECP/WCP_wt%WWi_hTT, where wt% is the relative amount of wood in weight, WWi is the wood type, h is the duration of pre-treatment in hours, and TT is the type of treatment.

Prismatic specimens of 160 mm x 40 mm x 40 mm with a water/cement ratio of 0.3 and cement pastes with a water/cement ratio of 0.5 were produced to perform the mechanical tests and hydration heat tests, respectively. The wood was previously ground, sieved and standardised by discarding particles that passed through the 1 mm sieve. The wood was then saturated for 24 h and the free surface water was discounted from the mix content. The water used for saturation was discarded, and tap water was used instead (except when studying the effect of wood extractives). The mix preparation and subsequent curing process followed the procedures of standard EN 1015-11:2019 [38] for cement pastes.

Table 3.2: Wood-cement pastes (WCPs) used in the hydration heat evaluation (wood particle size = 10 mm)

Sample reference	Parameter	Wood waste type	Wood waste (w %)	Wood waste pre-treatment
Control	-	-	-	-
WECP_WW1_E24hCW	Extractives	WW1 extract (24 h cold water)	-	-
WECP_WW1_E48hCW		WW1 extract (24 h cold water)	-	24 h cold water
WECP_WW1_E2hHW		WW1 extract (2 h hot water)	-	-
WCP_5%WW1*	Wood type	WW1	5	24 h cold water
WCP_5%WW2		WW2	5	
WCP_5%WW3		WW3	5	
WCP_5%WW1*	Wood content	WW1	5	24 h cold water
WCP_10%WW1			10	
WCP_15%WW1			15	
WCP_5%WW1_4hCW	Wood pre-treatment	WW1	5	4 h cold water
WCP_5%WW1_6hCW			5	6 h cold water
WCP_5%WW1_8hCW			5	8 h cold water
WCP_5%WW1*			5	24 h cold water
WCP_5%WW1_2hHW			5	2 h hot water
WCP_5%WW1_24hCH			5	24 h Calcium hydroxide
WCP_5%WW1_24hSS1%			5	24 h Sodium silicate 1%
WCP_5%WW1_24hSS10%			5	24 h Sodium silicate 10%

*Same sample

Table 3.3: Wood-cement pastes (WCPs) used in the mechanical characterisation (wood particles were immersed in water for 24 hours before inclusion in the cement paste)

Sample reference	Parameter	Wood waste type	Wood waste (w %)	Particle size (mm)
Control	-	-	-	-
WCP_5%WW1*	Wood type	WW1	5	10
WCP_5%WW2		WW2	5	10
WCP_5%WW3		WW3	5	10
WCP_5%WW1*	Wood content	WW1	5	10
WCP_10%WW1			10	10
WCP_15%WW1			15	10
WCP_5%WW1*	Particle size	WW1	5	10
WCP_WW1_4mm			5	4

*Same sample

Prior to the mechanical performance characterisation, the wood-cement pastes (WCPs) were evaluated for consistency in the fresh state through the flow table test as recommended in EN 1015-

3:1999/A2:2006 [39]. Three parameters, namely, wood waste incorporation content, particle size gauge, and wood waste type, were chosen to assess their influence on the consistency of the WCP in the fresh state. Therefore, six WCPs, plus the reference, were selected to evaluate consistency.

A preliminary assessment of the possibility of developing a wood-cement concrete (WCC) was carried out next. Three concrete mixes were developed by partially replacing the mineral aggregates for the studied wood waste types. An ordinary Portland cement concrete composition was used as reference for comparison and aggregates replacement. To produce the reference concrete and the wood-concrete composites, as well as WW1, WW2 and WW3, three mineral aggregates were used: sand 0/4 (S0/4), gravel 0/5 (G0/5) and gravel 1 (G1). Portland cement CEM II/A-L 42.5 R, classified according to EN 197-1:2011 [40] was used. The wood wastes were incorporated after 24 h submerged in water by replacing 25 v% the mineral aggregate (aggregate fractions were replaced based on the particle size distribution of each wood waste). The water absorbed by the wood was discounted from the contents. All wood-concrete composites also included a superplasticiser (Dynamon SP1, Mapei), used to improve the workability. The mix designs of the reference concrete and wood-concrete composites are detailed in Table 3.4.

Table 3.4: Wood cement concrete (WCC) mixes (proportions in weight)

Mix	Cement	Water	S0/4	G0/5	G1	Wood waste (dry)	Superplasticiser (1)
Reference	1.00	0.40	1.73	1.15	1.68	-	-
WCC_WW1	1.00	0.40	0.93	0.88	1.63	0.18 (WW1)	0.07
WCC_WW2	1.00	0.40	1.57	0.67	1.18	0.17 (WW2)	0.05

(1) Dynamon SP1, Mapei

3.3. Methods

This section provides comprehensive details regarding the methodologies employed for conducting chemical and physical tests, evaluating hydration heat, and performing mechanical tests.

3.3.1.Chemical characterisation

All the samples were first reduced to a particle size below 4 mm using a laboratory blade mill (Retsch, SM 100). Aqueous extracts of the different wood residues were then produced based on a one-stage batch test of 24 h at a liquid to solid ratio (L/S) of 10 L/kg dry matter according to EN 12457-2:2002 [41]. For this purpose, the sample material was brought into contact with an appropriate amount of deionized water in a polypropylene flask and mixed for 24 h at 10 rpm using a rotary shaker (VELP Scientifica, Rotax 6.8 overhead mixer). Note that this method, specifically developed to assess chemicals that can be leached from waste materials, assumes that equilibrium or near-equilibrium is achieved between the liquid and solid phases while the test is carried out. Subsequently, the solid residue was separated by filtration (0.45 µm pore filter) and the resulting eluates analysed by inductively coupled plasma optical emission spectrometry (Perkin Elmer, Optima 8000), gas chromatography associated with mass spectrometry (Bruker, SCION 456-GC, EVOQ TQ MS), liquid chromatography (Perkin Elmer, Flexar uHPLC), combustion-infrared (Analytik-Jena, multi N / C 3100) and other classic chemical methods.

3.3.2.Physical characterisation

The previously mentioned wood samples, were characterised in terms of water absorption, density and free surface water by adapting the procedures described in EN 1097-6:2013 [42]. Accordingly, the wood samples were dried at 105 ºC for 24 h using a heating oven (Memmert, UF110) and ground into particles of varying size using the same laboratory blade mill coupled to different sieves. The three wood samples (WW1, WW2 and WW3) were characterised using particles ≤ 10 mm. The untreated wood sample (WW1) was additionally characterized using wood particles ≤ 4 mm, with a view to studying the influence of the particle size. A sample of 22 ± 4 g each of dried and ground wood was weighed and introduced into the pycnometer. To determine the progress of water absorption, the pycnometer was weighed after 5 min (m_0), 60 min (m_1), 120 min (m_2), 240 min (m_4), 330 min ($m_{4.5}$), 1260 min (m_{21}) and 1440 min (m_{24}). After the last weighing, the wood was left to drain for 5 min and weighed again. Then, the wood was gently dried with absorbent paper for 15 sec to remove the free surface water and weighed once again.

3.3.3.Hydration heat evaluation

A hydration heat study was conducted using an isothermal calorimeter (I-Cal 4000 HPC, Calmetrix) to evaluate the influence of the wood on the heat of hydration of a cementitious paste at 23 °C. Performance calibration was conducted in accordance with the manufacturer's specifications.

The assessment was carried out by first evaluating the wood waste extractives' influence on the heat of hydration. This was done by producing cement pastes in which the water was replaced with wood waste extractives. The aqueous extractives were prepared with WW1, first soaking it in cold water (laboratory temperature), for 24 h and 24 h + 24 h, and then in hot water at 80 °C, for 2 h. Afterwards, WW1, WW2, and WW3 particles were incorporated in the cement pastes and the influence of the different wood waste types evaluated. Finally, the influence of the incorporation by weight (5%, 10% and 15%) for wood waste WW1 was also evaluated. Generally, the incorporation of wood fibres delays the cement setting time and decreases the hydration heat of cement, mainly because of the hydrolysis and solubilisation of the wood extractives [43]. In this context, wood waste WW1 was treated in cold water, hot water (80 °C) and a saturated solution of calcium hydroxide ($Ca(OH)_2$) prior to sample preparation, aiming to reduce wood extractives. The strategy of mineralising wood residues by treating the wood with sodium metasilicate (1 and 10%) was also exploited for WW1. Except for hot water treatment, in which the wood has been treated with hot water for two hours, wood waste was always extracted for 24 h with the different extractive solutions. The ratio of wood to the extractive solutions was 1:10 by volume. All wood waste incorporated in the cement pastes had prior cold-water extraction for 24 h, except for the pre-treatment analysis. A cement paste without wood or wood extractives was used as control.

To guarantee the cement content and a proper measurement temperature, the accurate amount of liquid was first measured and left for at least 2 h inside the calorimeter cell to stabilise at 23 °C. Meanwhile, cement was weighed, and the cement paste was prepared directly in the sample vial that was later placed inside the calorimeter cell. All samples had a fixed value of 40.00 g of cement and 20.00 g of water, under the range specified by the ASTM C1702-17 [17]; samples that had wood waste incorporated had the free surface water discounted from the added water. The samples were hand mixed for 30 s using a plastic spoon that was left inside the sample cup to prevent cement loss. The isothermal calorimeter measures the heat flow by means of a heat flow sensor, which is under the sample cup and in contact with a heat sink. To determine the heat of hydration of each sample, the measured thermal powers were integrated from the beginning to 48 h. Data were recorded per minute. The experimental design is detailed in Table 3.2.

3.3.4. Mechanical tests

To evaluate the mechanical properties of the wood-cement pastes (WCPs), flexural (3- point) and compressive strength tests were performed according to EN 1015-11:2019 [38]. An electromechanical universal testing machine, Instron model 59R5884 with a load cell of 10kN, was used in both tests. The load was applied without shock at a uniform rate of 10N/s and 50N/s, in the flexural and compressive strength tests, respectively. The compressive strength is determined from the two parts provided by the flexural strength test. For each mix, three prismatic specimens of 160 mm x 40 mm x 40 mm were produced to perform three flexural strength tests and six compressive strength tests.

Flexural strength, St_F, in N/mm^2, was determined according to equation $St_F = 1.5(F_F \, x \, l)/(b \, x \, d^2)$, where F_F is the maximal load, in N, l the span (distance between support rollers), 100 mm and *b* and *d* correspond to the width and height of the specimen (both 40 mm).

Compressive strength, St_C in N/mm^2, was calculated by dividing the maximal load test, F_C in N, by the area of the cross section of the specimen, A (1600 mm^2).

To evaluate the mechanical properties of the wood-cement concrete (WCC) mixes, compressive strength tests were performed according to EN 12390-3:2019 [44]. The compressive strength σ, in N/mm^2, was assessed at 7 and 28 days for three cubic specimens from each composition at each age. A compression press (Controls, 50-C56V2) with a load cell of 3000 kN was used. The load was applied at a rate of 0.6 ± 0.2 MPa/s.

3.4. Results and discussion

This section presents the experimental results of the chemical and physical characterisation, the hydration heat evaluation and the mechanical tests.

3.4.1.Chemical characterisation

Although there is no specific EU legislation regulating the use of end-of-life wood in construction products, it is common practice to screen for potential leachable substances that may represent a risk for the health and environment. As previously mentioned, taking into account the origin of the wood waste and the decade of production, it can be expected that the wood samples used in this work may contain creosote, CCA or ACQ preservatives.

Thus, to ascertain the nature of any preservatives and assess the amount of leaching substances, aqueous extracts of the different wood residues were produced according to EN 12457-2:2002 [41]. The aqueous extracts were then chemically analysed according to the procedures and criteria established for the acceptance of waste at landfills, originally established by the EU Council Decision 2003/33/EC [45] and later transposed into the law of the various Member States. Table 3.5 summarizes the results obtained, highlighting those exceeding the limits for the acceptance of waste in landfills for inert waste and non-hazardous waste.

Although most of the parameters surveyed did not have quantified, a few chemicals exhibited values above the limits of quantification (LOQ) of the methods (and, in some cases, above the acceptance limits of inert and non-dangerous landfill sites), confirming the presence of the chemical preservatives indicated in Table 3.1. As expected, no relevant heavy metals or organic compounds were detected in the eluate of the WW1 sample, assigned to untreated wood. The eluates of the WW2 and WW3 samples, respectively assigned to ACQ and CCA treated wood, revealed the presence of relevant heavy metals. In this case, only copper was detected in the eluate of the WW2 sample in a significant amount, while smaller amounts of several heavy metals (e.g. copper, arsenic and chromium) were detected in the eluate of the WW3 sample. As previously mentioned, the environmental risk of using wood particles containing heavy metals is low, since cement composites are found to fix such elements quite well [14]. Finally, relevant organic compounds given by the phenol index, mineral oil and PAH parameters were detected in the eluate of the WW4 sample, assigned to creosote treated wood.

Additional GC-MS studies were carried out to further investigate the composition of the eluates, concluding that a great variety of organic compounds were leached from WW4 sample, such as quinoline and its isomers, substituted quinolines, o-cresol and p-cresol, phenolic compounds and PAH (e.g. acenaphthylene, phenanthrene and naphthalene, etc.). The total ionic current (TIC) chromatogram for the eluate of the WW4 is presented in Figure 3.2.

Table 3.5: Leaching results according to EN 12457-2:2002 [41]

Parameter	LOQ	Wood sample			
		WW1	WW2	WW3	WW4
pH (25 ºC)	---	4.6	7.1	5.1	5.3
Electric cond. 25 ºC (mS/cm)	---	153	610	141	220
Chloride (mg/kg)	40	<LOQ	132	177	44
Fluoride (mg/kg)	4	<LOQ	<LOQ	<LOQ	<LOQ
Sulphate (mg/kg)	40	<LOQ	72	114	68
Phenol index (mg/kg)	0.50	2.2	3.8	1.2	827 *
As (mg/kg)	0.1	<LOQ	<LOQ	129 *	0.3
Ba (mg/kg)	2.0	<LOQ	<LOQ	<LOQ	<LOQ
Cd (mg/kg)	0.01	<LOQ	<LOQ	0.3	<LOQ
Cr (mg/kg)	0.2	<LOQ	<LOQ	21 **	<LOQ
Cu (mg/kg)	0.4	<LOQ	643 **	65 **	<LOQ
Hg (mg/kg)	0.01	<LOQ	<LOQ	<LOQ	<LOQ
Mo (mg/kg)	0.2	<LOQ	<LOQ	<LOQ	<LOQ
Ni (mg/kg)	0.1	<LOQ	<LOQ	<LOQ	<LOQ
Pb (mg/kg)	0.1	<LOQ	<LOQ	<LOQ	<LOQ
Sb (mg/kg)	0.02	<LOQ	<LOQ	0.1 *	<LOQ
Se (mg/kg)	0.02	<LOQ	<LOQ	<LOQ	<LOQ
Zn (mg/kg)	0.2	0.8	0.7	0.2	0.7
TOC (mg/kg)	250	502	1195	187	5814
Mineral Oil C10-C40 (mg/kg)	100	<LOQ	105	<LQ	1265 *
BTEX (mg/kg) (1)	0.15	<LOQ	<LOQ	<LOQ	<LOQ
PCB (mg/kg) (2)	0.35	<LOQ	<LOQ	<LOQ	<LOQ
PAH (mg/kg) (3)	16.0	<LOQ	<LOQ	<LOQ	43.1 *

(1) BTEX - Benzene, Toluene, Ethylbenzene, m-Xylene, p-Xylene, o-Xylene

(2) PCB - PCB 28, PCB 52, PCB 101, PCB 118, PCB 138, PCB 153, PCB 180

(3) PAH - Acenaphthene, Acenaphthylene, Anthracene, Benzo(a)anthracene, Benzo(a)pyrene, Benzo(b)fluoranthene, Benzo(g,h,i)perylene, Benzo(k)fluoranthene, Chrysene, Dibenzo(a,h)anthracene, Phenanthrene, Fluoranthene, Fluorene, Indene(1,2,3-cd)pyrene, Naphthalene, Pyrene

* Exceed the limits for the acceptance of waste in landfills for inert waste

** Exceed the limits for the acceptance of waste in landfills for non-hazardous waste

LOQ - Limit of quantification, i.e. the smallest concentration of a substance that is possible to be determined by means of the respective analytical method.

As expected, some organic compounds commonly found in virgin wood were also detected in the eluate of this sample (WW4), as well as in the eluates of the WW1 and WW2 samples. However, very low amounts of organic compounds were found in the eluate of the WW3 sample. To illustrate this point, a stacking representation of all chromatograms is shown in Figure 3.3.

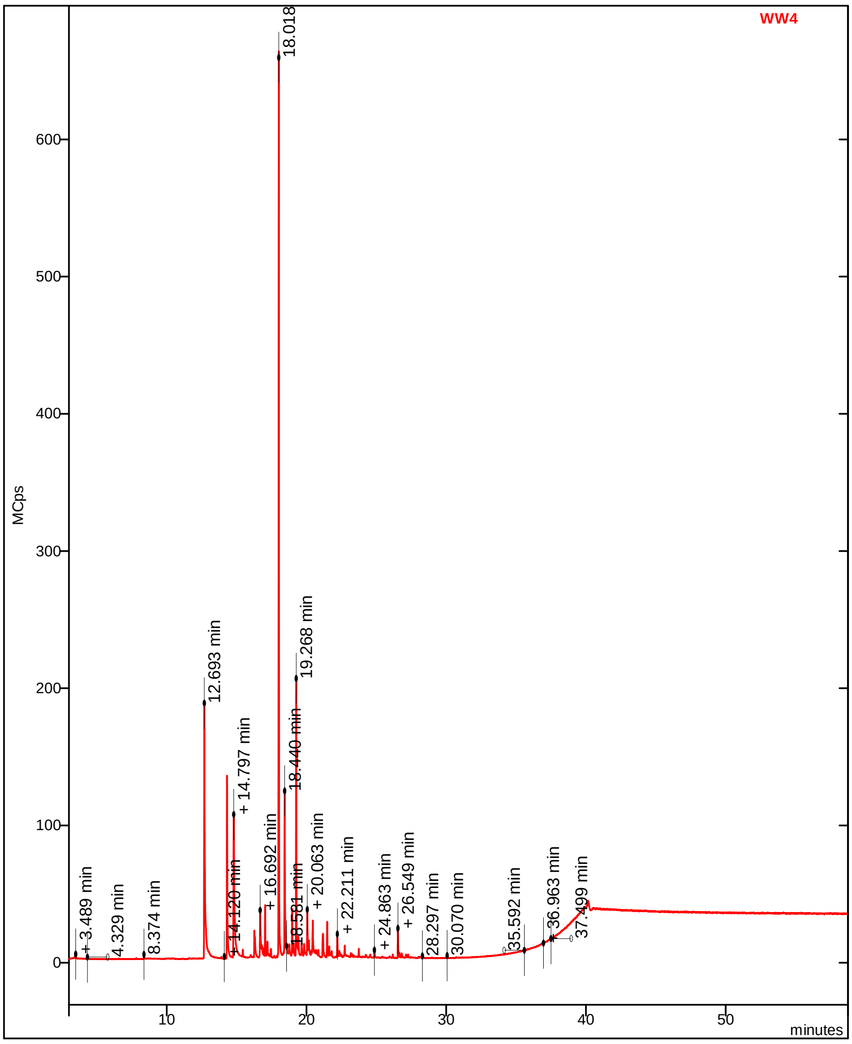


Figure 3.2: Total ionic current (TIC) chromatogram for the eluates of the WW4 sample.

Given the nature and the amount of chemicals found in the eluate of the WW4 sample that represent a significant risk for the human health and environment, was decided not to proceed with the physical characterization of this wood waste and subsequent incorporation in the cement composites. As noted earlier, some of the compounds found in creosote-preserved wood have been linked with harmful effects to human health.

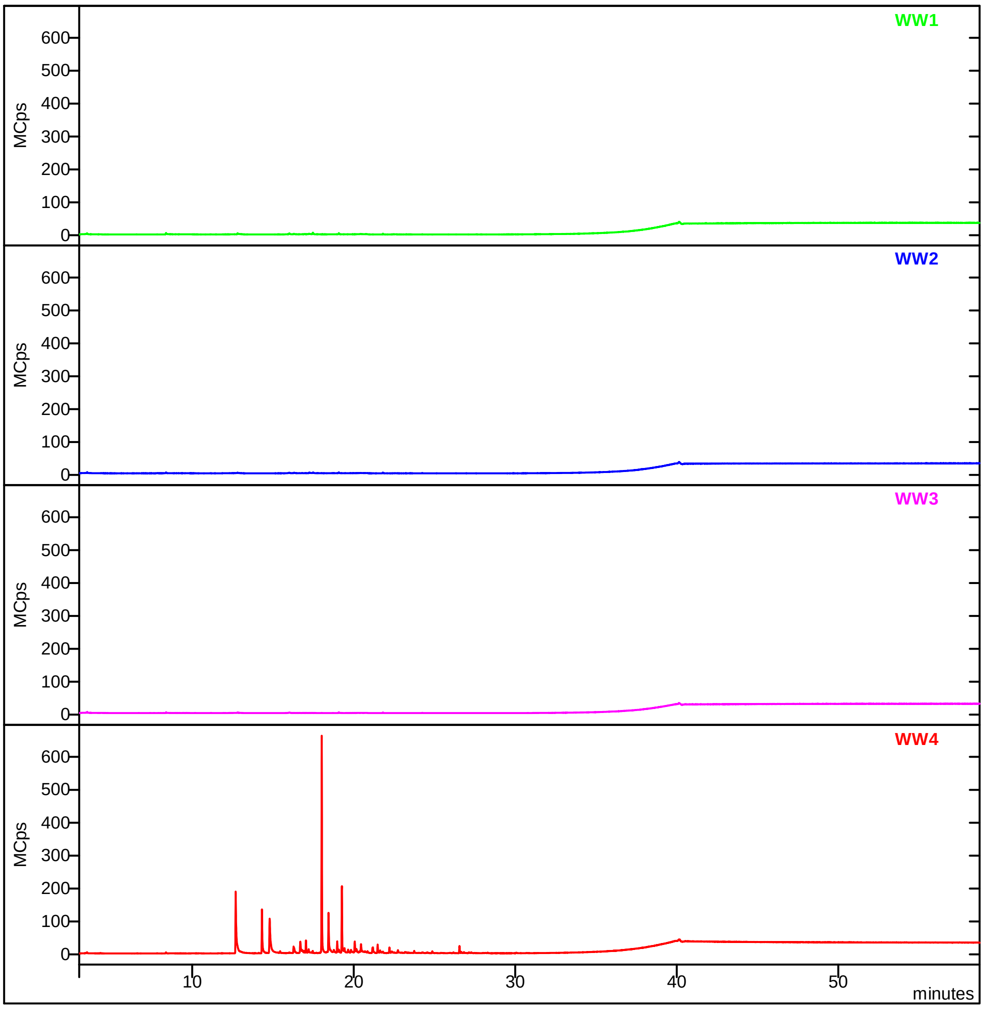


Figure 3.3: Stacking representation of the total ionic current (TIC) chromatograms for the eluates of the WW1, WW2, WW3 and WW4 samples.

3.4.2.Physical characterisation

Besides the chemical aspects, the design of innovative composites also requires a complete physical characterisation of the wood waste. This should cover, for example, water absorption capacity and density, and it is stressed that particle size can have a significant influence on these properties.

Thus, each wood waste type was physically characterised in terms of density, water absorption and free surface water by adapting the procedures of the European Standard EN 1097-6:2013 [42].

The three as-received wood waste types were placed in a drying oven at 105 ºC for 24 h to dry, after which they were grinded into small particle size using a powder grinder and a screen. The influence of the particle size gauge was studied for the virgin wood (WW1) ground with a 4 mm and 10 mm screen. The other two wood wastes were studied for only one particle size (10 mm screen).

The wood waste physical characterisation results are given in Table 3.6 and the water absorption is shown in Figure 3.4.

Table 3.6: Wood waste physical characterisation

Wood waste type	Maximum size (mm)	Density (kg/m^3)		Water content (%)		
		Oven dried	Saturated with dry surface	Water absorption	Free surface water	Total
WW1	4	280	1070	239	54	293
	10	380	1090	193	47	240
WW2	10	390	1060	154	61	215
WW3	10	390	1070	147	67	214

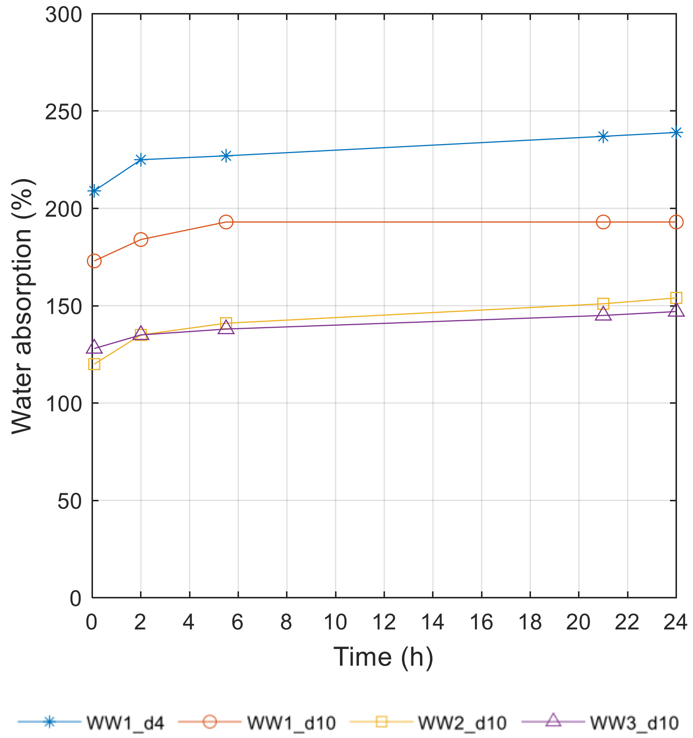


Figure 3.4: Water absorption by different wood waste type (WW1, WW2 and WW3) and wood particle size (4 mm, 10 mm) over time.

The results show that a substantial amount of water is absorbed by the wood fibres or dragged in the surface after immersion (free surface water). It also shows that the total water content varies significantly between the untreated wood sample (240%) and treated wood samples (214 % and 215 %) for the same particle size (10 mm), which could be related to the micropore structure of the different wood waste samples [36]. Additionally, as expected, an even greater effect is observed when particle size changes from 10 mm (240%) to 4 mm (290%), which is likely to occur due to the easier water intake considering the larger surface area of the wood particles.

The results of water absorption over time further show that, although most water is absorbed after 2 h (> 90%), longer may be needed to achieve complete hydration of the wood fibre. During the production of cement composites, incomplete hydration of the fibre may result in competition for water.

3.4.3.Hydration heat evaluation

Since monitoring the hydration heat of cement is one of the best ways to check its chemical compatibility with different additions, 15 different cement pastes containing wood extractives and wood particles were produced as previously described and the hydration heat over 48 hours was evaluated against a control mix. For the purposes of the study, variations were introduced in terms of the type of wood (WW1, WW2 and WW3), the wood content (5 w%, 10 w% and 15 w%) and the pre-treatment of wood (cold water extraction, hot water extraction, calcium hydroxide extraction and sodium silicate mineralization). The results are summarised in Table 3.7.

Table 3.7: Heat of Hydration (HoH) after 48 hours for the different wood-cement pastes (WCPs)

Sample reference	**Parameter**	**48 h HoH**		**Setting time (h)**
		HoH (J/g)	**Reduction (%) relative to the control sample**	
Control	-	243.9	-	6.67
WECP_WW1_E24hCW	Extractives	235.8	3	7.38
WECP_WW1_E48hCW		240.1	2	6.97
WECP_WW1_E2hHW		240.9	1	8.28
WCP_5%WW1*	Wood type	233.3	4	7.68
WCP_5%WW2		236.0	3	7.50
WCP_5%WW3		236.3	3	7.43
WCP_5%WW1*	Wood content	233.3	4	7.68
WCP_10%WW1		216.6	11	9.07
WCP_15%WW1		209.6	14	9.63
WCP_5%WW1_4hCW	Wood pre-treatment	230.1	6	7.83
WCP_5%WW1_6hCW		231.4	5	7.90
WCP_5%WW1_8hCW		232.1	5	7.94
WCP_5%WW1*		233.3	4	7.68
WCP_5%WW1_2hHW		235.2	4	7.97
WCP_5%WW1_24hCH		231.3	5	7.37
WCP_5%WW1_24hSS1%		234.1	4	7.68
WCP_5%WW1_24hSS10%		237.6	3	9.17

*Same sample

As mentioned above, a control mix was analysed resulting in a 48 h HoH of 243.9 J/g of cement. Regarding the extractive influence, the pastes does not show a significant 48 h HoH reduction in comparison with the control mix, with the WECP_WW1_E24hCW, WECP_WW1_E48hCW and WECP_WW1_E2hHW pastes showing respectively 3%, 2% and 1% of 48 h HoH reduction. Note that a study carried out with the control sample for 6 replicas recorded a standard deviation of 1.3 J/g with a variation coefficient of 0.6%. However, according to EN 196-11:2018 [16], two results for the same sample should not differ by more than 10 J/g, a value only slightly exceeded for 10% and 15% incorporation of wood particles. A setting time delay was also observed for all the cement pastes, with WECP_WW1_E2hHW presenting the highest impact (≈ 2 h). These results can be explained since some of the wood extractives are expected to generate a delay in the setting time without significantly affecting the extent of HoH. Figure 3.5 shows the HoH (left) and the thermal power (right) plots for pastes containing different wood extracts from that in the control.

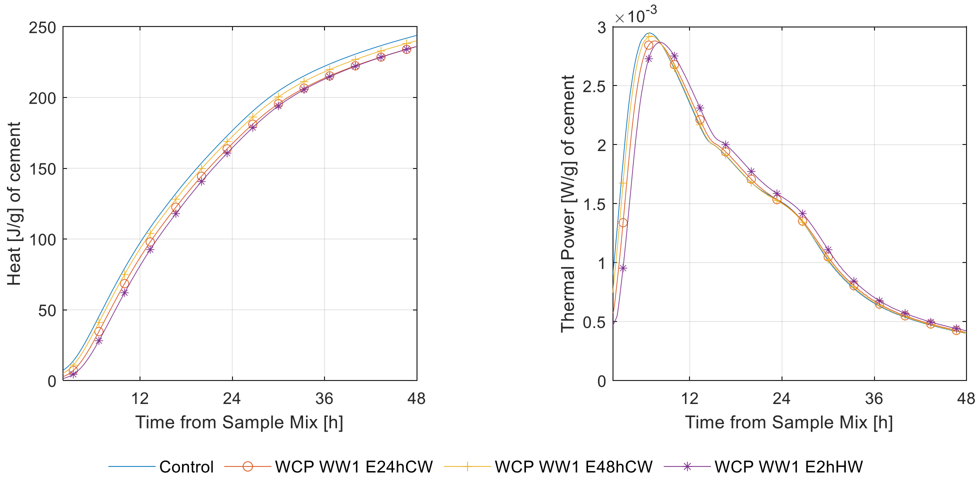


Figure 3.5: Evolution of HoH (left) and thermal power (right) for different wood-cement pastes (extractive influence).

Regarding the waste type, WCP_5%WW1 had the worst performance by reducing the 48 h HoH by 4% relative to the control mix, while WCP_5%WW2 and WCP_5%WW3 reduced it by only 3%. WCP_5%WW1 also recorded the longest setting time, nearly 1 h. Both results were expected because WW2 and WW3 had been leached during their service life, as opposed to WW1. Furthermore, the preservative treatments could be responsible for reducing the release of undesired wood extractives. Figure 3.6 shows the HoH development (left) and the thermal power progress (right) for pastes containing different waste type in comparison with the control.

The HoH results from the wood incorporation by weight decreased significantly, based on the incorporation increase where WCP_5%WW1, WCP_10%WW1 and WCP_15%WW1 respectively saw 4, 11, and 14 % reductions in HoH. Note that a greater effect of the wood particles on the cement paste was expected, compared with the wood extractives, considering the liquid/solid ratio used to produce the eluates. In terms of setting time, a significant time increase was also noted where

WCP_15%WW1 took almost 3 h longer than the control and almost 2 h more than WCP_5%WW1. The increase of wood content also increases the disturbance and the extractive content in the cementitious matrix, thereby justifying the results. Figure 3.7 shows the HoH (left) and the thermal power plots (right) for pastes with different wood contents from the control.

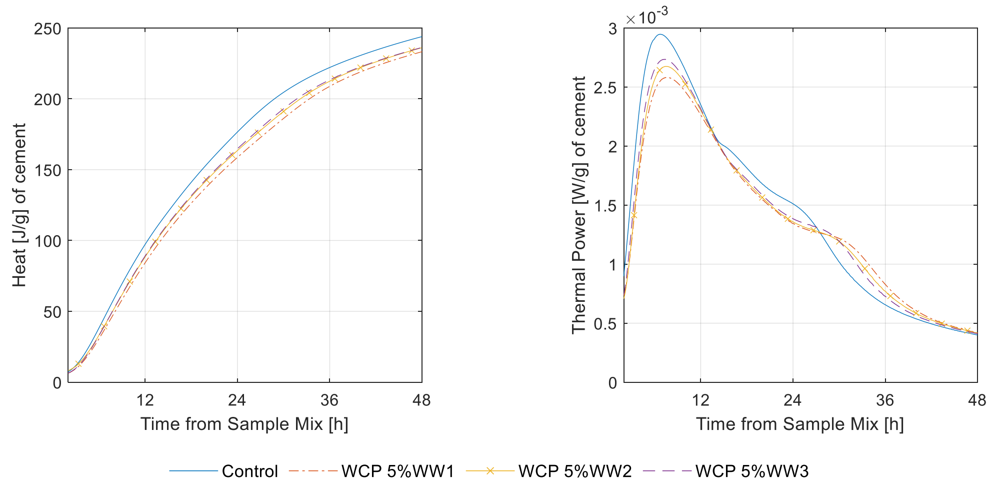


Figure 3.6: Evolution of HoH (left) and thermal power (right) for different wood-cement pastes (wood type influence).

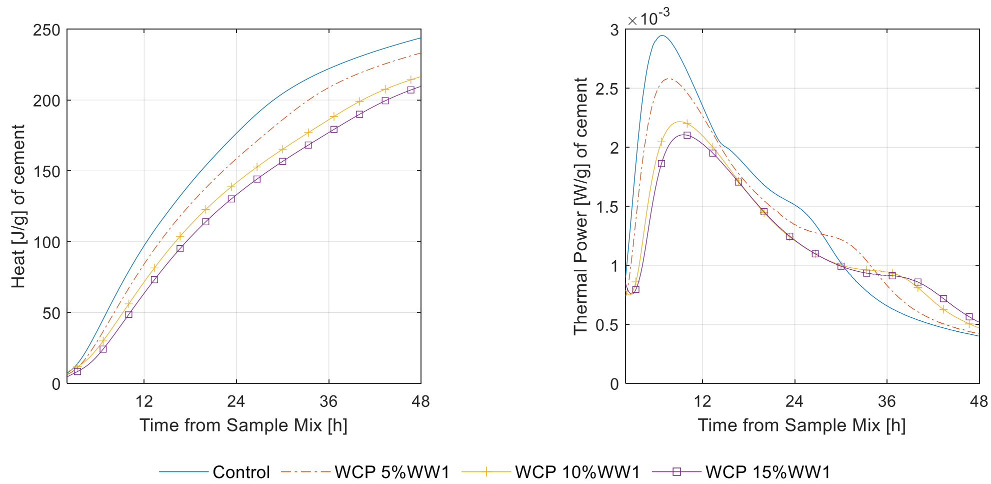


Figure 3.7: Evolution of HoH (left) and thermal power (right) for different wood-cement pastes (wood content influence).

Although the wood pre-treatments did not lead in general to any significant improvement in the HoH performance of the cement pastes, a slight improvement was exhibited by WCP_5%WW1_24hSS1%, WCP_5%WW1_24hSS10% and WCP_5%WW1_2hHW compared with WCP_5%WW1. Comparing now WCP_5%WW1_4hCW, WCP_5%WW1_6hCW and WCP_5%WW1_8hCW, it was found that the cold-water extraction time has little influence on the results of the HoH. Apart from the impact on the HoH, WCP_5%WW1_2hHW, WCP_5%WW1_4hCW, WCP_5%WW1_6hCW and WCP_5%WW1_8hCW had a setting time similar to that identified in WCP_5%WW1, which emphasises that the impact of the presence of particles in disturbing the cementitious matrix is greater than that of the wood extractives. Besides having improved HoH performance, WCP_5%WW1_24hSS10% recorded an almost 2 h longer setting time than the other mixes. Figure 3.8 shows the HoH (left) and the thermal power (right) evolution for pastes containing wood with different pre-treatments, compared with the control.

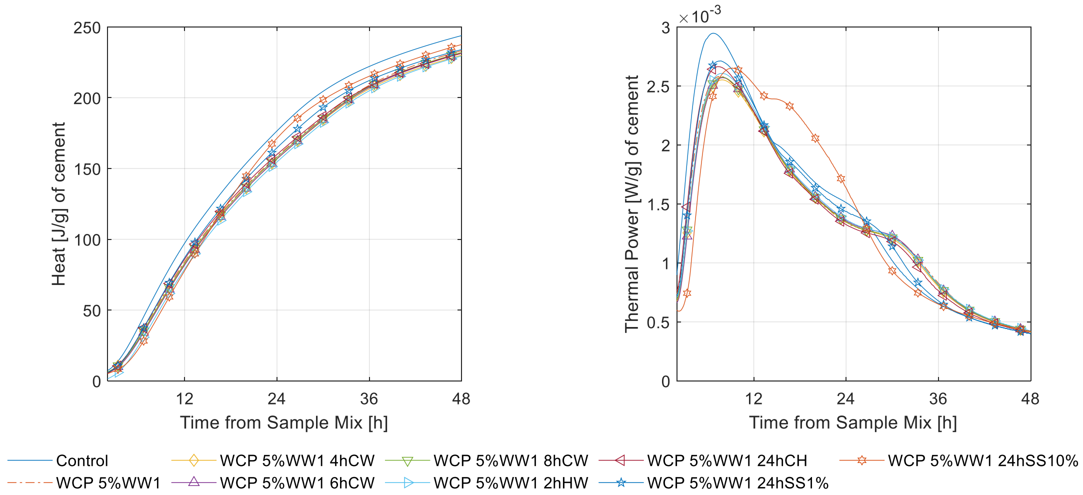


Figure 3.8: Evolution of HoH (left) and thermal power (right) for different wood-cement pastes (wood pre-treatments influence).

3.4.4.Mechanical tests

To further study the effect of wood waste incorporation on the mechanical properties of cement composites, nine cement pastes containing wood particles were produced as previously described. For the purposes of the study, variations were introduced in terms of the type of wood (WW1, WW2 and WW3), the wood content (5 w%, 10 w% and 15 w%) and wood particle size (4 mm and 10 mm).

The consistency of six WCPs was determined by the flow table test in the fresh state during the prismatic specimen preparation (water/cement ratio of 0.3). The consistency results from the wood waste incorporation content showed a decrease in the consistency with increased incorporation of wood in the mix, which can be related to the organisation of the fibres into the cementitious matrix. This behaviour is similar to a consistency assessment made by researchers who replaced cement with sawdust in up to 5 w% [46]. However, compared with the reference paste, WCP_5%WW1 showed a small increase in consistency. When evaluating the wood particle size, WCP_5%WW1_4MM showed a significant increase in flowability compared with WCP_5%WW1 (10 mm) and with the reference. The water absorption behaviour of the wood fibres could explain this characteristic and the lower consistency recorded for WCP_5%WW2 and WCP_5%WW3. On the one hand, the higher water absorption of the 4 mm gauge WW1 can lead to water being released into the mix because of the heat generated in the initial hydration of the cement. On the other hand, the low water absorption of WW2 and WW3 can justify the differences found in the results when different wood waste types were incorporated (WCP_5%WW1, WCP_5%WW2 and WCP_5%WW3). The results of the consistency test are presented in Table 3.8.

Table 3.8: Consistency in fresh state (flow table test)

Paste	Consistency (mm)	Variation (%) relative to the reference sample
Reference	193 ± 2	-
WCP_5%WW1	203 ± 3	5
WCP_10%WW1	193 ± 0	0
WCP_15%WW1	165 ± 2	15
WCP_5%WW1_4MM	218 ± 2	13
WCP_5%WW2	189 ± 1	2
WCP_5%WW3	187 ± 5	3

The results of the mechanical tests are presented in Figure 3.9. The compressive strength results show that the incorporation of wood fibres leads to a considerable reduction in compressive strength relative to the reference. It seems, however, that the main impact is related to the wood incorporation content, while only small variations were found when changing the wood waste type and particle size. Reductions of 43%, 64% and 80% of compressive strength at 28 days were found for WCP_5%WW1, WCP_10%WW1 and WCP_15%WW1, respectively. A similar work that studied mortars containing not only cement but also fine aggregates, reports that adding sawdust to replace 5 w% of cement, which is nearly 2 w% of the sample total mass, led to a reduction of 28% in compressive strength [47]. Other researchers assessed wood-cement pastes in which cement was replaced with sawdust in amounts of around 9%, 17% and 23 w% found that compressive strength fell by 49%, 57% and 76 % at 28 days, respectively [37]. However, smaller effects were reported on the mechanical properties of wood-cement boards when using wood ashes as a partial replacement for cement up to 30% [36].

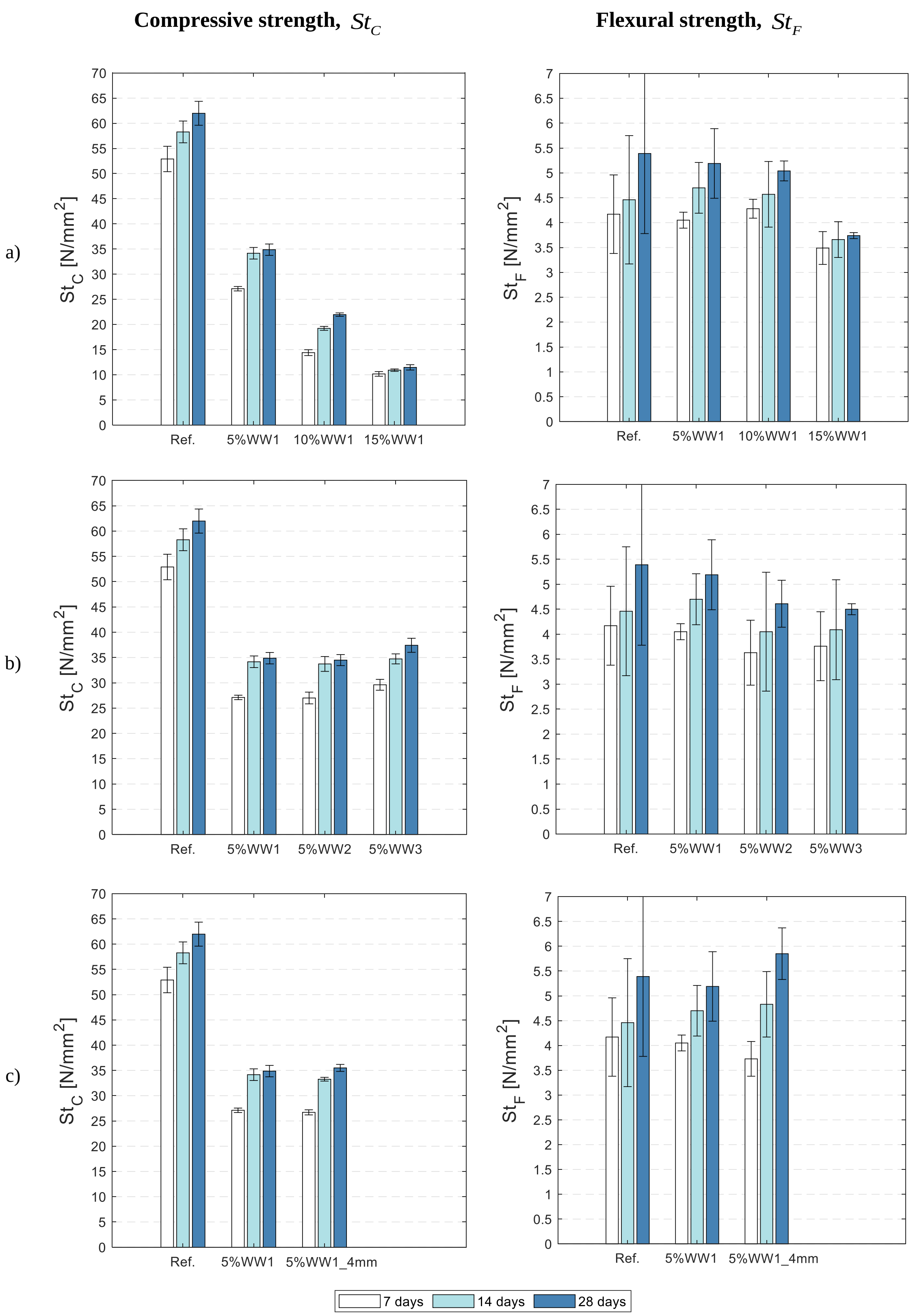
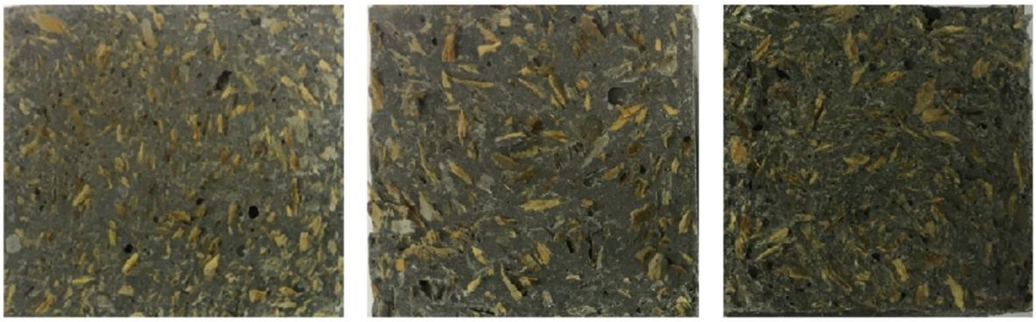


Figure 3.9 : Compressive strength, St_C , (left) and Flexural strength, St_F , (right) mean results (including the $\pm$ standard deviation): a) Wood waste content; b) Type of wood waste; c) Maximum size.

Although small variations can be seen between the different samples, the high variability of the flexural strength results means that conclusions cannot be drawn on the actual effect of wood incorporation. This could be caused by the heterogeneous dispersion of wood particles measuring up to 10 mm, when test specimens of 160 mm x 40 mm x 40 mm are used. Additionally, the percentage of volume occupied by wood particles is significant, even with low incorporation of wood (Figure 3.10). Researchers who carried out a similar study with a mortar containing nearly 2 w% of sawdust in the sample total mass, recorded a reduction of 20% in flexural strength [47]. This decrease could be related directly to the cement reduction differing from the present work, which had no inert besides the wood waste.



5%WW1_4mm	5%WW1	15%WW1
39%	38%	43%

Figure 3.10: Test specimens' cross-section images and percentage of area occupied by the wood fibres calculated with Image J software (version 1.52a).

The compressive strength of the wood-cement concrete has been also assessed. This highlighted that, like WCP, the incorporation of wood in the concrete significantly reduced the mechanical performance of the composites. When the composites were being prepared, it was clear that the workability of the mixes was poor and compromised the composite production and strength development. This can be seen from the voids distributed in the cubic specimen and the mass of the samples. Therefore, it is important to analyse the compressive strength results not only in terms of mean value, but also related to their respective density. Mean values of density and compressive strength for the reference mix and wood-concrete composites are presented in Table 3.9.

Table 3.9: Wood-cement concrete (WCC) mixes: density and compressive strength.

Mix	Harden density water-saturated (kg/m^3)		Compressive strength (MPa)	
	7 days	28 days	7 days	28 days
Reference	2403 ± 11	2426 ± 18	58.0 ± 0.4	64.3 ± 4.0
WCC_WW1	2202 ± 29	2230 ± 15	34.8 ± 3.1	42.3 ± 1.2
WCC_WW2	2104 ± 8	2121 ± 81	28.9 ± 1.5	33.0 ± 8.6
WCC_WW3	2184 ± 24	2157 ± 30	35.7 ± 1.9	36.6 ± 4.2

The WCC, where the mineral aggregates were partially replaced with wood waste in 25 v%, had a compressive strength reduction in the range of 38-50% and 34-48% at 7 and 28 days, respectively. Although the strength development could be partially influenced by the superplasticizer content, the compressive strength reduction seems to be more related to WCC density than to the waste type. As Figure 3.11 shows, an almost linear relationship between the composites' density and compressive strength is obtained, with coefficient of determination (R^2) of 0.982 and 0.998 at 7 days and 28 days, respectively.

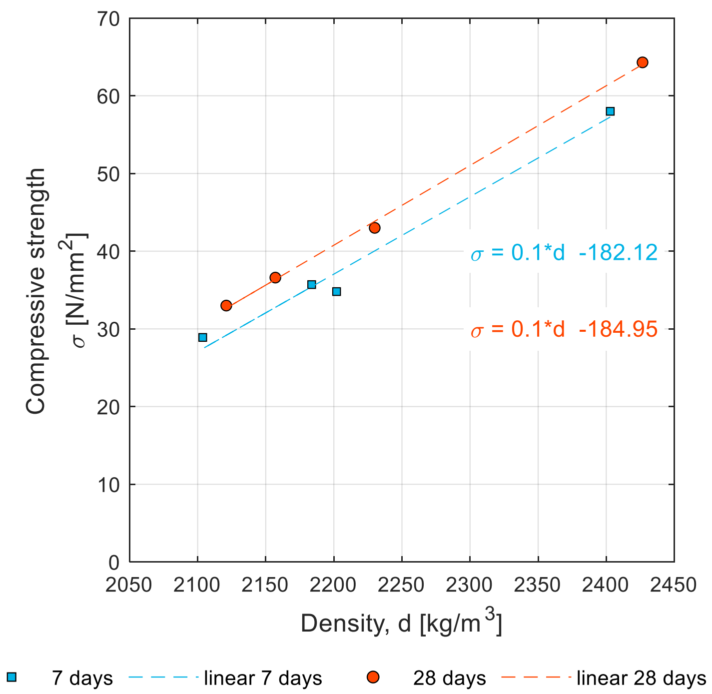


Figure 3.11: Compressive strength of wood-cement concrete (WCC) mixes as a function of density.

Similar results have been reported in other studies. A wood-cement concrete with 15 v% of fine aggregates being replaced with sawdust led to a compressive strength reduction of 42% and 40% at 7 and 28 days, respectively [39]. A compressive strength reduction of 63% and 64% at 7 and 28 days, respectively, have been observed for a WCC where fine aggregates were replaced with sawdust in 20 w% [40].

The incorporation of wood waste does not limit the application of these composites to non-structural applications, since the compressive strength is above 25 MPa. Although there are promising aspects in this domain, further studies are needed to explore the advantages of these composites, especially in terms of physical performance (hygrothermal and acoustic), weight reduction, durability, and sustainability.

3.5. Conclusions

The practical feasibility of using end-of-life treated wood for producing innovative lightweight cement composites was investigated. This included a characterisation of wood residues from different sources to assess the presence of leaching substances and determine the physical properties relevant to the production of cement composites. It also included the production of cement pastes containing different wood waste particles for determining the hydration heat and mechanical properties as a function of wood waste origin, wood content, wood particle size and wood pre-treatment. Concrete mixes containing selected wood particles were also produced for a preliminary examination of the effect of wood waste on the mechanical properties of a reference concrete.

The results show that the concentration of leaching substances can vary significantly depending on the source of wood waste, exceeding in some cases the acceptance limits for inert or non-hazardous waste landfills. As expected, no relevant chemicals were detected in the eluate of the WW1 sample, assigned to untreated wood. For their part, the eluates of the WW2 and WW3 samples, respectively assigned to ACQ and CCA treatments, revealed the presence of significant amounts of some heavy metals (e.g. copper, arsenic and chromium). Finally, relevant organic compounds were detected in the eluate of the WW4 sample, assigned to creosote treated wood. However, while the environmental risk of using wood particles from WW2 and WW3 sources is low, since cement composites are likely to fix such heavy metals quite well, wood particles from the WW4 source poses a higher risk because such organic compounds are not expected to bind cement matrixes in an efficient manner.

Although small variations were found in the hydration heat profile of different cement composites containing up to 5 %(w/w), the incorporation of increasing quantities of wood particles in cement pastes leads to a more significant reduction in the HoH released. Small variations were also found when changing the types of wood waste and pre-treatments. As expected, untreated wood from sawmills (WW1) affected the hydration heat profiles slightly more than both the treated woods containing preservatives from agriculture posts and fences (WW2, WW3), which is plausible taking into account the leaching process of the latter over the service life.

The results also show that a significant reduction of compressive strength was observed with increasing percentages of wood particles, which can be attributed to the greater impact of the wood particles in disturbing the cementitious matrix in comparison to that of the wood extractives. The incorporation of wood particles also resulted in a significant reduction of the mechanical performance of the hardened material, though the use of such composites in applications with low-structural requirements has not been limited.

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CHAPTER 4

CONCRETE CONTAINING WOOD CHIPS AND SAWDUST

4.1. Introduction

In Europe, several thousands of cubic meters of wood products become waste every year, of which less than 50% is recycled [1,2]. With an increasing focus on recycling [3], wood waste has emerged as a central source of secondary raw materials. However, from a recycling perspective, wood waste is a complex material [4]. For instance, a huge amount of wood waste is disposed because it contains dangerous chemical preservatives. Sources of contaminated wood include railways, bridges, buildings, and fencing posts. This scenario has boosted research into incorporating wood waste in cement composites, intending to develop novel sustainable construction materials with good performance, durability, and cost-effectiveness. Several alternative wood–cement composites have been developed using wood as a filler [5], wood waste ash to partially replace cement [6], and wood waste to partly or wholly replace conventional aggregate [7]. Moreover, wood cement-bonded boards [8–10] are already in use, mostly for parking decks, basement ceilings, floor units, loft conversion, or timber frame construction as sound barriers for acoustic absorption. Lightweight applications with thermal and acoustic advantages but with low mechanical performance have already been reported.

Several published studies on wood waste cement composites highlight certain benefits of wood incorporation [11–13]. Zwicky [14] developed an economically competitive wood–cement composite with regular lightweight concrete with a 70–80% eco-balance reduction. Caldas et al. [15] argued that wood waste could be considered a CO_2 sink when producing wood-based concrete. This type of composite could also provide additional functional features, e.g., contributing to thermal and acoustic insulation, and thereby compensating for their reduced mechanical properties [16,17]. Fu et al. [18] highlighted the advantages of using coarse aggregates with beech wood chips to reduce self-weight and improve the thermal insulation of concrete in timber-concrete composite structures. A summary of published studies on the replacement of aggregate by wood particles is given in Table 4.1.

Table 4.1 : Published studies on the replacement of aggregate by wood particles.

Reference	Year	Composites Type
[7]	2017	Sand concrete with a wood-to-cement weight ratio of 1 23 (w/c = 0.26, Portland cement type II A-L 42.5 R).
[16]	2007	Sand concrete incorporating wood shavings with proportions varying from 0 to 100 kg/m^3.
[17]	2015	Wood cement compounds based on sawdust and mineralized wood fibre. Different binders were used (standard Portland cement CEM I 52.5, CEM II 42.5 N, and aluminate cement), different wood/cement ratios were considered (0.33 and 0.2) as well as different w/c ratios (0.35 to 0.56).
[18]	2020	Concrete with replacement of 15% in volume of coarse aggregates by wood chip (w/c = 0.598, Portland cement CEMII/B–S 42.5 R).
[19]	2022	Concrete with replacement varying from 0 to 50% of sand by wood chip (w/c = 0.50, Portland cement type I 42.5 N).
[20]	2021	Sand concrete with replacement varying from 0 to 50% of sand by wood chip (w/c = 0.49, Portland cement type I 42.5 N).
[21]	2019	Concrete blocks with replacement varying from 0 to 40% of gravel by wood chip (w/c = 0.41).
[22]	2021	Concrete with replacement varying from 0 to 60% of sand by sawdust while coarse aggregates remain unchanged (w/c = 0.45, Portland cement type II/B-M).
[23]	2020	Concrete with replacement of 15% of coarse aggregates by wood chip (w/c = 0.598, Portland cement type II/B-S 42.5 R).
[24]	2018	Concrete with replacement of varying from 0 to 15% of sand by sawdust while coarse aggregates remain unchanged (w/c = 0.50, Portland cement type I).
[25]	2021	Sand concrete with replacement of varying from 0 to 30% of sand by sawdust (Portland cement type II of class 45).
[26]	2022	Concrete with replacement of cement by fly ash (varying from 0 to 20%), of sand by sawdust (10 and 40%), PET (0 to 60%), or polystyrene (0 and 20%) (w/c = 0.5, Portland cement type II 42.5 R).

Analysing Table 4.1, it can be observed that cement type II 42.5 is frequently used, the replacement of aggregate by wood particles ranges from 5% to 60%, and the water cement ratio varies from 0.26 to 0.60. It can also be noted that wood wastes are incorporated into concrete by replacement of sand and less by gravel. The use of wood wastes combined with other types of waste is less common.

Despite all the work reported on the wood cement mixes, several aspects still need to be investigated and optimized, taking into account the nature of the wood particles under study (e.g., aggregate replacement ratio, the water-cement ratio, and the use of additives). Additionally, there is a lack of knowledge on how those wood waste cement composites behave over time and under different aging conditions. These are essential aspects to ensure that such composites can be, in fact, exploited in terms of the production of new construction elements.

The present work has already discussed the potential use of wood waste in cement composites in the previous chapter , where the chemical and physical properties of wood waste from different sources were characterized [11]. At that time, cement pastes containing either wood extractives or wood particles were used to assess the wood-cement compatibility based on hydration heat and mechanical properties. Some concrete mixes were also produced for a preliminary assessment of the feasibility of their production. Now, in the present chapter, the objective is to investigate the mechanical, physical, and durability performance of wood–concrete composites incorporating wood chips and sawdust. Several compositions were defined and produced, evaluating their mechanical performance and bearing in mind the different structural and non-structural intended applications (e.g., fence poles, façade panels, slabs, and construction elements for small residential buildings). Two compositions of concrete were then selected to proceed with durability and hygrothermal tests based on the following criteria: maximize wood incorporation (v%), minimize density (below 2125 kg/m^3), and ensure compressive strength above 25 MPa. Additional test specimens were prepared to assess the viability of using a layer of these new compounds to mitigate the impact of sound transmission.

The chapter is divided into five main sections. The next section (Section 4.2) presents the characterization of the concrete and cement-composites constituents, and explains how the compositions were designed. Section 4.3 describes the experimental campaign. Section 4.4 comprises the experimental results, while Section 4.5 delves into a discussion of these results, focusing on the mechanical performance, which is crucial for building applications, the durability assessment, assessing possible premature aging caused by the presence of wood, and the hygrothermal and acoustic behaviour, to evaluate complementary benefits of the formulated compounds. Note, however, that while all the composites were mechanically assessed, only two optimized mixes were selected based on the established criteria to proceed to hygrothermal and durability characterization. Conclusions are drawn in Section 4.6.

4.2. Materials

The wood chips (WC) and sawdust (SD) residues for developing wood–cement composites were provided by Toscca Wood & Solutions from its regular industrial activity.

A Portland cement (OPC) concrete was used as reference (REF) for comparison purposes and as a starting point to incorporate wood waste. OPC CEM II/A-L 42.5 R, manufactured by Secil Group, was used to produce the reference concrete and the mixes incorporating wood. Preliminary tests (not included in this thesis) showed that the use of this cement would lead to a significantly higher compressive strength than a less resistant cement (OPC CEM II/A-L 32.5 R) without a significant price increase.

One sand type and two pebble-shaped gravels provided by Sabril-Sociedade de Areias e Britas, Lda were used as mineral aggregates. All mineral and wood aggregates were physically characterized according to European mineral aggregate standards before the concrete composition was defined. The particle size distribution [27], particle density, water absorption [28], and water content [29] of all aggregates were determined.

4.2.1. Characterisation of materials

The mineral aggregates, Sand 0/4 (S0/4), Gravel 0/5 (G0/5), and Gravel 1 (G1), were characterized in terms of the maximum size, density, water absorption, moisture content, and particle size distribution. The maximum dimension and particle size analyses were carried out in accordance with the standard EN 933-1:2012 [27], where the aggregates were first dried inside a climatic chamber at 110 ± 5 °C until reaching constant mass, washed to remove the fine fraction that passed through a 63 µm sieve, and then dried again up to constant mass. Constant mass was considered as achieved when the results of weighing the specimens twice with an interval of 24 h did not differ by more than 0.1% of the mass of each test specimen. Afterwards, the aggregate was poured into a sieve column and shaken until the aggregate fraction was fully separated between the sieves. Finally, each aggregate fraction was weighed, and the particle size distribution curve was plotted. The particle density and water absorption were evaluated according to standard EN 1097-6:2013 [28]. The aggregates were then washed and sieved, and only the 4–32 mm and 63 µm–4 mm fractions were selected for the coarse and fine aggregates, respectively. Afterwards, the selected fractions were poured into a pycnometer filled with water at 22 ± 3 °C and the entrapped air removed. The pycnometer was subjected to a water bath at 22 ± 3 °C for 24 ± 0.5 h. To evaluate the saturation with dry surface weight, the coarse aggregate fraction was dried with absorbent cloth and the fine aggregate fraction was placed in an oven to evaporate surface moisture. The saturated surface dry state of the fine aggregate fraction was confirmed by filling a cone with the aggregate and checking its consistency. The aggregate is assumed to be dry when it splits and does not take a cone shape. Finally, the aggregates were weighed and the particle density and water absorption were determined. The moisture content of the aggregates was determined following standard EN 1097-5:2008 [29]. The aggregates were first weighed and placed inside a climatic chamber at 110 ± 5 °C to achieve constant mass. Finally, the weight of dried aggregates was measured and the moisture content calculated.

Mineral aggregate particle size distribution showed that S0/4, G0/5, and G1 had a nominal maximum size of 8 mm, 10 mm, and 16 mm, respectively. As expected, all particle density and water absorption at 24 h ranged from 2620 to 2650 kg/m^3 and 0.1% to 0.4%, respectively. Both gravels, G0/5 and G1, had 0.1% water content, and S0/4 had 1.6%. Particle size distribution of mineral aggregates is represented in Figure 4.1, while their physical properties are summarised in Table 4.2

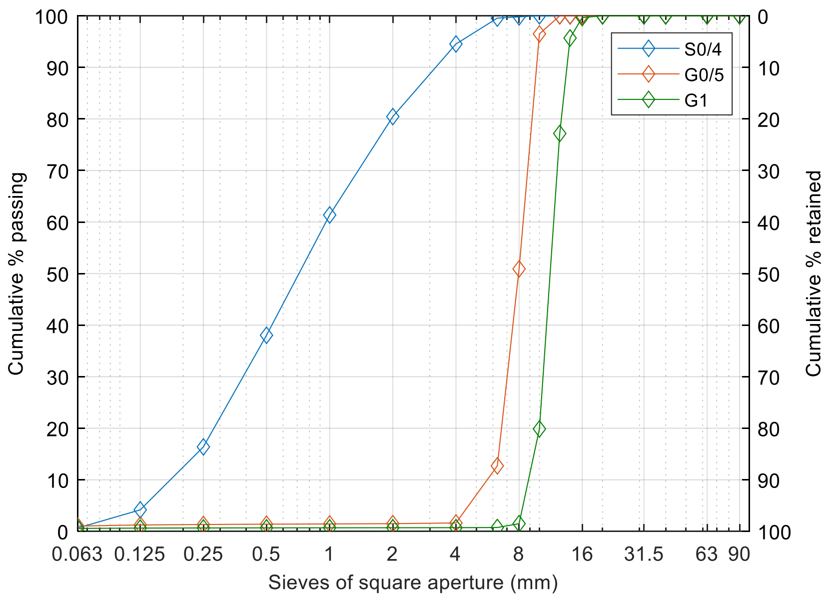


Figure 4.1: Particle size distribution of mineral aggregates.

Table 4.2 : Physical properties of mineral aggregates

Aggregates		S0/4	G0/5	G1
Particle density (kg/m^3)	Oven dried	2640 ± 30	2620 ± 05	2620 ± 20
	Saturated with dry surface	2650 ± 20	2630 ± 10	2630 ± 15
Nominal maximum size (mm)		8 ± 0	10 ± 0	16 ± 0
24 h water absorption (%)		0.1 ± 0.0	0.4 ± 0.0	0.3 ± 0.0
Water content (%)		1.6 ± 0.2	0.1 ± 0.0	0.1 ± 0.0

Wood aggregates, WC and SD (Figure 4.2), were also characterized by their maximum size, density, water absorption, and particle size distribution. The maximum dimension and particle size analyses were carried out following the standard EN 933-1:2012 [27]; the particle density and water absorption were determined by adapting standard EN 1097-6:2013 [28]. The wood particles' free surface water was evaluated based on collecting the weight of the wood in two stages, namely after draining the water from the wood through a sieve for 5 min and after wiping the particles. The oven dry particle density of the sawdust and the wood chips were 340 and 410 kg/m^3, respectively, while the saturated surface dry particle density ranged from 1090 to 1110 kg/m^3.

Sawdust had the highest water absorption at 24 h (411%), more than twice that of the wood chips due to their particle size distribution and corresponding specific surface area. Similarly, it had the highest free surface water (190%) in comparison to wood chips (33%). The wood aggregates' particle size distribution curves are given in Figure 4.3, and their physical characterization is shown in Table 4.3.

a) b)

Figure 4.2: Photographic record of the wood aggregates: (a) wood chips (WC); (b) sawdust (SD).

4.2.2.Mix design

The compounds were developed using wood chips and sawdust residues as wood aggregates, partially or totally replacing mineral aggregates from a reference mix. In the presence of partial substitution, mixes are mentioned as concrete mixes and those in which wood is the only aggregate are named cement compounds. These cement- compounds were studied only as acoustic insulation for slabs.

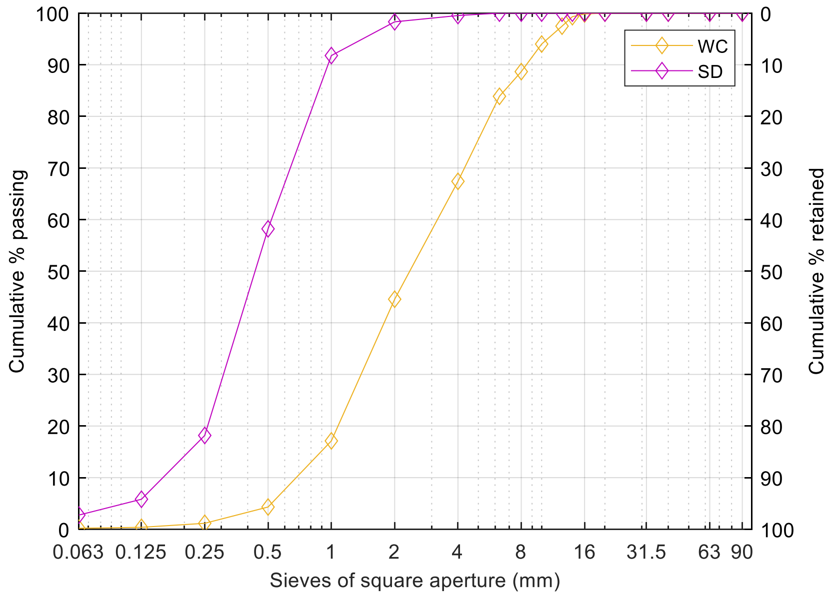


Figure 4.3: Particle size distribution of wood chips (WC) and sawdust (SD).

Table 4.3: Physical properties of wood aggregates

Aggregates	Particle density (kg/m³)		Nominal maximum size (mm)	24 h water absorption (%)	Free surface water (%)
	Oven dried	Saturated with dry surface			
Wood chip	410 ± 20	1090 ± 35	16 ± 0	200 ± 12	33 ± 5
Sawdust	340 ± 15	1110 ± 60	4 ± 0	411 ± 59	190 ± 24

The concrete compositions were developed with three objectives in mind: to design a concrete with a density below 2125 kg/m^3 (density reduction without compromising strength); to obtain a compressive strength above 25 MPa at 28 days (meeting the requirement of 17 MPa given by ACI 318-08 [30]), and to maximize the volume content of wood (v%). With these aims in mind, 12 mixes were developed by varying the amount of wood chips and sawdust in replacement of the mineral aggregates. In an initial phase, the concrete composites developed were characterized in terms of compressive strength at 7 and 28 days, and in terms of modulus of elasticity and flexural strength at 28 days. Then, in a second phase, 2 of those compositions that complied with the predefined criteria were selected for a more extensive characterization.

All mixes were prepared with CEM II/A-L 42.5 R cement. The w/c (water/cement) ratio was 0.4. As mentioned before, one of the 12 mixes was the OPC reference mix (REF) designed with mineral aggregates only, and the other 11 compositions incorporate wood chips (WC), sawdust (SD), or both wood aggregates (WC + SD). Five compositions included only WC in 5 v%, 10 v%, 15 v%, 20 v%, and 25 v% replacement ratios; three incorporated only SD in 5 v%, 10 v%, and 15 v% replacement ratios; and the other three included a combination of WC + SD with 7.5 + 7.5

v%, 12.5 + 7.5 v%, and 20 + 5 v% replacement ratios of WC and SD, respectively. The amount of cement was kept constant in all mixes.

Mix design started by selecting a commonly used reference concrete. The aggregate replacement was defined to generate minimal disturbance of the particle size distribution of the aggregates. Therefore, the particle size distribution curves of WC and SD were compared with the mineral aggregates' curves to assess the correspondence of the retained material at each sieve size between the mineral and wood aggregates. The aggregate replacement was calculated by volume (%) to prevent volumetric variations between different compositions, considering the materials' saturated surface dry density.

In order to prevent variations in the specified water/cement ratio, the total water of the concrete compositions came from three sources: (i) added water, i.e., water that was added to the mix during the composite's fabrication; (ii) free surface water, i.e., the water content on the wood particles' surface (calculated in the wood aggregates' water absorption test); and (iii) absorbed water after 24 h (calculated from the wood aggregates' water absorption). Thus, the total water content was the sum of the added water (water added during mixing), the free surface water on the wood particles, and the water absorbed during the soaking time.

The wood aggregates were added into the mix in a saturated state. Therefore, the possible amount of wood incorporation was limited by the point when the free surface water added to the absorbed water exceeded the total water content desired. The wood aggregates were first saturated for 24 h followed by 5 min draining through a sieve before being weighed and added to the electric vertical shaft concrete mixer 130 l (Controls). The concrete mixing process started by adding coarser to finer aggregates, then half of the added water was poured into the concrete mixer. Cement was added afterwards followed by the other half of the water.

To improve workability with less available water, a superplasticizer Dynamon SP1 Mapei (SP) was used in all mixes except the reference one (without wood). The amount of SP was defined based on the amount of cement and the available water (less water is available as wood content increases in the mix, which requires the introduction of a higher amount of SP). SP was diluted in the water to be added into the concrete mixer.

Table 4.4 summarizes the studied concrete compositions. They were labelled Tp according to the wood aggregate type (T = WC, T = SD, or T = WC SD) and the wood aggregate's replacement ratio in volume (p).

Table 4.4: Concrete compositions containing Sand 0/4 (S0/4), Gravel 0/5 (G0/5), Gravel 1 (G1), wood chips (WC), sawdust (SD), and superplasticiser (SP)

Code	Mix composition (kg/m^3)							
	Cement	S0/4	G0/5	G1	WC	SD	Added water	SP (10^{-6})
REF	400	690	467	674	-	-	162	-
WC5	400	626	444	670	43	-	133	2
WC10	400	562	421	665	86	-	105	2
WC15	400	498	397	661	128	-	76	3
WC20	400	434	374	657	171	-	48	4
WC25	400	370	351	653	214	-	19	5
SD5	400	598	467	674	-	60	113	3
SD10	400	507	467	674	-	121	65	4
SD15	400	415	467	674	-	181	16	5
WC7.5SD7.5	400	457	432	667	64	90	46	4
WC12.5SD7.5	400	393	409	663	107	90	18	5
WC20SD5	400	342	374	657	171	60	0	5

The wood-cement compounds were designed based on the previous mixes. The type and the cement content were the same. Furthermore, the proportion between wood and sawdust remained unchanged to ensure consistency across the compounds. To enhance workability, the maximal amount of superplasticiser was incorporated, as the manufacturer recommended. Additionally, the water/cement ratio was adjusted to 0.45 to achieve proper workability. The summary of the studied wood-cement compounds can be found in Table 4.5, with the distinct suffix (WCC) used to differentiate them from the concrete compositions. The wood-cement compounds were prepared as the concrete mixes, and all the procedures and equipment were maintained.

Table 4.5: Wood-cement compositions containing Wood chips (WC), Sawdust (SD), and superplasticiser (SP)

Code	Mix composition (kg/m^3)				
	Cement	WC	SD	Added water	SP (10^{-6})
WC25 (WCC)	400	282	-	180	5
_ WC20SD5 (WCC)	400	176	37	180	5

Besides the concrete mixes, two samples of loosely laid material were additionally prepared. Only wood chips, and wood chips and sawdust (in the same proportion of those presented in Table 4.5, but without cement), water or superplasticiser were used. They were labelled as before but followed with the suffix of (LL) of loosely laid material.

4.3. Methods

As mentioned above, the experimental program was divided into four evaluation campaigns: mechanical performance, ageing resistance, and hygrothermal behaviour, for the concrete compositions. The wood-cement compounds were only tested for acoustic performance.

To assess the mechanical performance, six cubic specimens (side 150 mm) of all 12 concrete mixes were produced to be tested for compressive strength, Poisson's ratio, and modulus of elasticity at 7 and 28 days, amounting to a total of 72 specimens. The Poisson's ratio and the modulus of elasticity were calculated first since those procedures do not involve destroying the test specimens. Three beams measuring 150 mm × 150 mm × 600 mm were produced to be tested for flexural strength at 28 days. The compositions with either 15 v% or 25 v% of wood incorporation (WC15, WC25, SD15, WC7.5SD7.5, and WC20SD5) plus the reference mix (REF) were selected for these tests, amounting to a total of 18 specimens. All these specimens were kept in the moulds for two days before immersion in a water tank at 20 °C until testing age.

According to the predefined criteria, WC25 and WC20SD5 were selected for the durability and hygrothermal tests because they had the highest wood incorporation (v%), the highest density reduction (%), and the compressive strength results exceeded 25 MPa. These compositions correspond to the ones with highest replacement of both coarse aggregate and sand. A total of 78 cubic (side 150 mm) specimens were produced to assess the durability against different aging scenarios (12 for each different aging scenario). An extra 42 specimens were produced to assess the compressive strength development (3 specimens for each age set) at seven curing times (7, 28, 60, 90, 120, 150, and 180 days), while 36 specimens were produced to carry out three durability cycles (wet–dry, freeze–thaw, and thermal shock). A total of 6 specimens were prepared for each durability cycle set, 3 to test after the durability cycles and 3 of the same age to test without undergoing any durability cycle. The compressive strength loss was used to assess the durability performance of the test specimens.

Three cubic specimens (side 150 mm) of each mix were also prepared for hygrothermal characterization, totalling 21 specimens. After 28 days of curing, some of the specimens were cut into slices 50 mm thick to proceed with thermal conductivity and water absorption analysis (12 specimens), and the other 9 specimens were used for water absorption tests. Four beams of each mix, measuring 100 mm × 100 mm × 500 mm, were produced to determine the shrinkage and expansion behaviour (2 for shrink-age and 2 for expansion), totalling 12 specimens. They were subjected to a particular conditioning method. All test specimens were kept in the moulds for two days before being immersed in a water tank at 20 °C until testing age.

Four quadrangular specimens (side of 1200 mm) were prepared to assess the acoustic performance. Different specimen thicknesses were tested: 10 mm, 23 mm, 30 mm, and 40 mm. The specimens were cast (in the case of wood-cement compounds) upon a reference slab in wood frames, ensuring the desired dimensions (1 cm bigger than the specimen's dimensions) and thickness. After 28 days, the frame was removed.

The experimental programme of the concrete mixes and wood-cement compounds are summarised in Tables 4.6 and 4.7, respectively, including the studied properties, curing/conditioning, and test methods.

Table 4.6: Experimental programme of the concrete mixes

Section	Property	Curing/conditioning	Test	Series
Mechanical	Compressive strength	Curing in water tank	Compressive strength	all
	Poisson's ratio and modulus of elasticity	Curing in water tank	Poisson's ratio and modulus of elasticity	all
	Flexural strength	Curing in water tank	Flexural strength	REF WC15 WC25 SD15 WC7.5SD7.5 WC20SD5
Durability	Compressive strength development over time (for comparison purposes)	Curing in water tank	Compressive strength	WC25 WC20SD5
	Wet–dry cycles	Curing in water tank followed by wetting–drying cycles	Compressive strength	WC25 WC20SD5
	Freeze–thaw cycles	Curing in water tank followed by freeze–thaw cycles	Compressive strength	WC25 WC20SD5
	Thermal shock	Curing in water tank followed by thermal shock	Compressive strength	WC25 WC20SD5
Hygrothermal	Thermal conductivity	Curing in water tank followed by conditioning at ambient conditions	The guarded hot plate method	REF SD15 WC25 WC20SD5
	Shrinkage and expansion	Shrinkage: curing in climatic chamber Expansion: curing in water tank	Shrinkage and expansion	REF WC25 WC20SD5
	Water absorption	Curing in water tank followed by conditioning at ambient conditions	Water absorption coefficient	REF WC25 WC20SD5

Table 4.7: Experimental programme of wood-cement compounds

Section	Property	Curing/conditioning	Test	Series
Acoustic	Normalised impact sound pressure level	28 d at ambient conditions	Impact sound transmission	WC25 (LL) WC20SD5 (LL) WC25 (WCC) WC20SD5 (WCC)

4.3.1.Mechanical

The mechanical characterization comprises the assessment of compressive strength according to EN 12390-3:2019 [31] (σ), Poisson's ratio (μ), modulus of elasticity (E), and flexural strength (f), according to EN 12390-5:2019 [32]. The apparent mass density (ρ) of the tested specimens was also determined according to EN 1602:2013 [33]. The details are given next.

Compressive strength

An electromechanical compressive testing machine, Controls model 50-C56V2, was used with a load cell of 3000 kN (Figure 4.4a). The load was applied at a rate of 0.6 ± 0.2 MPa/s. The compressive strength was obtained by dividing the failure load by the average cross-sectional area.

Poisson's ratio and modulus of elasticity

Poisson's ratio and the modulus of elasticity can be determined by measuring the deformations generated by the application of axial loads or by estimating the allowed body dilatational and shear wave velocities within the material. In the present study, Poisson's ratio and the modulus of elasticity were determined through a non-destructive dynamic method that allows the evaluation of those wave velocities [34,35]. The longitudinal and shear pulse waves were generated using an electro-acoustic transducer. The travel time of these pulses along a known path length (cube edge) is used to define those velocities. This is done using a direct arrangement that consists of placing the emitting source and the receiver on two opposite faces of the test specimen. This ensures an easier detection of the dilatational and shear wave pulses. The equipment used was a commercial portable Pundit Lab unit used to generate and receive ultrasonic pulses. Two pairs of P and S wave transducers with nominal frequencies of 54 kHz and 250 kHz, respectively, were used. A couplant was used to facilitate the ultrasonic energy transmission from the firmly attached transducers into the test specimens (Figure 4.4b). Poisson's ratio (μ) and the modulus of elasticity (E) were then defined using the following known elastic relationships:

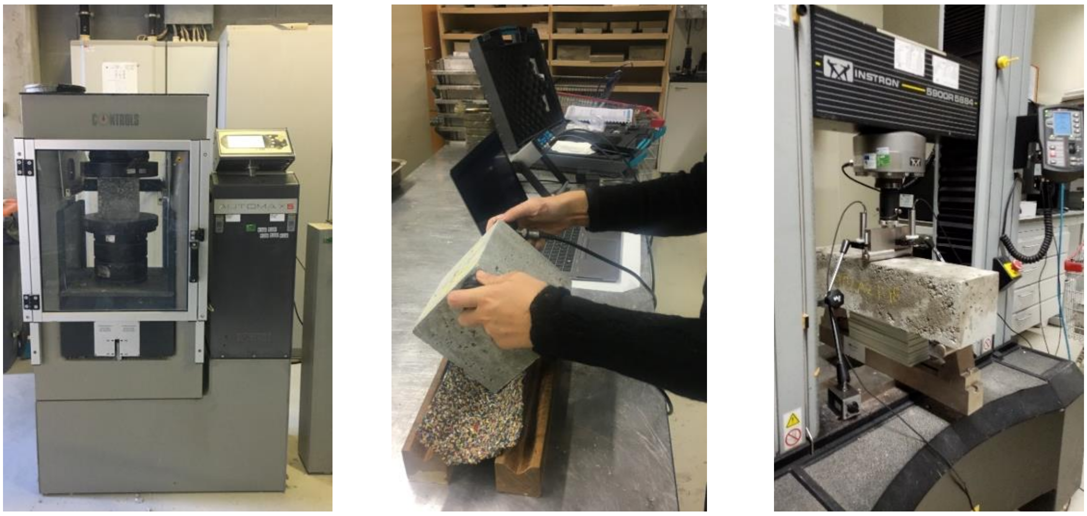
$$\mu = \frac{Vp^2 - 2Vs^2}{2(Vp^2 - Vs^2)} \quad (4.1)$$

$$E = 2\rho Vs^2(1 + \mu) \quad (4.2)$$

where Vp and Vs are the measured P-wave and S-wave velocities, respectively, and ρ is the mass density.

Flexural strength

The flexural strength test was performed using an electromechanical universal testing machine Instron, model 59R5884 with a load cell of 150 kN (Figure 4.4c). The load was applied in one-point (3-point bending test) at mid-span distance, with a span (distance between supports) of 500 mm.



a) b) c)

Figure 4.4: Mechanical characterisation tests: a) Compressive strength; b) Dynamic elastic properties; c) Flexural strength.

4.3.2.Durability

Besides evaluating the compressive strength with age, the aging effect under extreme conditions was assessed by conducting artificial aging cycles (wetting–drying, freeze–thaw, and thermal shock) in three samples before subjecting them to compressive strength tests. Control samples were tested at the same testing age without undergoing artificial aging cycles to evaluate the decay of the compressive strength. At this stage, WC25 and WC20SD5 were selected according to the initial criteria previously defined. The details are given next.

Compressive strength development

The evaluation of compressive strength with age is of practical importance to control construction schedules. Seven different points of curing time were considered: aging 7, 28, 60, 90, 120, 150, and 180 days.

Wet–dry cycles

The wet–dry cycles were performed to assess potential damage to the concrete or to the wood–cement bond, e.g., cracking and shrinkage. Ten artificial cycles were performed. Each cycle consisted of immersion for 24 h in a water tank at a constant temperature of (20 ± 2) °C for 24 h followed by dry conditions for 24 h in a laboratory room at a constant temperature of (20 ± 2) °C and 50% relative humidity.

Freeze–thaw cycles

The specimens were subjected to 7 freeze–thaw cycles over a period of 7 days, according to EN 12371:2010 [36]. Each cycle included 11.5 h in dry conditions created in a cold chamber with a constant temperature of (−20 ± 2) °C followed by 11.5 h of immersion in a water tank with a constant water temperature of (20 ± 2) °C, equipped with a device to keep the test specimen in place. The transition between conditions (−20 to 20 °C) lasted 1 h.

Thermal shock cycles

Thermal shock cycles were conducted to measure the ability of a material to withstand abrupt changes in temperature conditions, according to EN 10545-9:2013 [37]. Ten thermal shock cycles were defined. Each cycle consisted of placing the test specimens in a climatic chamber at (105 ± 5) °C for 18 h, followed by immersion in a water tank at a constant water temperature of (20 ± 2) °C for 6 h. The test specimens were immediately transferred between conditions (105 to 20 °C).

4.3.3.Hygrothermal

The hygrothermal characterization evaluates four relevant properties: thermal conductivity (λ), water absorption (W_{w24}), shrinkage, and expansion. Following the initial criteria and similarly to the durability assessment, the physical characterization was performed on REF, WC25, and WC20 SD5 compositions. The details are given next.

Thermal conductivity

The guarded hot plate method was used to determine thermal conductivity using a λ-Meter EP500 model, according to ISO 8302:1991 [38]. The test procedure followed EN 12664:2001 [39]. The specimens were conditioned in a ventilated climatic chamber at (23 ± 2) °C and (50 ± 5) % relative humidity until a constant mass was reached (using the criteria mentioned above). The specimens were subjected to a 15 °C temperature difference between the upper and the lower plates of the equipment, with a mean temperature of 23 °C.

The equipment quantifies the steady-state heat flow through a test specimen placed between two plates with thermal sensors. The goal is to reproduce a constant unidirectional heat flow between the two plates. The plates measure 500 mm × 500 mm, with an area measuring 150 mm × 150 mm in the centre where the heat is generated. The specimens were placed in an expanded polystyrene (EPS) frame to ensure the direction of the heat flow and mitigate lateral heat transfer.

Water absorption

Water absorption is a very important parameter, closely related to the durability of its application in the case of concrete materials. This property was evaluated by partial immersion following the standard ISO 15148:2002 [40]. The test consists of measuring the change in mass of the specimens for at least 24 h. The mass gain per face area (g/m^2) was determined as a function of the square root of time in seconds.

The four lateral faces of the test specimens, 150 mm × 50 mm, were sealed with paraffin wax so that the area in contact with water was limited to the bottom face. Then, the samples were immersed in water at (23 ± 2) °C to a depth of (5 ± 2) mm, and the mass was measured 8 times (at 5 min, 20 min, 1 h, 2 h, 4 h, 8 h, 24 h, and 48 h). The surface water was removed by wiping the specimen with absorbent lab paper before weighing and then immediately placing the sample in the water again. The water absorption coefficient after 24 h, W_{w24} [kg/(m^2/h$^{0.5}$)], can be calculated as:

$$W_{w24} = \frac{\Delta m_{24} - \Delta m_0}{\sqrt{24}} \tag{4.3}$$

where Δm_{24} [kg/m^2] is the value of Δm (kg/m^2) after 24 h and Δm_0 (kg/m^2) is where the linear regression of Δm function of $\sqrt{t}$ intersects the vertical axis.

Shrinkage and expansion

The shrinkage and expansion behaviour, a relevant property given the hygroscopicity characteristic of wood particles, was determined by measuring the distance between two reference points in the beam before and after conditioning under specific conditions (under water in the expansion assessment and in a climatic chamber in the shrinkage assessment). For both cases, the beams were demoulded at 24 ± 1 h of age, and the conditioning period was for 90 ± 1 day. To assess the shrinkage, after demoulding, 2 specimens of each mix were placed in a climatic chamber (20 ± 2 °C and 50 ± 5% HR) in such a way that all sides were in contact with the air.

The distance between the reference points was measured at the end of the conditioning period. To determine the expansion, two other specimens were placed in a water tank at 20 ± 2 °C and the distance between the reference points was measured again at the end of the conditioning period. Measurements were taken using digital callipers, and the final results correspond to the mean of three measurements. The shrinkage and expansion were obtained by the difference between the measurements, divided by the initial one, following the procedure indicated in [41].

4.3.4.Acoustic

The impact sound transmission was assessed through laboratory tests conducted in vertical acoustic chambers, following the standards set by ISO 10140-1:2016 [42], ISO 10140-3:2010 [43], and ISO 10140-4:2010 [44]. These acoustic chambers consist of a two-part mobile system with a removable upper chamber facilitated by a crane. The upper chamber is a cube-shaped structure measuring approximately 3.7 m on each side, featuring multi-layered walls 0.10 m thick, constructed from wood-cement panels. The lower chamber, known as the receiving room, is a parallelepiped measuring 3.92 m × 3.92 m × 4.72 m, and it has double-layered reinforced concrete walls 0.20 m thick, separated by fibrous material. The inner floor of the receiving room is supported by a grid of springs, while the outer floor is laid over a resilient material. The two chambers are separated by a referenced reinforced concrete slab 0.14 m thick (movable), as illustrated in Figure 4.5.

The wood-cement composites were cast on the reference reinforced concrete slab out of the two chambers, Figure 4.6. After 28 days, the specimens were tested. In the case of loosely laid material, the wood frames were also used to ensure the thickness and were kept during test. The tests could be carried out right away since there was no need cure.

To perform the tests, the reference slab with the specimens is placed above the lower chamber. The upper chamber is also placed in the right position (above the reference slab). The specimens are now accessed by entering the upper chamber like a building division. After that, a 40 mm thick concrete slab with the same side dimensions was positioned on top of the specimen, and a B&K 3207 tapping machine was placed on top of the slab. The impact sound pressure levels were measured in the receiving room (lower chamber) using a microphone (B&K 4190) placed on a rotating microphone boom (B&K 3923). The reverberation time in the receiving room was determined using the interrupted noise method, utilizing an omnidirectional sound source (B&K 4292) to generate the excitation signal. The impact sound insulation was evaluated across one-third of octave bands within the mid-frequency range of 100 to 3150 Hz. The results of the normalized impact sound pressure level ($L_{n,r}$) and the single value of the weighted reduction of the impact sound reduction index (ΔL_w) were determined in accordance with ISO 717-2:2013 [45].

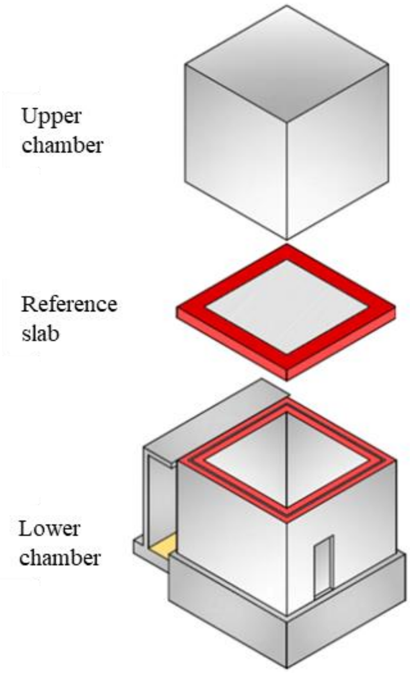
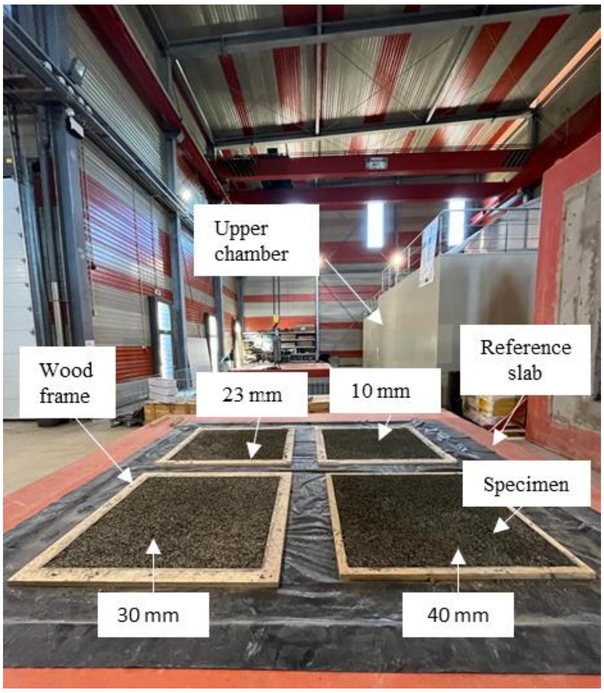
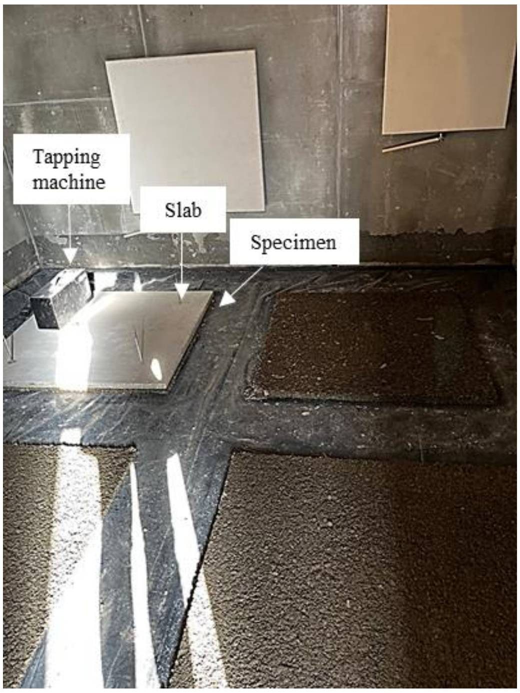


Figure 4.5: Scheme of the vertical acoustic chambers at Itecons used to perform the impact sound insulation tests (adapted from[46]).



a)



b)

Figure 4.6: Impact sound transmission set-up: a) Specimens positions on the reference slab: b) Inside the upper acoustic chamber.

At the end of the test, the specimens were cut to dimensions of 200 x 200 mm and placed under controlled temperature conditions of (23 ± 2) ºC and 50% HR. until they reached constant mass. These specimens were then used to determine density.

4.4. Results

As above mentioned, the experimental program was conducted by initially performing mechanical tests on several concrete compositions. After selecting two of those incorporating the maximum amount of wood with good mechanical properties, further tests to assess durability and hygrothermal behaviour were performed. Additionally, impact sound transmission tests were performed on loosely laid material and two wood-cement compounds. All the experimental results are presented in this section and discussed in the next. To facilitate the interpretation of the results, considering the natural variability of the samples, mean ± standard deviation values are included for all the tests.

4.4.1. Mechanical

Compressive strength

As mentioned above, 12 mixes were prepared based on the incorporation of wood chips or sawdust or a mixture of both. For reference purposes, an additional sample was produced with mineral aggregates only. As expected, concrete density at 28 days decreased with the increase in the wood content, with WC25 and WC20SD5 displaying the most significant density reduction (up to 11%). Furthermore, unsurprisingly, the compressive strength of all composites increased steadily according to the curing age (15%, or 6.6 MPa on average).

Compared with REF, the compressive strength reduction at 28 days for WC compositions containing 5 v%, 10 v%, 15 v%, 20 v%, and 25 v% wood chips was 6.79%, 10.27%, 19.14%, 28.27%, and 33.35%, respectively. The incorporation of sawdust seemed to have less impact on compressive strength, with a reduction of 0.93%, 8.25%, and 9.9% in compressive strength at 5%, 10%, and 15% of SD incorporation, respectively. The compressive strength reduction in compositions containing a mixture of both woods with the respective amount of WC+SD of 7.5 + 7.5 v%, 12.5 + 7.5 v%, and 20 + 5 v% was 12.14%, 23.70%, and 41.29%, respectively. A smaller loss in strength could be obtained by increasing the amount of cement. However, this approach would impact on the final price and environmental performance.

Table 4.8 lists the compressive strength and respective density obtained for each composition. Compressive strength results for all compositions at 7 and 28 days are also summarized in Figure 4.7.

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Table 4.8: Compressive strength (mean ± standard deviation) at 7 and 28 days

Sample	**Density (kg/m^3)**	**Compressive strength (MPa)**	
	28 d	**7 d**	**28 d**
REF	2303 ± 18	57.97 ± 0.42	64.27 ± 4.00
WC5	2248 ± 6	55.53 ± 1.53	59.90 ± 3.81
WC10	2201 ± 2	49.30 ± 1.35	57.67 ± 1.72
WC15	2170 ± 2	46.37 ± 1.60	51.97± 4.12
WC20	2082 ± 9	39.60 ± 2.61	46.10 ± 1.65
WC25	2050 ± 15	34.80 ± 3.14	42.83 ± 1.21
SD5	2266 ± 33	57.30 ± 1.15	63.67 ± 3.20
SD10	2229 ± 14	51.10 ± 0.95	58.97 ± 1.76
SD15	2197 ± 24	50.37 ± 2.08	57.90 ± 1.71
WC7.5SD7.5	2223 ± 15	50.87 ± 0.45	56.47 ± 2.61
WC12.5SD7.5	2130 ± 2	42.30 ± 0.50	49.03 ± 1.50
WC20SD5	2057 ± 12	31.60 ± 1.21	37.73 ± 1.08

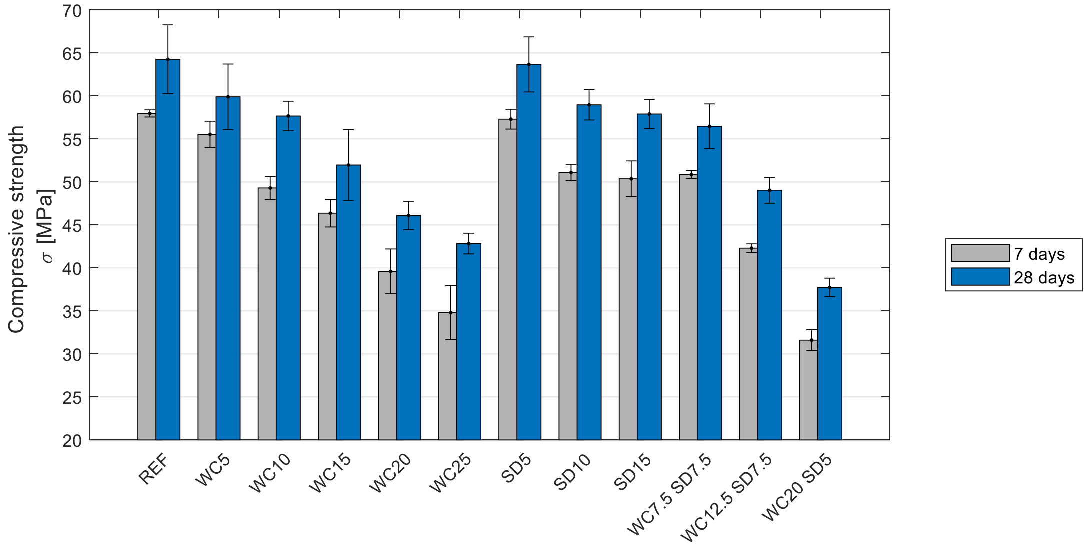


Figure 4.7: Compressive strength of the wood-concrete samples, mean values and standard deviation at 7 and 28 days

Figure 4.8 illustrates the relationship between the compressive strength reduction and the wood incorporation content.

The regression analysis applied to the data showed that the compressive strength of concrete decreased linearly as the wood content increased for the three types of concrete (WC, SD, and WC + SD). The coefficient of determination (R^2) was found to be close to 1.0, in a range of [0.952 to 0.995], except in the case of the sawdust mix at 28 days, which had an (R^2) below 0.90. Additionally, the relationship between wood amount and compressive strength was linear for both ages (7 and 28 days), regardless of the composition type. Compressive strength development at an early age showed promising results, with only the WC20SD5 composite having a result below 30 MPa.

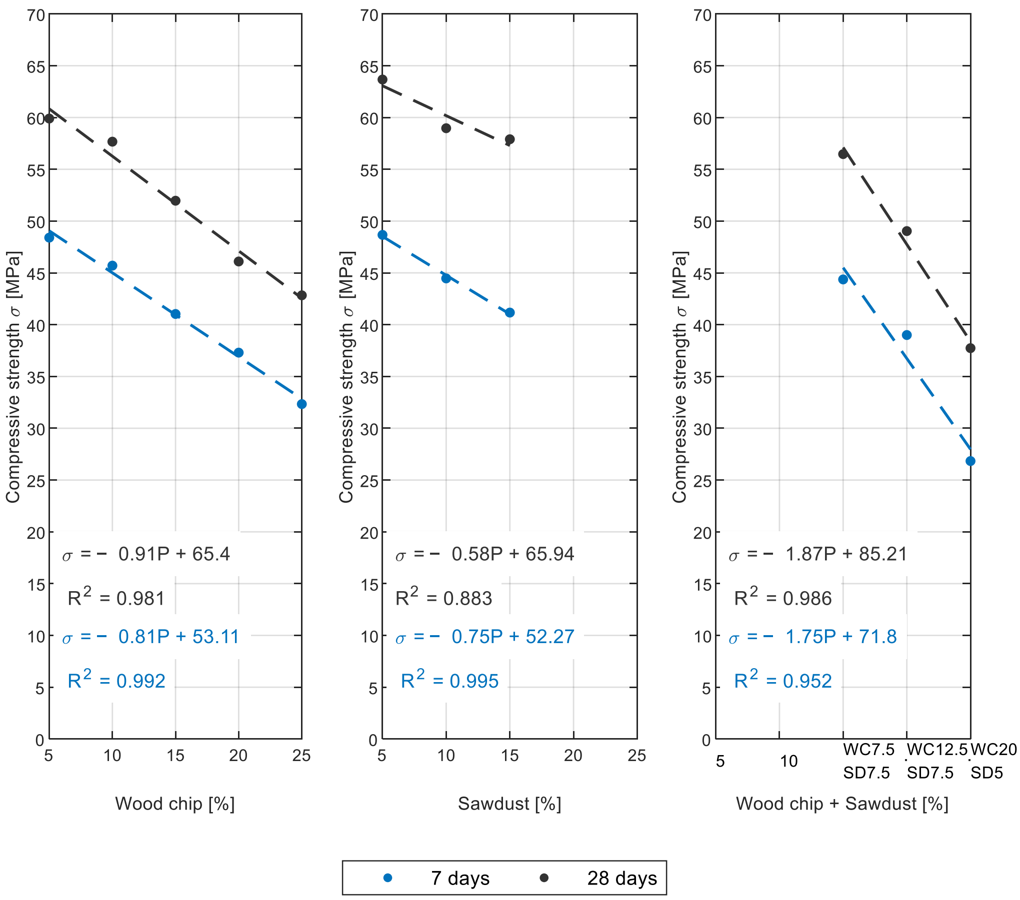


Figure 4.8: Mean values of compressive strength vs. wood percentage incorporated.

As discussed, the SD compressive strength results were less affected by the incorporation of wood than those of the WC composites for both ages. However, WC + SD composites had the highest compressive strength reduction, affected by the incorporated wood content. Morales-Conde et al. [47] studied the incorporation of wood waste in wood–gypsum composites. Although the binder used was different, they also noted that the strength values were slightly higher for composites containing sawdust than for those containing wood in the form of wood shavings. This could be related to density, where denser samples are more likely to develop higher compressive strength.

The decrease in compressive strength could be caused by several factors: the weaker nature of the wood particles compared to mineral aggregates; the compressible nature of wood particles; and the poor bond between the wood particles and cement paste. To inspect the wood particles embedded in concrete, the two samples containing the highest volume percentage of wood (WC25 and WC20S5) were examined by means of stereoscopic microscopy and scanning electron microscopy (SEM). The reference sample was also examined for comparison purposes. A good wood–cement bond and a uniform wood distribution were observed. Representative stereoscopic micrographs are presented in Figure 4.9 to illustrate it.

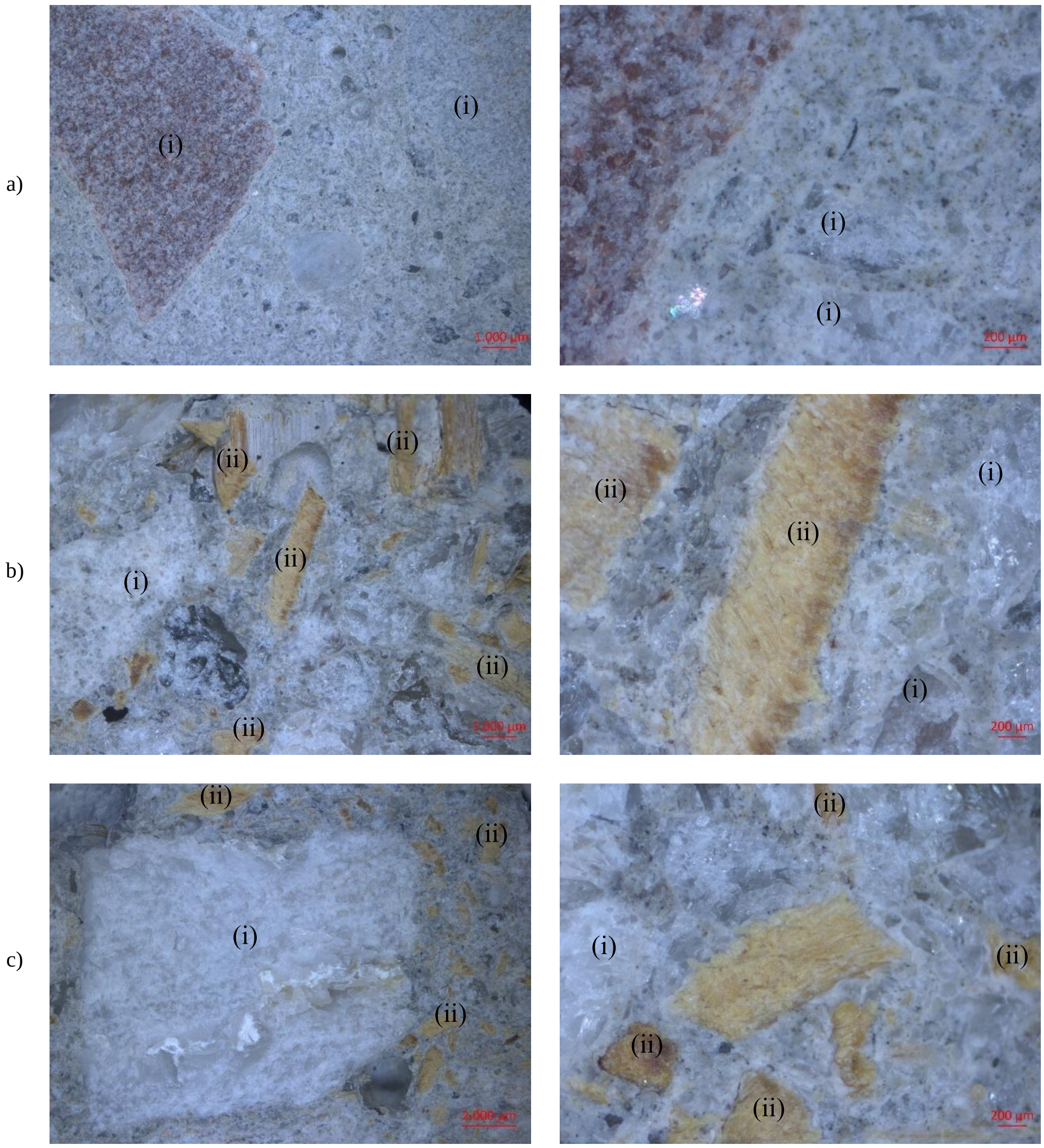


Figure 4.9: Stereoscopic micrographs, indicating some of the mineral aggregates (i) and wood particles (ii) embedded in the cement matrix: a) REF; b) WC25; c) WC20S5.

To obtain insight into the composites' microstructure and a close look at the interfaces between the different aggregates and the cementitious matrix, representative SEM micrographs were also recorded for the same samples (Figure 4.10). The images in the left column correspond to observations where a good interface between the aggregates and cement matrix were visible, while figures presented in the right column correspond to observations suggesting weak bonds or bond failure between aggregates and the cement matrix. As expected, more cases of micro-cracking were observed in wood–cement interfaces (WC25 and WC20S5), which is likely to be due to the stress generated by water loss or gain or/and bonding failure. Beltran and Schlangen [48] also reported a loss of interface bond due to the volume changes of wood fibres in the presence of water. However, similar effects were also observed for the reference sample (REF), suggesting that this phenomenon was not exclusive to the wood–cement composites.

a)

b)

c)

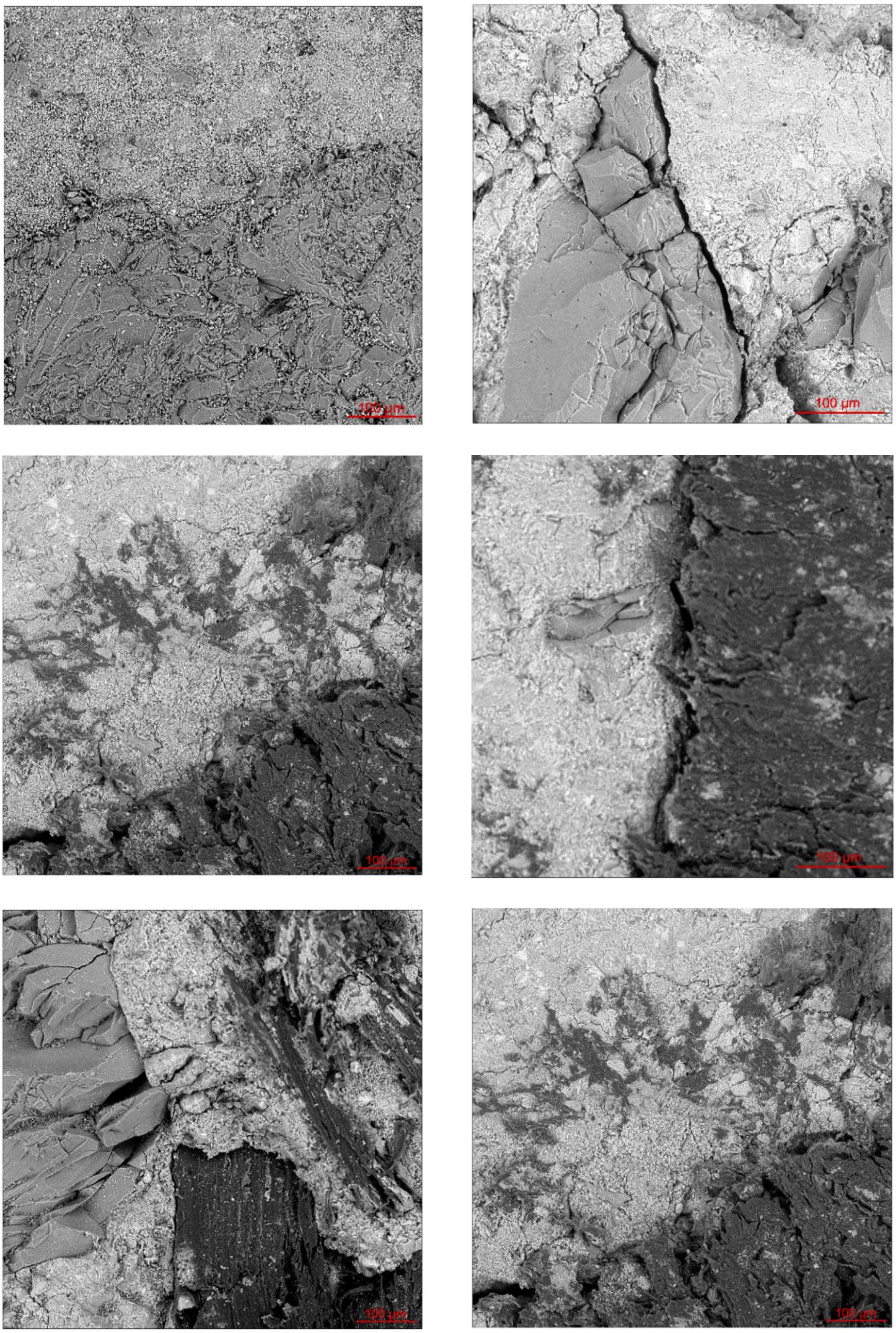


Figure 4.10: SEM micrographs with and without evidence of micro-cracking in the interface between aggregates and cement matrix in the right and left column, respectively: a) REF; b) WC25; c) WC20S5.

Dynamic elastic properties

The dynamic modulus of elasticity and Poisson's ratio were determined for all compositions at 7 and 28 days in order to compare the stiffness and deformation behaviour of the various concrete mixes containing different amounts of wood chips and sawdust (Table 4.9).

Table 4.9: Dynamic elastic properties (mean ± standard deviation)

Sample	Dynamic modulus of elasticity (GPa)		Poisson's ratio
	(7 d)	(28 d)	(28 d)
REF	37.59 ± 0.02	39.01 ± 0.34	0.32 ± 0.01
WC5	36.89 ± 0.37	38.18 ± 0.73	0.34 ± 0.01
WC10	37.40 ± 0.39	38.03 ± 0.01	0.33 ± 0.00
WC15	36.11 ± 0.76	37.36 ± 0.16	0.34 ± 0.03
WC20	30.94 ± 1.39	32.11 ± 1.49	0.32 ± 0.02
WC25	29.18 ± 2.57	31.55 ± 3.27	0.30 ± 0.03
SD5	38.17 ± 0.30	38.53 ± 0.02	0.33 ± 0.01
SD10	36.63 ± 0.65	36.57 ± 0.30	0.33 ± 0.01
SD15	35.25 ± 0.29	35.95 ± 0.37	0.34 ± 0.00
WC7.5SD7.5	34.76 ± 0.21	34.46 ± 0.12	0.34 ± 0.00
WC12.5SD7.5	34.54 ± 0.05	33.53 ± 1.48	0.32 ± 0.02
WC20SD5	30.11 ± 0.38	31.55 ± 0.90	0.29 ± 0.03

As expected, and similarly to what had been observed for compressive strength, the modulus of elasticity increased from 7 to 28 days and decreased as the wood content increased (Figure 4.11).

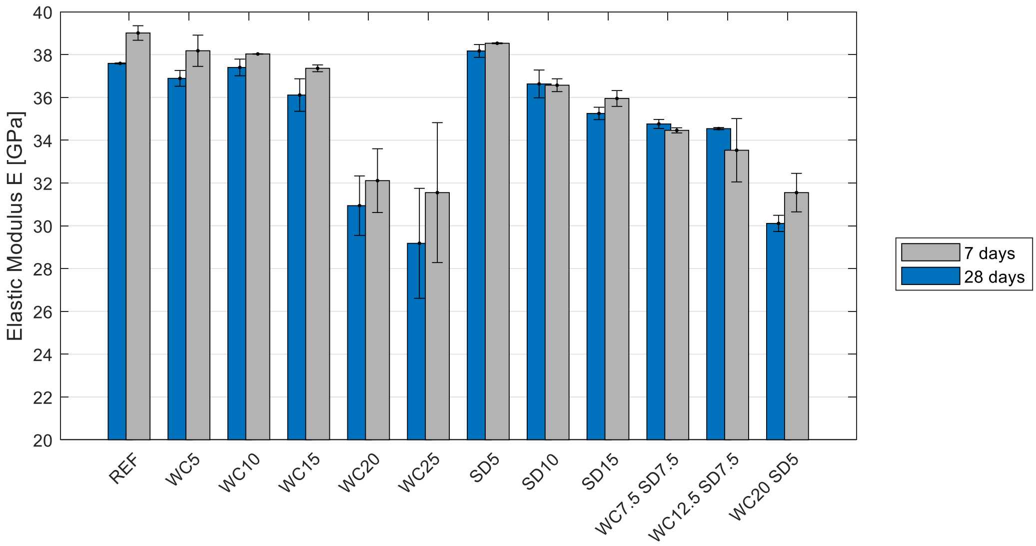


Figure 4.11: Modulus of elasticity of the wood–concrete samples (mean values ± standard deviation) at 7 and 28 days.

However, a significant drop in the results of the modulus of elasticity was observed for WC20 and WC25, which may be related to their lower density. In fact, as shown in Figure 4.12, a close linear relationship could be obtained between the density and the mechanical properties, with coefficients of determination (R^2) of 0.963 and 0.819 for the compressive strength and modulus of elasticity, respectively.

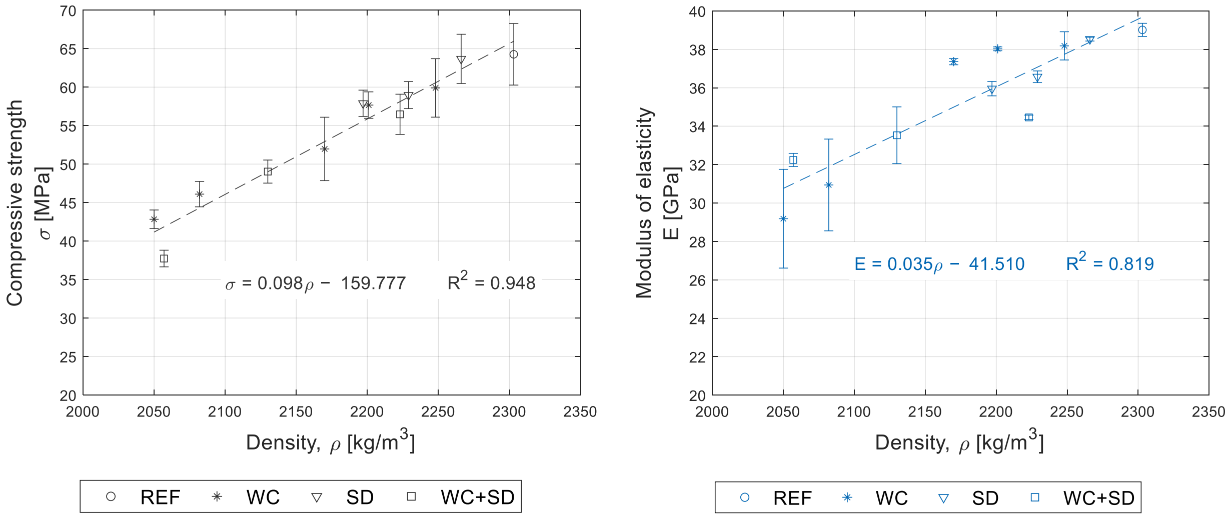


Figure 4.12: Variation in the compressive strength and modulus of elasticity with density.

Despite the high dispersion of results, some linear correlation ($R^2 = 0.756$) could be seen between the modulus of elasticity and compressive strength results (Figure 4.13).

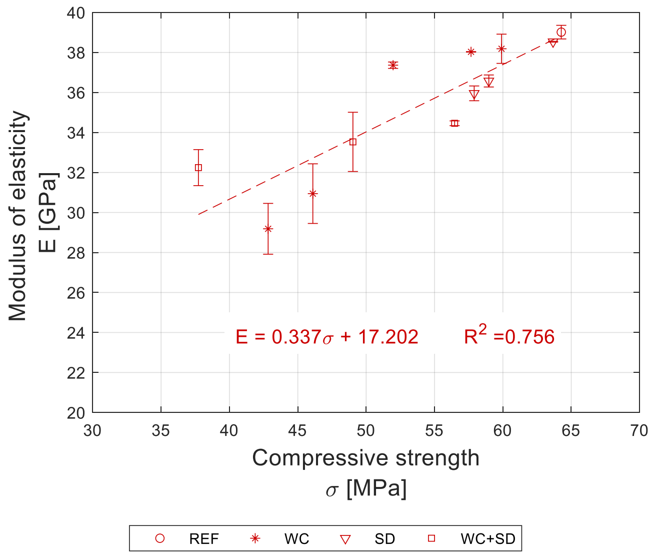


Figure 4.13: Variation of the modulus of elasticity with compressive strength.

Regarding Poisson's ratio (μ), values ranging from 0.29 to 0.34 were obtained, with the reference concrete sample recording a value of 0.32.

Note that most of the building codes for concrete assume that Poisson's ratio is equal to 0.2; Eurocode 2 [49]. However, published studies show that Poisson's ratio obtained using a dynamic approach often leads to higher values[50–52], which agrees with the results obtained.

Flexural Strength

The flexural strength results for the six tested compositions are summarized in Figure 4.14. As expected, a significant strength reduction resulted from incorporating wood particles, with the WC20SD5 having the highest decrease in flexural strength (32% lower than the reference mix).

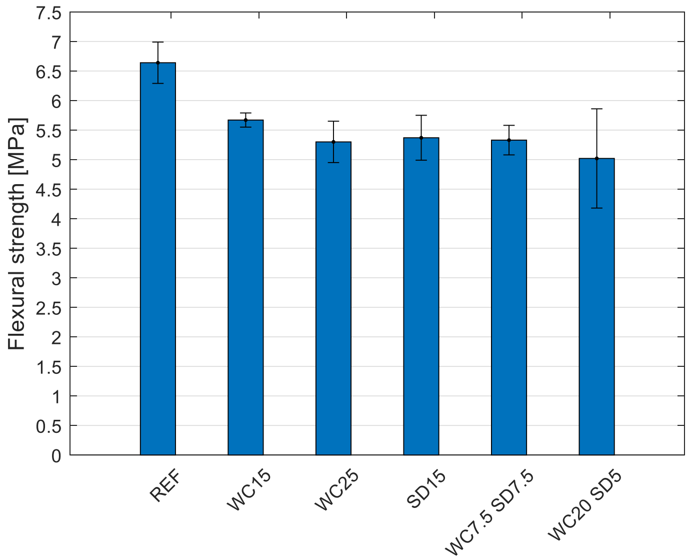


Figure 4.14: Flexural strength (mean values ± standard deviation) for the wood–concrete samples at 28 days.

As per the previously defined criteria (density below 2125 kg/m^3, compressive strength above 25 MPa, and maximum volume content of wood), and based on all the results of this section, the two mixes selected to proceed with further characterization were WC25 and WC20SD5, as above mentioned.

4.4.2.Durability

Compressive strength development

To help interpret the results of the artificial aging tests and act as an aging control, compressive strength development was evaluated over 180 days for the two selected series. Figure 4.15 shows compressive strength evolution with age. The results showed that both concrete mixes developed compressive strength up to 120 days. Compressive strength results remained constant after this age and for up to 180 days.

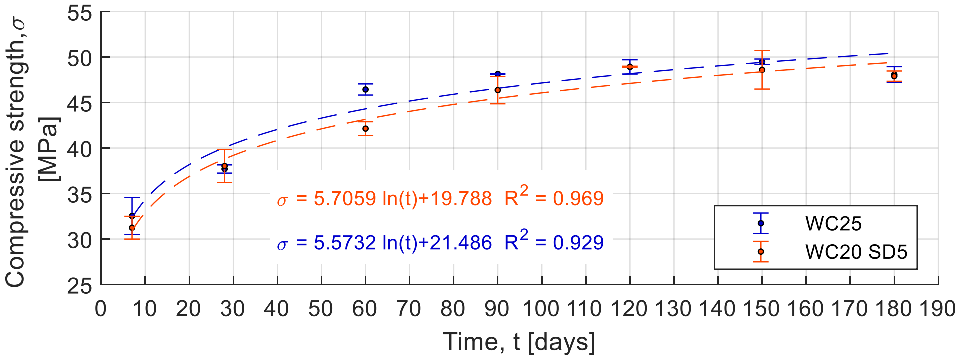


Figure 4.15: Compressive strength development over time (mean ± standard deviation).

Wetting–Drying, Freeze–Thaw, and Thermal Shock Cycles

As mentioned in the methods section, the results concerning the artificial aging cycles were determined by evaluating the compressive strength after subjecting the test specimens to different accelerated aging cycles and comparing them with samples of the same age but not subjected to any accelerated aging condition. These results are presented in Figure 4.16

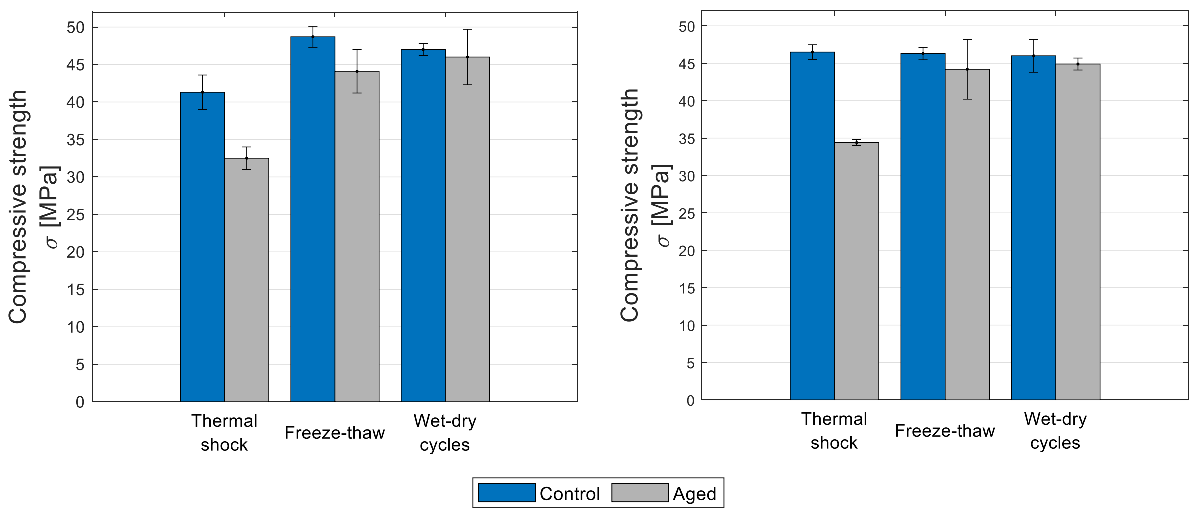
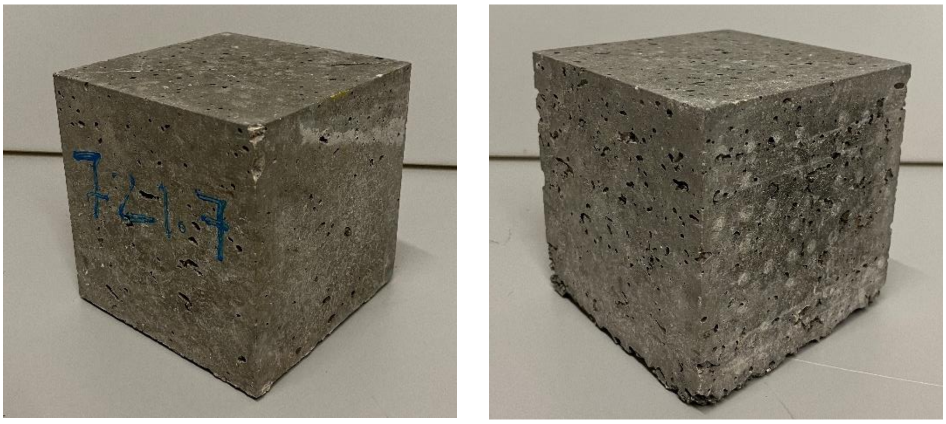


Figure 4.16: Artificial aging cycles: a) WC25; b) WC20SD5.

After being subjected to wet–dry cycles, none of the samples showed any visual damage, such as cracking or material disaggregation (see Figure 4.17). Moreover, samples of both series performed equally well before and after the wet–dry cycles in terms of compressive strength.

Similarly to the wet–dry cycles, none of the specimens from the two series exhibited any visual defect after being subjected to the freeze–thaw cycles. However, a slight reduction in compressive strength was registered for WC20SD5. At the same time, the WC25′s performance fell by 10% compared with the specimens that were tested at the same age but not subjected to the freeze–thaw cycles. Nevertheless, in both cases, the compressive strength after the freeze–thaw cycles was higher than that achieved at the age of 28 days, demonstrating that the compressive strength reduction would not compromise the material's usability.



a) b)

Figure 4.17: Test specimens after being subjected to wet–dry cycles: a) WC25; b) WC20S5.

There was no visible cracking or damage to the specimens after the thermal shock cycles. However, as expected, a drop in compressive strength was found for both compositions, with WC25 and WC20SD5 falling around 21% and 26%, respectively. In both cases, the compressive strength after the thermal shock cycles was lower than at 28 days. The WC25′s performance was similar to that at 7 days, indicating that the thermal shock cycles significantly affected the composites' durability performance. Note, however, that the conditions imposed on the specimens in the thermal shock test were very aggressive, with a temperature amplitude of approximately 85 °C. In a real application, the thermal shock is not expected to be as harsh.

4.4.3.Hygrothermal

Thermal Conductivity

The results showed a considerable thermal conductivity (λ) decrease for WC20S5 (54%) and WC25 (52%) compared with the reference sample (Figure 4.18). Additionally, the reduction in thermal conductivity seemed to be linearly related to density. To better assess this relationship, the thermal conductivity was also determined for the SD15 mix and corroborated the previous assumption. A determination coefficient (R^2) of 0.941 was found for the set of samples tested. This means that wood chips and sawdust can be used to produce more sustainable concrete with lower weight and lower thermal conductivity.

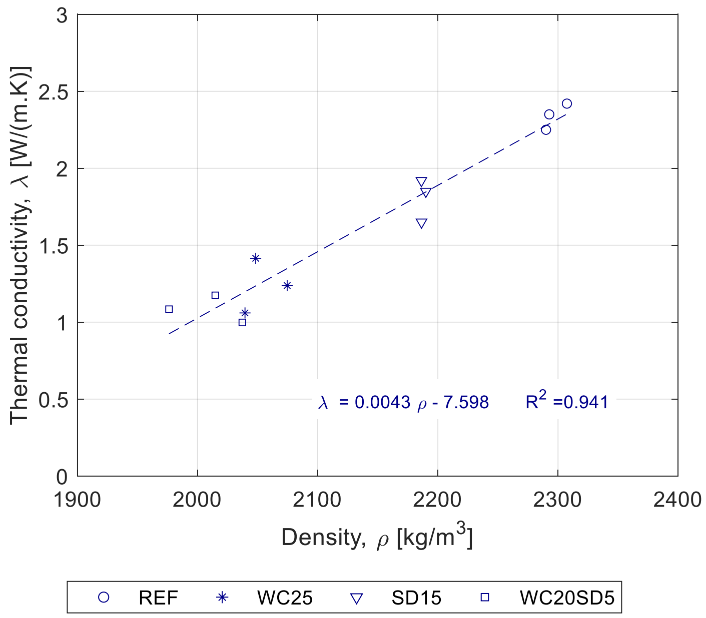


Figure 4.18: Relation between thermal conductivity and density

Water absorption

A high water absorption coefficient means there are chloride ions near the steel reinforcement bars embedded in concrete, which initiate their corrosion, leading to long-term performance and durability concerns with respect to concrete structures [53]. The water absorption coefficient $W_{w,24}$ and the total water absorption, both determined after 24 h for each set of specimens, are presented in Table 4.10.

Table 4.10: Water absorption coefficient at 24h

Sample	Ww24 [kg/(m^2.h$^{0.5}$)]	Total water absorption (%)
REF	0.18 ± 0.03	0.9 ± 0.1
WC25	0.18 ± 0.02	1.0 ± 0.1
WC20SD5	0.19 ± 0.02	1.1 ± 0.1

Mean results over time for each set of three specimens are also represented in Figure 4.19. The resulting plots follow straight trend lines with correlation coefficients (R^2) greater than 0.970. As expected, the compositions with wood recorded greater absorption than the reference one, although the values were quite small.

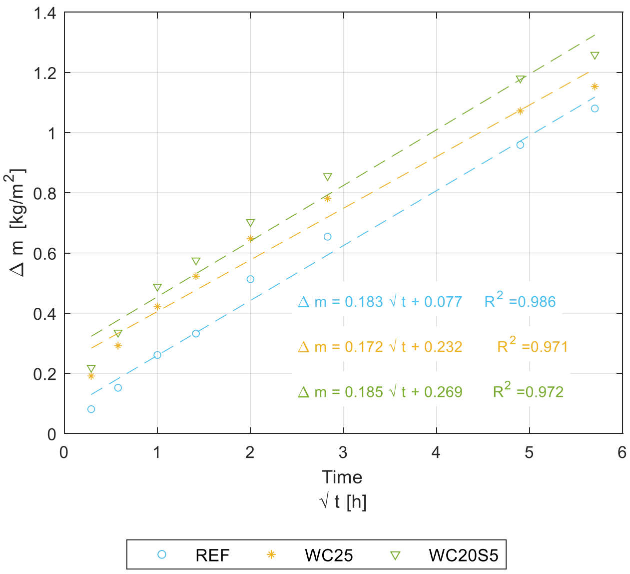


Figure 4.19: Mass gain per face area over time

Shrinkage and expansion

Shrinkage and expansion results showed that the compositions containing wood particles performed as well as or better than the reference sample. Table 4.11 shows that the shrinkage did not vary significantly for the three of them and that the expansion behaviour of the wood concrete mixes under water was of the same order of magnitude as that of the reference, thus confirming the poor ability of the composites to absorb water. Concrete made with lightweight aggregates exhibited a higher moisture movement (i.e., a higher rate of drying shrinkage) [54].

Table 4.11: Mean results of shrinkage and expansion

Sample	Shrinkage (10^{-4})	Expansion (10^{-5})
REF	4.45 ± 0.33	7.0±1.6
WC25	2.65 ± 1.67	1.9±2.0
WC20SD5	4.44 ± 0.22	1.9±1.8

4.4.4.Acoustic

The impact sound was characterized using one-third octave bands for mid-frequencies ranging from 100 to 3150 Hz. The normalized impact sound pressure level ($L_{n,r}$) results were calculated in accordance with ISO 717-2:2013 [45], for loosely laid material and wood-cement compounds. The computed weighted reduction of the impact sound reduction index (ΔL_w) are listed in Table 4.12.

Table 4.12: Impact sound reduction index (ΔL_w).

Sample	Reference and thickness	Mean density [kg/m^3]	ΔL_w [dB]
Wood loosely laid	WC25_10 mm	213 ± 8	23
	WC25_23 mm	133 ± 3	25
	WC25_30 mm	143 ± 4	24
	WC25_40 mm	143 ± 6	26
	WC20S5_10 mm	213 ± 7	22
	WC20S5_23 mm	133 ± 5	23
	WC20S5_30 mm	143 ± 6	25
	WC20S5_40 mm	143 ± 4	26
Wood-cement compounds	WC25_10 mm	741 ± 45	17
	WC25_23 mm	641± 40	18
	WC25_30 mm	719± 10	18
	WC25_40 mm	717± 12	20
	WC20S5_10 mm	700± 50	20
	WC20S5_23 mm	727± 15	21
	WC20S5_30 mm	670± 21	21
	WC20S5_40 mm	623 ± 21	20

4.5. Discussion

This section summarizes the main findings in terms of mechanical, durability, hygrothermal and acoustic properties. The results obtained for the selected compositions are further compared with those reported in the literature.

Although compressive strength did decline with the amount of wood chips and sawdust, all composites recorded compressive strength above 30 MPa. Compared to the reference sample, the compressive strength reduction of WC containing up to 25 v% wood chips content was found to range from 7% to 33%. The amount of sawdust up to 15 v% seemed to have less impact on compressive strength, which showed a reduction of between 0.9% and 10%. The compressive strength reduction of composites containing a mixture of chips and sawdust ranged from 12% to 41%. Note that compressive strength and modulus of elasticity seemed to be closely related to density, with the denser samples presenting higher values of both properties. The flexural strength also declined by up to 32% with the incorporation of wood particles (25 v%). Optical and electronic microscopy inspection showed similar micro-cracking effects for the reference sample and composites containing wood particles.

An aging control test showed that the two selected composites (WC25 and WC20S5) developed compressive strength within 120 days, without loss of strength after that, for up to 180 days. The results for the durability assessment (artificial aging) further showed that the thermal shock affected the compressive strength more than the other aging cycles (wet–dry and freeze–thaw). However, the compressive strength was still higher than 30 MPa for the selected mixes after all the accelerated aging tests.

Water absorption was very low (approximately 1% at 24 h), suggesting that the wood content did not contribute significantly to water absorption of the hardened material. Additionally, the thermal conductivity dropped by about 50%, comparing the two selected mixes with the reference sample. The incorporation of sawdust seemed to have less impact on the thermal conductivity, which was probably because of the higher compactness of specimens.

A summarized table comparing the results obtained for the selected compositions with those available in the literature is now presented for comparison purposes (Table 4.13).

Table 4.13: Results obtained for the selected compositions compared with those in the literature.

	Property	**WC25**	**WC20SD5**	**Reported Values from the Literature**
Physical and Mechanical	Compressive strength at 28 d (MPa)	42.83 ± 1.21	37.73 ± 1.08	7.9 ± 0.66 [19] 7.3 [20] ≈ 11 [21] ≈ 7 [22] 25.8 ± 3.79 [23] ≈ 34 [24]
	Density (kg/m^3)	2050 ± 15	2057 ± 12	764.06 ± 36.35 [7] 1706 ± 1.55 [19] 2217 [22] 2200 [23] 2173 [24] 2408.4 [50](a) 2307 [55] (b)
	Poisson’s ratio	0.30 ± 0.03	0.29 ± 0.03	0.296 [50] (a) 0.11 [55] (b) 0.241 [50] (c)
	Modulus of elasticity (GPa)	31.55 ± 1.27	31.55 ± 0.90	≈ 12 [19] 31.44 [35] (d) 23.98 [50] (a) 48.25 [56] (c)

	Property	WC25	WC20SD5	Reported Values from the Literature
	Flexural strength (MPa)	5.3 ± 0.35	5.02 ± 0.84	2.5 [7] 1.8 [20] ≈ 2 [22]
Durability (loss of compressive strength)	Wet–dry cycles (%)	2	2	-
	Freeze–thaw cycles (%)	9	5	-
	Thermal shock (%)	21	26	-
Hygrothermal	Thermal conductivity [W/(m.k)]	1.24 ± 0.18	1.09 ± 0.09	2.00 [24] 0.8 [25] 0.89 [26] 1.05 [26]
	Shrinkage	2.65 ± 1.67 (10^{-4})	4.44 ± 0.22 (10^{-4})	-
	Expansion	1.9 ± 2.0 (10^{-5})	1.9 ± 1.8 (10^{-5})	-
	Water absorption at 24 h (%)	1.0 ± 0.1	1.1 ± 0.1	29.7 ± 4.54 [7] 15.1 [19] 17.6 [20] 3.62 [24]
Acoustic	Normalised impact sound pressure level [dB]	LL (t =30 mm) 24 LL (t=40 mm) 26 WCC (t=30 mm) 18 WCC (t= 40 mm) 20	LL (t =30 mm) 25 LL (t=40 mm) 26 WCC (t=30 mm) 21 WCC (t= 40 mm) 20	28 [57] [e] (t =30 mm) 17 [57] [f] (t =30 mm) 16 [58] [g] (t=40 mm)

[a] Mineral concrete (w/c = 0.55, pozzolana Portland cement). [b] Polyethylene fibre-reinforced concrete (9 kg/m^3 of fibre content). [c] High-performance fibre-reinforced concrete—2% of steel fibre volume (w/c = 0.28, Portland cement type I 52.5 N). [d] Concrete with replacement of 15% of cement by rubber (w/c = 0.40). [e] expanded cork granules (loosely laid material). [f] Screed mix with replacement of 80% of sand by expanded cork (w/c = 0.50), 400 kg/m^3 of cement. [g] Screed mix with 100% of expanded cork (w/c = 0.50), 342 kg/m^3 of cement.

Analysing the results in Table 4.13, it can be seen that the compressive strength values obtained in this work are higher than those found in the literature for composites integrating wood. In some of the cases presented, the compressive strength is relatively small, even for identical density values.

The flexural tests, commonly used to assess the effect of wood fibres in bending, showed that adding wood chips did not appear to improve the flexural resistance of the composites. This is probably because of the shape of the fibres (not needle shape).

The dynamic Poisson's ratio and elastic modulus obtained in this work agree with those found in the literature. In most cases, they are higher than those found for mineral concrete mixes.

Regarding the durability of composites of this kind, little information is found in the literature, which suggests that further research needs to be carried out.

As far as the hygrothermal behaviour is concerned, it is clear from the literature that adding wood particles to concrete results in a better thermal performance than that of conventional concrete.

However, this gain is usually followed by a significant reduction in the mechanical resistance. Water absorption was found to be much less than that found in the literature for composites integrating wood, which is dependent on the density. The denser specimens present less water absorption.

When comparing the acoustic properties in terms of normalised impact sound pressure level, it has been observed, as supported by existing literature, that loosely laid materials provide superior impact sound insulation compared to cement compounds.

4.6. Conclusions

Several composites containing different wood chips and sawdust content were developed and tested to evaluate the potential of wood waste to replace conventional mineral aggregates in concrete. The characterization involved an extensive campaign assessing the mechanical performance, durability, and hygrothermal properties. After performing mechanical tests on twelve different composites of varied composition, two were selected based on predefined criteria (density below 2125 kg/m^3, compressive strength above 25 MPa, and maximum volume content of wood) for further characterization by assessing the durability performance and hygrothermal properties.

All compositions showed compressive strength above 30 MPa. The durability assessment of selected compositions further showed that compressive strength after relevant artificial aging was still higher than the predefined criteria. Promising hygrothermal properties were also recorded, i.e., approximately 1% of water absorption in 24 h and thermal conductivity up to 54% lower than the reference concrete.

The results obtained suggest, in the opinion of the author, that optimized concrete mixes containing up to 20 v% of wood chips and sawdust present physical, mechanical, and durability properties that make them suitable to be used in both structural and non-structural applications, including fence poles, slabs, façade panels, and street furniture.

Possible future research work on the topic could include the study of the bond behaviour of concrete, integrating wood waste with steel bars, and the fabrication and test of full-scale constructive building elements using the selected compositions.

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CHAPTER 5

STEEL CONCRETE BOND OF CONCRETE MIXES WITH WOOD WASTE

5.1. Introduction

The incorporation of wood waste in wood-cement compounds has been studied, particularly for non-structural applications such as walls, roof sheets and tiles, floor resilient layers, and sound barriers. These compounds have benefits, especially in terms of physical properties like good thermal and acoustic behaviour.

The application scenarios of these composites include the production of reinforced concrete structural elements, but further studies are needed to encourage their adoption. The steel–concrete bonding mechanism ensures the good behaviour of reinforced concrete structures by guaranteeing that both materials work together. The bond strength is essential to determine the required anchorage length [1]. The feasibility of using structural concrete that contains wood waste material should start by ensuring that steel and concrete work well together and provide good ductility [2]. This question is much more critical in prestressed concrete because the entire prestressing force is transferred to concrete through the bond. Bond failure can also cause the concrete to crack, which can lead to early localized corrosion of the reinforcement. For both types of reinforcement (ordinary and prestressed steel), numerous studies have been performed to investigate the bond behaviour of steel in conventional concrete [3,4]. Other types of reinforcement have also been studied, like GFRP rebars [5] and bamboo [6]. According to Reis et al. [4] recycled aggregate concrete (RAC) is the type of concrete with substitutions in which the bond between steel and concrete has been more studied. Several studies [7–10] show that bond stress decreases with the replacement of mineral aggregates by RAC. Concrete with partial aggregate replacement by waste tyre rubber has also been studied [11–13]. Results also show a reduction in bond strength. On the other hand, fibres seem to enhance concrete bond capacity by confining the bars [5,14–16]. But further research is needed for wood-concrete. This lack of knowledge can limit the use of this concrete in reinforced structures.

Thus, this work intends to contribute to a widespread application of these composites by investigating the steel-concrete bond of ordinary steel reinforcement bars and prestressed strands. It evaluates the bond strength through pull-out tests, which depend to a great extent on the bond length and the adhesion of this type of concrete (with wood waste) to the steel bars and strands, which needs to be well understood. In this chapter, the bond strength of ordinary reinforcement steel bars (ϕ6 and ϕ10) and of two-wire strands (ϕ4.5) was determined by adopting different bond lengths, 5 d (based on EN 10080:2005 [17]), the strand pitch, and 400 mm (based on ASTM A1081M-21 [18]).

Another important issue is possible excessive cracking due to the creep phenomenon. Creep effects are particularly relevant for prestressed structures because of their slenderness and high flexibility [19,20]. Aggregates with a low modulus of elasticity, such as wood shavings and sawdust, can decrease concrete's modulus of elasticity but also increase creep. However, creep is not only influenced by the modulus of elasticity of the concrete's aggregates. In fact, internal micro defects in concrete at wood-cement interfaces also may weaken creep resistance [21]. Creep tests were also performed for strands. The displacement was continuously measured for 120 hours, maintaining a constant force applied, to see whether the addition of wood influenced the concrete's creep.

Full-scale structural elements were then constructed, namely bar reinforced beams (ϕ6 and ϕ10), and prestressed columns (ϕ4.5). These were tested to assess the feasibility of using these composites in real applications such as ordinary cast-in-situ elements and prefabricated linear ones used in houses, small buildings/constructions, fences, and other agricultural facilities. Bending tests were used to determine the behaviour of the beams and columns under static bending load. Apart from performing these static tests to failure, dynamic bending tests (fatigue tests) were also carried out to evaluate the behaviour of elements of this kind under dynamic load conditions, such as wind and seismic loads.

The chapter is divided into five main sections. Details of the materials' characterisation, and the pull-out and creep tests are given in the next section. The results of these tests are then presented and discussed. The bending behaviour of structural elements developed with wood-concrete composites is also assessed in a separate section. The last section summarises the main conclusions of the study.

5.2. Materials

This section briefly describes the materials employed to investigate the behaviour of the steel-concrete bond. The materials include a series of mixes formulated in the preceding chapter, besides the reinforcement (ordinary and pre-stressed).

5.2.1. Concrete mixes

The previously designed mixes were defined to reduce density and maximize the percentage of wood (v%) without compromising strength. Three mixes produced with CEM II/A-L 42.5 R were selected. One mix, without wood, is used as the reference mix (REF). In one of the other two mixes, 25% volume of the aggregate was replaced with wood chip (WC25), and in the other 20% volume was replaced with wood chip and 5% with sawdust (WC20S5). The replacement of the aggregates, Sand 0/4 (S0/4), Gravel 0/5 (G0/5), and Gravel 1 (G1), was conducted with a view to causing minimal disturbance to the particle size distribution of the aggregates. The mix design is presented in Methods Section.

5.2.2. Reinforcement

The steel-concrete bonding behaviour was studied for the diameter of two steel bars and a two-wire strand, as presented in Table 5.1.

Table 5.1: Steel bars and strands

ϕ	Steel	Form of supply	Section area [mm²]	Height of ribs [mm]
4.5	Y1860S2	Coil of 1.4 m and 0.8 m (external and internal diameters)	7.95	-*
6	S500	12 m bar	28.27	0.52
10	S500	12 m bar	78.54	0.84

* Pitch of 9.3 mm

5.3. Methods

The methods used to characterise the materials (wood-concrete composites, and steel bars and strands) and a brief description of the mix design approach are presented first and then the bond resistance tests are described in more detail. A description of creep tests is also included.

5.3.1. Characterisation of materials and mix design

A Portland cement concrete mix was used as a reference (REF) for comparison purposes and as a starting point to incorporate wood waste into the composite, Table 5.2. Portland Limestone cement manufactured by the Secil Group and classified as CEM II/A-L 42.5 R according to EN 197–1:2011 [22] was used to produce the reference and the composite mixes. One sand type and two pebble-shaped gravels were used as mineral aggregates.

All mineral and wood aggregates were physically characterised according to European mineral aggregate standards. The particle size distribution, particle density, and water absorption of all aggregates were also determined in the previous chapter [23]. Only the water content of the mineral aggregates was checked since the wood aggregates were saturated for 24 h before being incorporated into the mix.

The aggregate replacement was calculated in volume (%) considering the materials' saturated surface-dry density to avoid volumetric variations between different mixes.

The wood aggregates were first saturated for 24 h in a covered container with a pre-defined water amount (more than required for the mix). Before preparing the mix, the contents of this container were carefully drained into a vessel on a weighing scale until the known amount of excess water was removed.

The water/cement ratio (w/c) of the reference mix, previously optimised, was kept unchanged (0.45). For the wood-concrete composites, in a first stage, four water/cement ratios (w/c) of 0.45, 0.50, 0.55, and 0.60 were studied to assess the main properties of the hardened mixes. Lower w/c ratios were tried, but their workability was inadequate.

The concrete mixing process started by adding coarser to finer aggregates and cement in the electric vertical shaft concrete mixer (Controls, 130 L). Then the water and the wood were poured into the concrete mixer. A superplasticiser Dynamon SP1 Mapei (SP) was used in the two mixes containing wood to improve workability. The amount of SP was based on the cement content, according to the manufacturer's indications.

Table 5.2: Mix composition [kg/m^3]

Series	Cement	S0/4	G0/5	G1	WC	SD	SP
REF	400	690	467	674	-	-	-
WC25	400	370	351	653	214	-	5
WC20SD5	400	342	374	657	171	60	5

5.3.2.Characterisation of the wood-concrete composites

Three properties were characterised, namely compressive strength, modulus of elasticity (static and dynamic), and water absorption for all mixes. Sets of three cubic specimens, with 150 mm edge, were used for all the tests except the static modulus of elasticity, for which sets of three specimens were used, measuring 100 mm in diameter and 200 mm in height. All specimens were cured in a water tank at 20 ºC.

Compressive strength

The compressive strength was determined according to EN 12390-3:2019 [24] at 7 and 28 days. An electromechanical compressive testing machine, Controls model 50-C56V2, was used with a load cell of 3000 kN. The load was applied at a rate of 0.6 ± 0.2 MPa/s. The compressive strength is obtained by dividing the failure load by the average cross-sectional area.

Modulus of elasticity

The modulus of elasticity was evaluated at 28 days through a non-destructive dynamic method using a commercial portable Pundit Lab to generate and receive ultrasonic pulses. Two pairs of P and S wave transducers were used, with nominal frequencies of 54 kHz and 250 kHz, respectively. Measuring the P-wave and S-wave velocities (V_p and V_s) enabled the modulus of elasticity to be calculated.

For validation purposes, the static modulus of elasticity in compression was experimentally determined according to DIN 1048-5:1991 [25], only for the w/c of 0.45 (the ones with larger compressive strength values). An Instron hydraulic press, model 600 RD, with a load cell of 600 kN was used, along with an additional extensometer HBK Ibérica S. L, model W1ELA/1 mm with a measurement range of 0-1 mm.

Water absorption

The water absorption percentage was determined considering the specimen with saturated mass (immersed in water at (23±2) ºC to a depth of (5±2) mm) and dry mass (conditioned in a climatic chamber at (23±2) ºC). The mass was assumed to be constant in both cases (saturated and dry) for a variation inferior to 0.5% of two consecutive weights, 24 h apart.

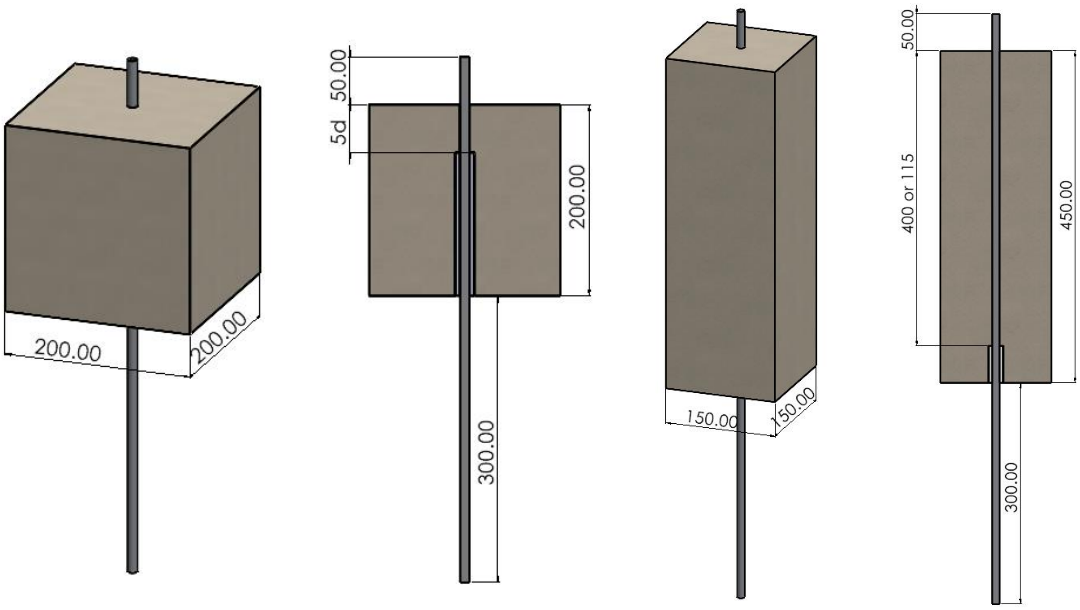
5.3.3. Characterisation of the steel bars and strands

The tensile strength was determined for three specimens of each sample according to ISO 15630-1:2019 [26] and ISO 15630-3:2019 [27] for the bars and the strand, respectively. A servo hydraulic testing machine, INSTRON SATEC 1200KN-J1D, was used with a load cell of 1200 kN, a 200 mm Instron M300B extensometer, and a 100 mm INSTRON 2630-119 clip-on extensometer, for the bars and the strand, respectively.

5.3.4. Bond resistance

The reinforcement steel bars were tested following the procedure indicated in EN 10080:2005 [17]. The mould dimensions and the bond length (bl) adopted were those shown in the standard, as illustrated in Figure 5.1a. The two-wire strand specimens were prepared based on both EN 10080:2005 [17] and ASTM A1081M-21 [18] (Figure 5.1). The specimens' test set-ups are summarised in Table 5.3.

The length of the upper bar/strand of the specimen (free end), and the length of the reinforced part where the load is applied (loaded end) is the same in both methods, 50 mm and 300 mm, respectively (Figure 5.1).



a) b)

Figure 5.1: Pull-out test specimens with the identification of bond length (mm) based on standard methods in a) EN 10080:2005 [17]; b) ASTM A1081M-21 [18].

Table 5.3: Bond resistance test set-ups

Type of reinforcement	Diameter [mm]	Method	Mould dimensions [mm]	Bond length [mm]	Free length [mm]	Pre-tension	Number of specimens
Reinforcement steel bar	6	EN 10080:2005 [17]	200 x 200 x 200	30	170	Not applicable	24
	10			50	150	Not applicable	24
Two-wire strand	4.5	ASTM A1081M-21 [18]	150 x 150 x 450	23	177	Yes	24
				115	335	Yes	24
				400	50	Yes	24

Eight specimens of each composite were prepared (REF, WC25, and WC20S5), making sets of 24 specimens for each test, in a total of 120 tested specimens. The differences between tests/samples derive essentially from the methods used (EN 10080:2005 [17] and ASTM A1081M-21 [18]).

Since the strands are supplied in coils, the unstressed strand may not be perfectly straight. During the pull-out test, the strands would tend to be straightened and compressed on the concave side and lose contact on the convex side. To mitigate this effect, the test specimens were cast and cured, with the strands being stretched by hydraulic jacks with a tension of 1500 ± 100 N (around 10% of $F_{p0.1\%}$), as per Figure 5.2.

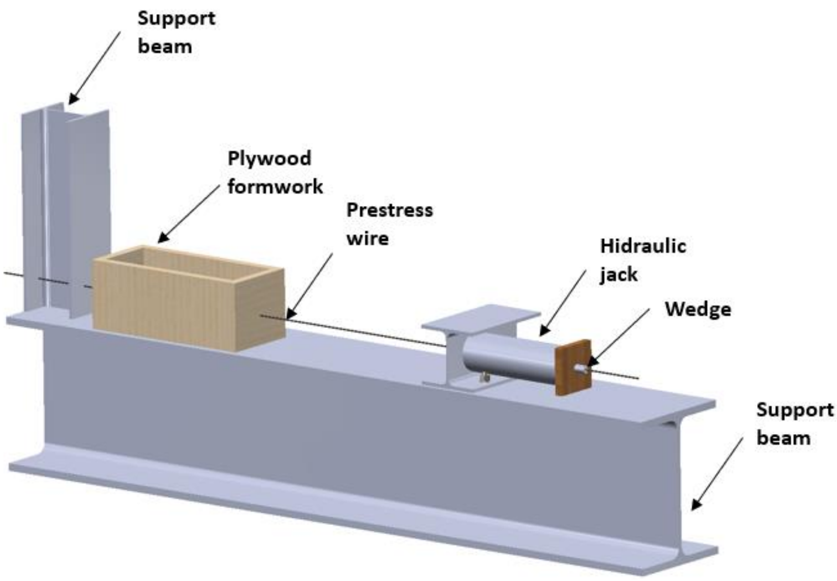


Figure 5.2: Prestress application (pull-out specimens).

Preparing the specimens involved the following steps: making a mould (with an open face for casting); drilling the centre of two opposite sides to allow the bar/strand to pass through the mould freely; inserting a polyvinyl chloride (PVC) pipe in the mould hole to create a free length. The reinforcement passes through the holes of the two wooden plates. The side where the tube is fixed has a hole with a diameter of 16 mm, and the tube length corresponds to the free length. This free length is given by subtracting the mould length (200 or 450 mm) from the bond length (Table 5.3). Since the tube diameter is bigger than the reinforcement bar, steel covers were provided for the tubes, with a hole of the same diameter as the bar/strand to prevent the slurry from entering the tube (Figure 5.3). The correct bond length is checked before casting.

Figure 5.3: Mould before casting.

Concrete was poured into the mould and then vibrated. During the casting of specimens to be submitted to pull-out tests, three additional 150 mm cubic moulds were prepared to test compressive strength at 28 d, for control purposes. The specimens were cured under ambient conditions of 23 ± 5 ºC. The mould was removed after 7 d, and pull-out tests were conducted after 28 d.

The designated loaded end of the steel strand/bar is gripped by the universal tensile testing machine Instron, model 59R5884, and pulled away from the concrete specimen at a loading rate of $56d^2$ N/s (1134, 2016 and 5600 N/s corresponding to the diameters of 4.5, 6 and 10 mm, respectively). As indicated in EN 10080:2005 [17], this loading rate ensures that the rate of increase of the bond stress is constant.

The tensile force on the loaded end of the strand is measured with an Instron load cell of 50 kN model 2525-181 and the corresponding free-end displacement measured with an Instron extensometer model 2630. The test was conducted until 1 mm of free end displacement was reached for all samples. Figure 5.4 presents the test set-up of the bond resistance test (pull-out test). The test result is the shear stress given by the maximum tensile force, measured at the loaded end of the specimen and divided by the bond area (bond length multiplied by the strand/bar perimeter).

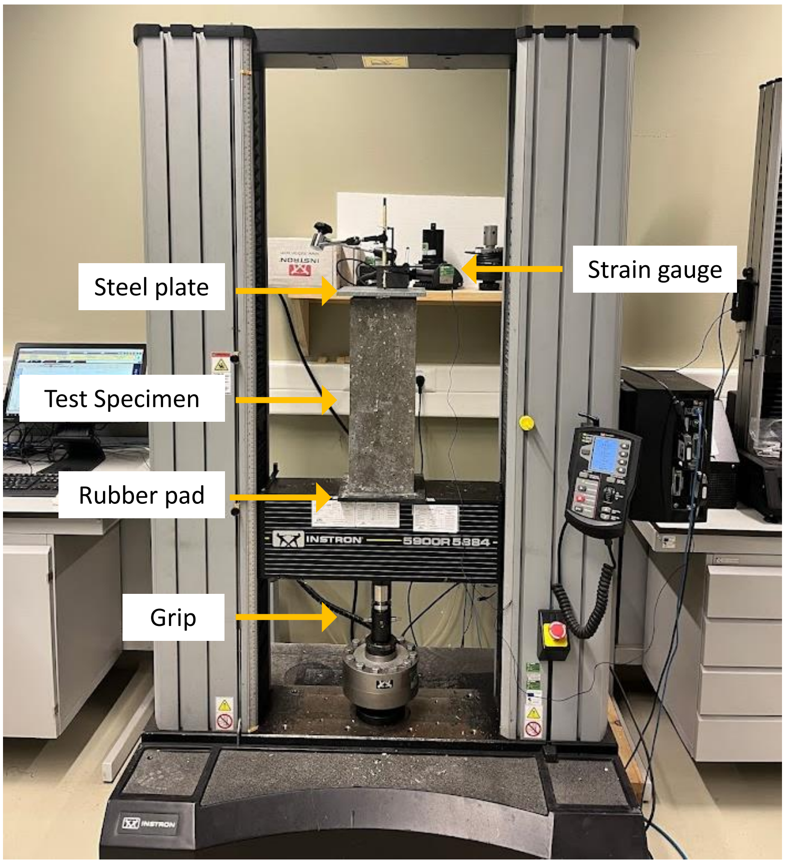


Figure 5.4: Pull-out test set-up.

Creep tests were performed for the two-wire strands using *walter+bai ag* isothermal stress relaxation equipment, model LFZ 325 kN (Figure 5.5).

The specimen was maintained with a constant force applied and the displacement was continuously measured for 120 hours. The load applied corresponds to 50% of the mean load resistance of the pull-out tests of the smaller value, corresponding to 2800 N (reference).

The test specimen type is the same as that used in the pull-out test, with a bond length of 400 mm. This test was only performed for strands and considered three test specimens of each mix.

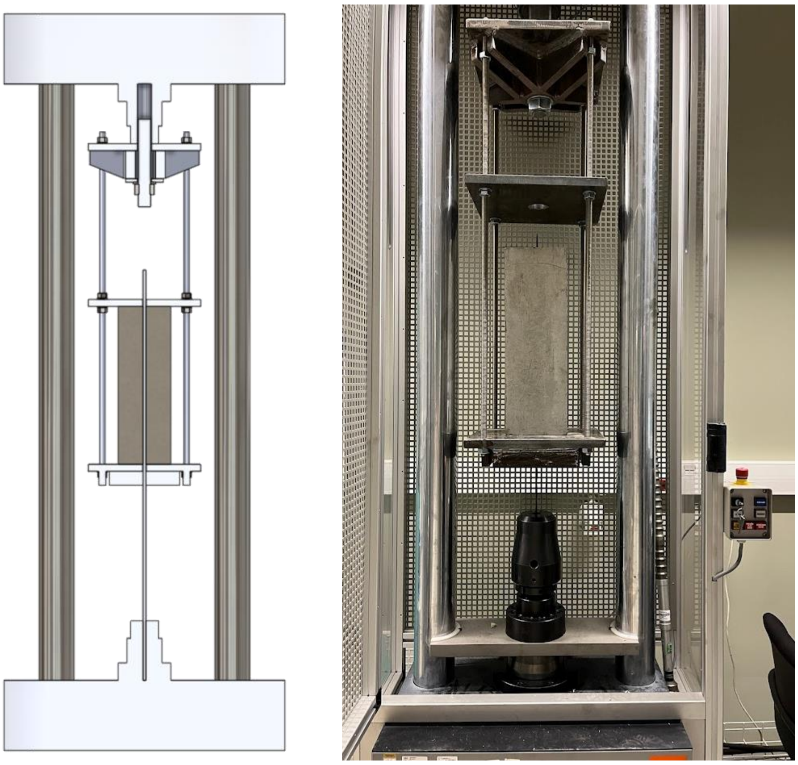


Figure 5.5: Creep test set-up.

5.4. Results and discussion

The experimental programme started by performing the material characterisation and assessing the bond resistance. The results are presented in the same order as the methods. The bond resistance of the bars' results is discussed first, followed by the results for the strands. Creep results are also presented.

The mean ± standard deviation values were calculated for all tests, indicated graphically using error bars to facilitate the interpretation of the results.

5.4.1. Materials characterisation

In the previous chapter, several composites containing different wood chips and sawdust content were developed and tested to evaluate the potential of wood waste to replace conventional mineral aggregates [23]. Compared to the reference sample, the compressive strength reduction of WC mixes containing up to 25 v% wood chips content was found to range from 7% to 33%. The compressive strength reduction of mixes containing a mixture of chips and sawdust also containing up to 25 v% ranged from 12% to 41%;

Since all mixes recorded compressive strength above 30 MPa, the author proceeded with the two compositions incorporating a higher percentage of wood waste.

Four w/c ratios (0.45, 0.50, 0.55, and 0.60) were studied for the wood-concrete composites and compared to the reference mix with w/c=0.45 for the chosen mixes.

Compressive strength

The results of the compressive strength of the wood-concrete composites are given in Figure 5.6. The reference mix results are presented for comparison purposes. Both compositions containing wood presented a significant reduction of compressive strength compared with a reference mix, although, between them, the differences were minor, with WC25 having a higher compressive strength. The compressive strength of the wood-concrete composites increased steadily according to the curing age and decreased steadily with increasing water/cement (w/c) ratio.

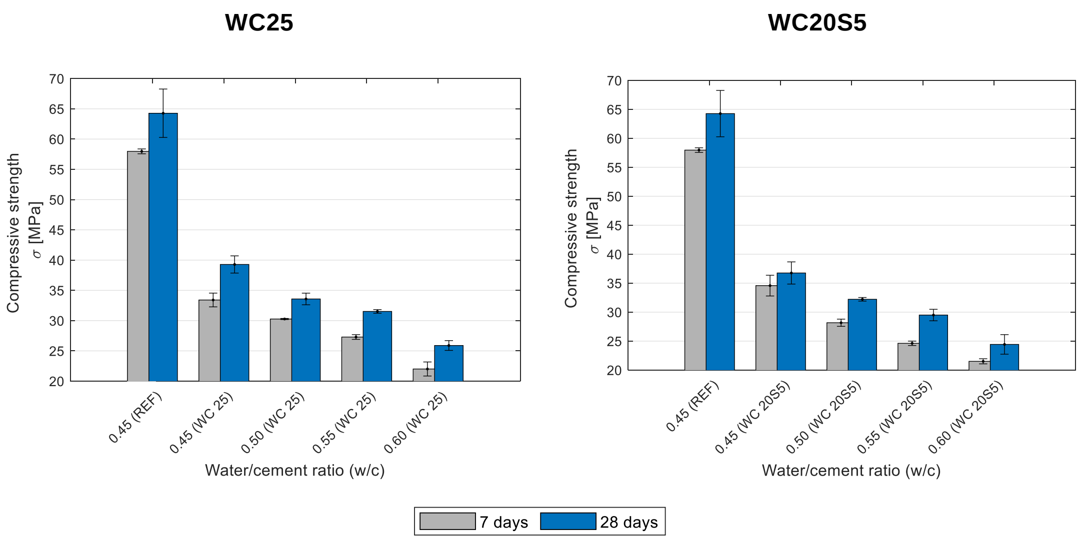


Figure 5.6: Compressive strength of the wood-concrete composites, mean values and standard deviation at 7 days and 28 days for different w/c ratios.

Modulus of elasticity

Several authors have studied the relationship between the static and dynamic modulus of elasticity of concrete. Equations relating the two are reported in the literature (e.g. Popovics [28], Chavhan & Vyawahare [29]) and even in some standards (e.g. BS 8110-2:1985 [30]). In the present work, the dynamic modulus obtained experimentally was also used to estimate the static modulus using the equation from BS 8110-2:1985[30]:

$$E_s = 1.25E_d - 19 \quad (5.1)$$

where E_s is the static modulus and E_d the dynamic modulus. Figure 5.7 presents the modulus of elasticity evaluated experimentally (static and dynamic). An estimation of the static modulus obtained using equation (5.1) of BS 8110-2:1985 [30] is also presented. These estimated values were obtained by substituting the E_d for the experimentally determined dynamic modulus in equation (5.1). The wood-composite samples that only incorporated chips recorded slightly larger moduli of elasticity values than the composites with chips plus sawdust.

The static value obtained experimentally was substantially lower than the dynamic value, although it is close to the value obtained using the BS 8110-2:1985 [30] approach. The modulus of elasticity falls slightly as the water/cement ratio increases, which is more evident for w/c of 0.6 in the case of WC20S5.

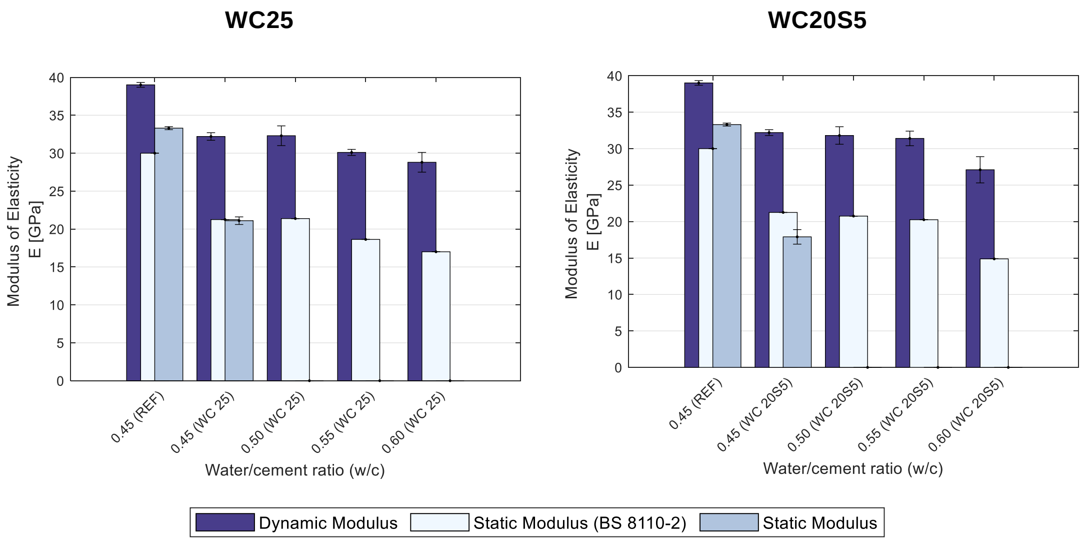


Figure 5.7: Modulus of elasticity (static and dynamic) of the wood-concrete composites, mean values and standard deviation for different w/c ratios.

Water absorption

The total water absorption results obtained are presented in Figure 5.8, for the different w/c ratios considered for the two composites and the reference mix. These results are also compared with the variation of mass density. Although it is a minimal value (less than 4%), the water absorption strongly increases with increasing w/c ratio, showing that the w/c ratio has more influence on the water absorption than the incorporation of the wood itself. These results agree with previous work [23], where the water absorption was found to be very low (approximately 1%) for a w/c of 0.45 for the same mixes. It can also be noted that as density decreases water absorption increases.

WC25 **WC20S5**

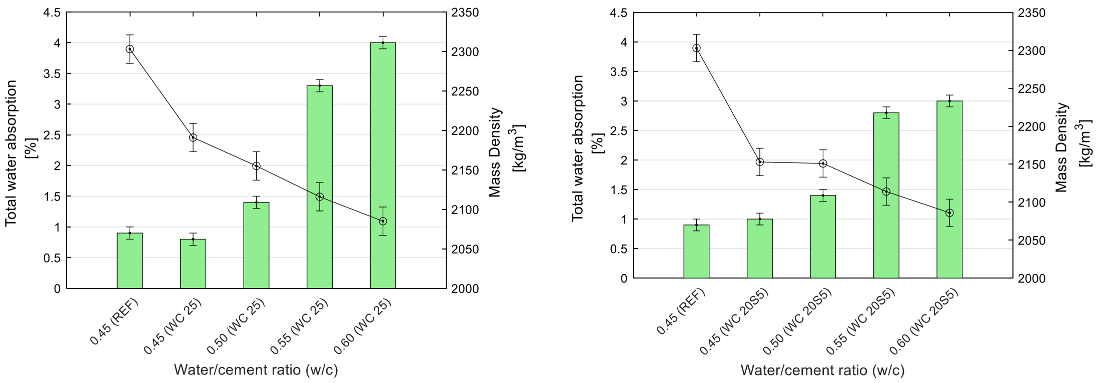


Figure 5.8: Total water absorption (green bars) and mass density (black line), mean values and standard deviation, for the four w/c ratios.

Based on these results, the water/cement ratio chosen to proceed with the study was 0.45 since it leads to higher compressive strength and does not adversely affect the water absorption of the composite.

w/c 0.45 **w/c 0.50** **w/c 0.55** **w/c 0.60**

a)

b)

Figure 5.9: Cross-section of the cubic specimens, with 150 mm edges: a) WC25; b) WC20S5.

Visual inspection

Cross-section photographs of hardened cubic specimens with 150 mm edges are presented in Figure 5.9. The cross-section images suggest a uniform wood distribution. Differences between

WC20S5 and WC25 specimens or between the different w/c ratios are not visually perceptible. Considering the water absorption results, it is possible that as the w/c ratio increases, porosity also increases as microporosity since it is not visible.

Steel bars and strands

The mean and standard deviation of tensile strength obtained are presented in Table 5.4. The stress/strain plots of the tests are displayed in Figure 5.10.

Table 5.4: Steel bars and strands characterisation

ϕ	Steel	Tensile strength [MPa]	Elongation at break	Modulus of elasticity [GPa]
4.5	Y1860S2	1971 ± 1	4,5 ± 1,7	211 ± 3
6	S500	660 ± 1	9,5 ± 0,8	199 ± 6
10	S500	646 ± 1	13,5 ± 0,9	197 ± 1

* Pitch of 9.3 mm

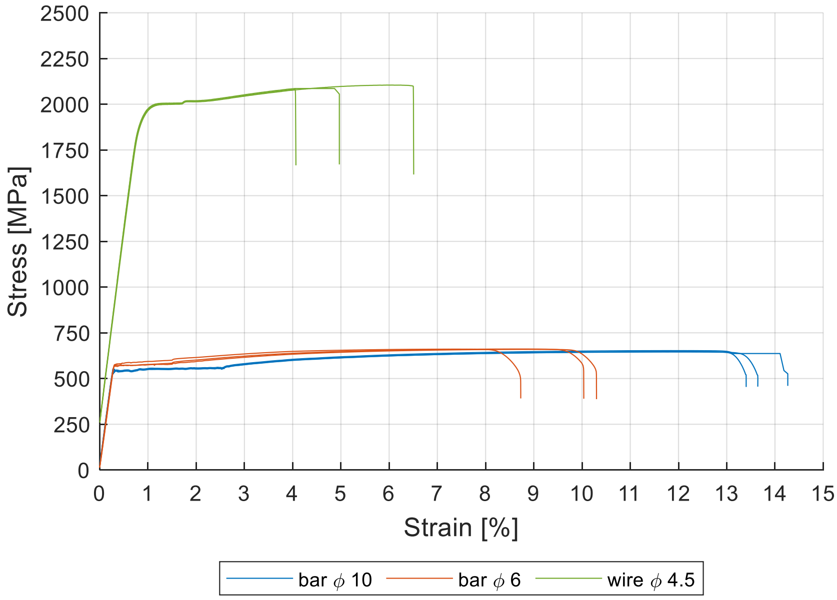


Figure 5.10: Stress/strain plots of the tensile strength test.

5.4.2.Bond resistance

Figures 5.11 and 5.12 show the load-slip plots of bars ϕ6 and ϕ10, respectively. The reference plots are shown for comparison purposes for both wood-concrete composites.

At the initial stage of loading (uncracked concrete) there was no slip, as the initial straight-line segment of the load-slip plots shows; this is mainly due to the friction effect between the steel bar and concrete. This stage persists for relatively higher loads for wood-concrete composites. The incorporation of wood appears to create a better mechanical interaction by increasing the friction component as a resistance mechanism. For the reference specimens, slip between the bar and concrete happens earlier. Upon further loading, the crushed or loose particles at the interface get compressed and densified and the mechanical interlock plays a significant role in sustaining the load.

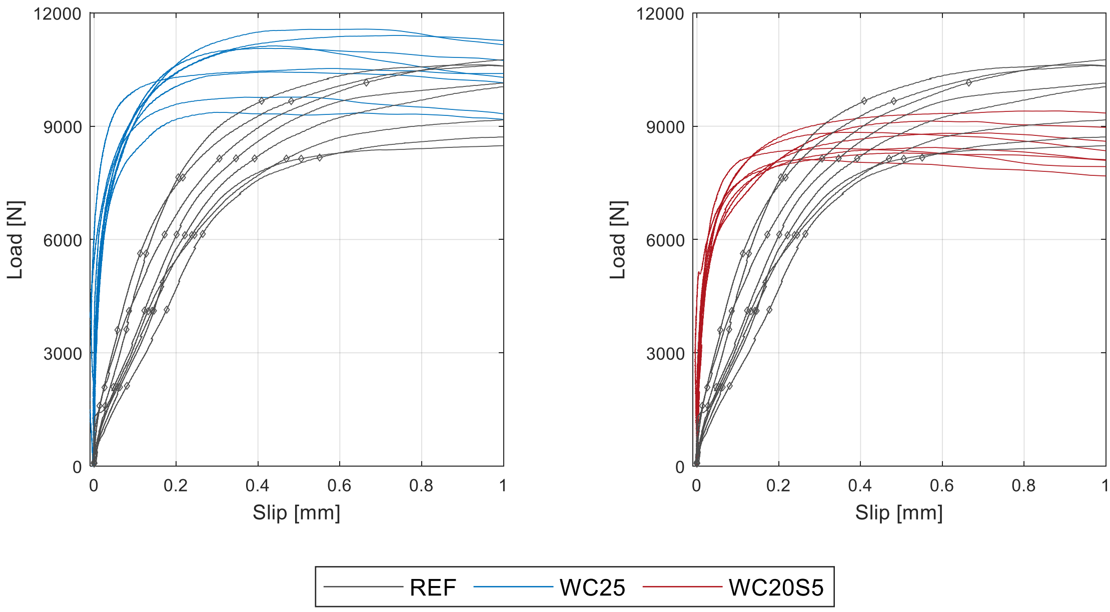


Figure 5.11: Load/slip plots of ϕ6.

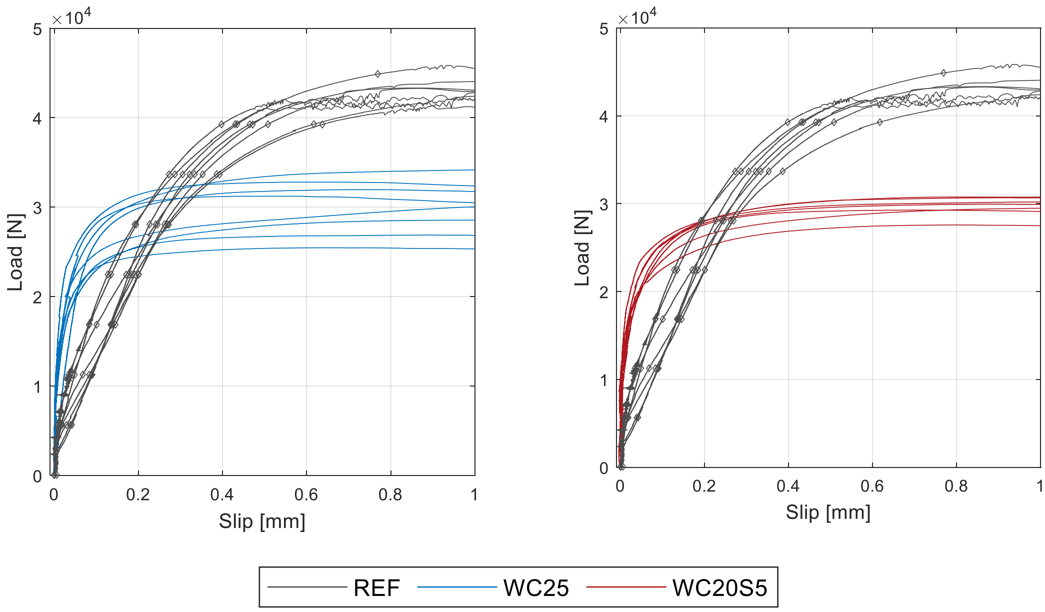


Figure 5.12: Load/slip plots of ϕ10.

The literature shows ([4,31,32]) that the bond strength is closely related to the compressive strength of concrete: higher compressive strength results in better bond strength. The compressive strength results of the pull-out specimens casting show that the reference mix has higher compressive strength (59 ± 4 MPa) than the wood-concrete composites, which both have mean values in the same range (38 ± 2 MPa); this explains the higher bond strengths obtained for the reference specimens. This difference is more apparent for the ϕ10 specimens than for the ϕ6 ones, which could be related to the bond length being too short.

The Building Code Requirements for Structural Concrete (ACI 318-19) [33] provides an equation to calculate the minimum bond length, also known as the development length. The equation and the calculated length are presented in the Appendix. Regarding the bars, the minimum length calculated for a diameter of 6 mm (considering the compressive strengths obtained), was approximately 5 d for wood-concrete and 4d for the reference (28 mm and 24 mm, respectively), which is in agreement with the value used for the tests and recommended by EN 10080:2005 [17] (5 d = 30 mm). For the 10 mm bars, the minimum length required is bigger, 8d and 7d for wood-concrete and reference, respectively, (corresponding to a length of 81 mm and 69 mm). The length used on ϕ10 specimens was 5 d (50 mm), much lower, especially when compared with the minimum length of the wood-concrete specimens. This can explain the difference between the reference and wood-concrete results (Figure 5.13).

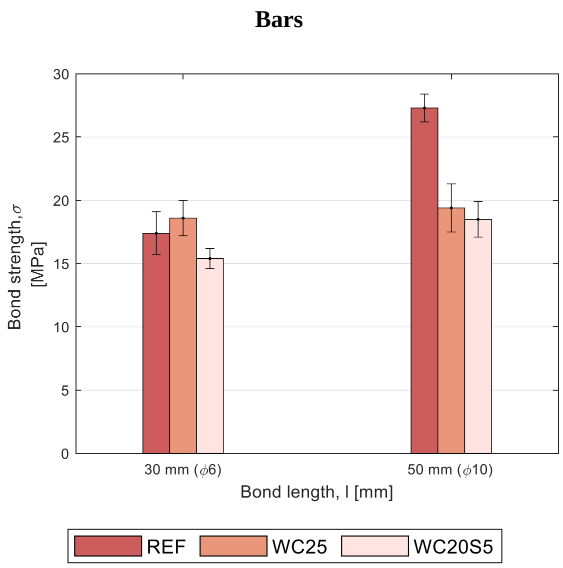


Figure 5.13: Correlation between bond strength and bond length, of bars.

The bond resistance values and mean and standard deviation for the reinforcement bar samples are presented in Table 5.5.

Table 5.5: Maximum load [N] and bond strength [MPa] of bars and mean and standard deviation

ϕ	REF		WC25		WC20S5	
	Load	**Shear stress**	**Load**	**Shear stress**	**Load**	**Shear stress**
ϕ6	9819 ± 905	17.4± 1.7	10504 ± 865	18.6 ± 1.4	8720 ± 464	15.4 ± 0.8
ϕ10	42941 ± 1764	27.3 ± 1.1	30138 ± 2996	19.4 ± 1.9	29129 ± 2243	18.5 ± 1.4

Figures 5.14, 5.15 and 5.16, present the load-slip plots of the two-wire strand specimens, corresponding to the bond lengths of 23, 115, and 400 mm, respectively. The reference mix plots are also presented for comparison purposes.

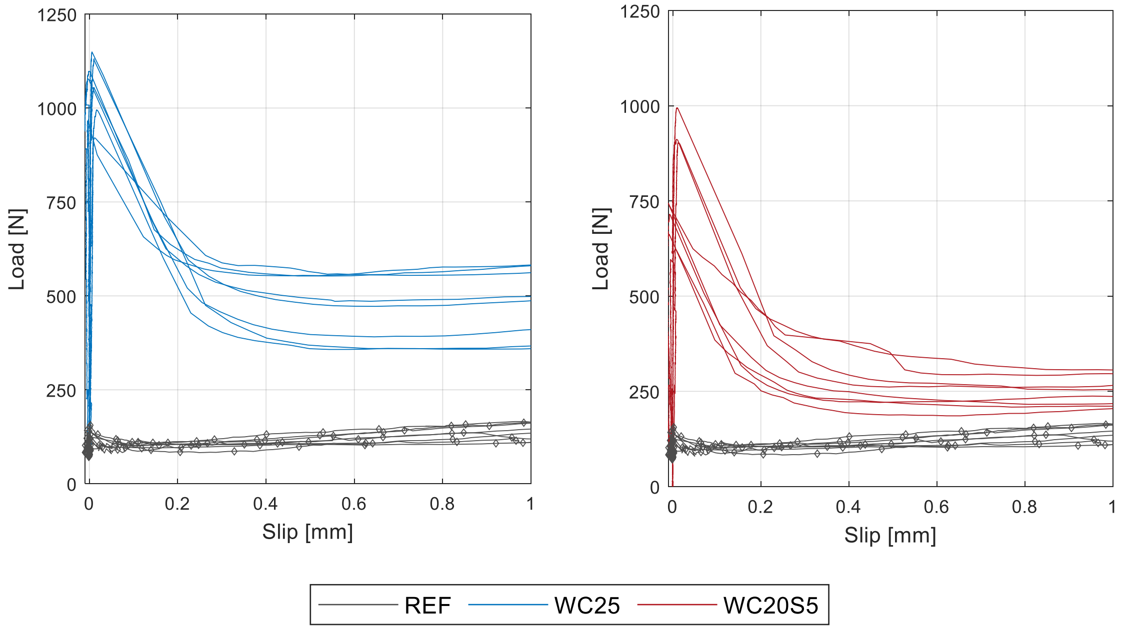


Figure 5.14: Load/slip plots for ϕ4.5(bl of 23 mm).

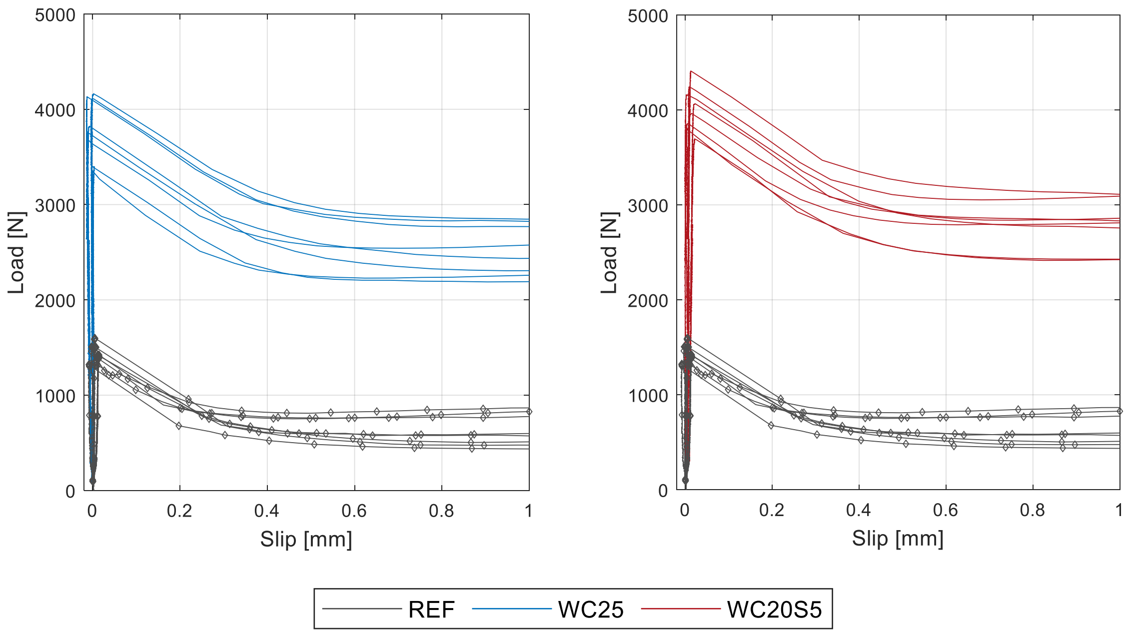


Figure 5.15: Load/slip plots for ϕ4.5 (bl of 115 mm).

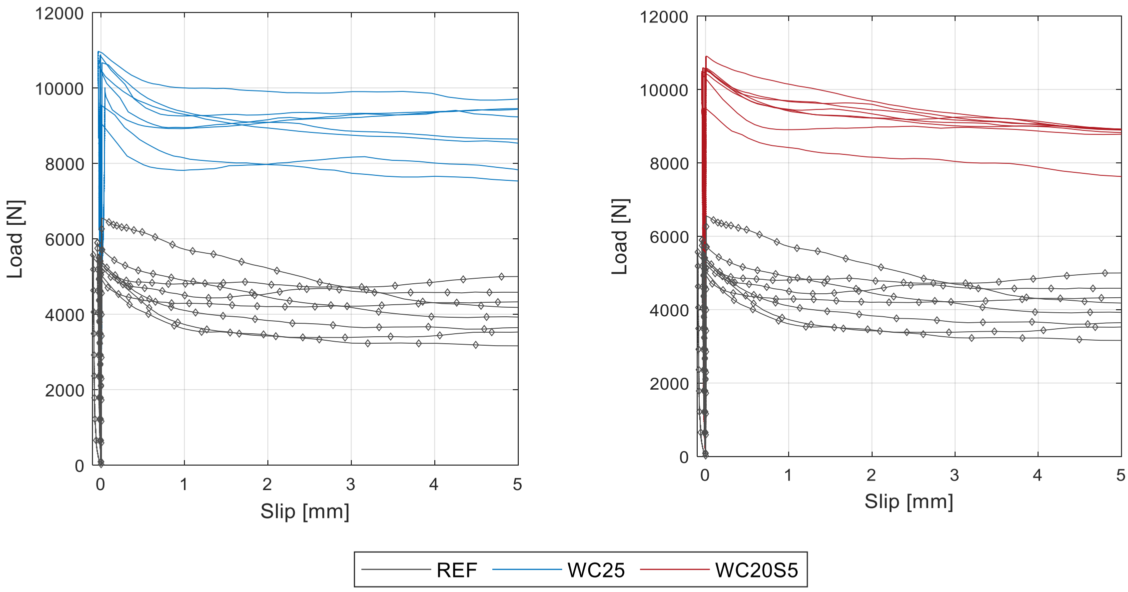


Figure 5.16: Load/slip plots for ϕ4.5 (bl of 400 mm).

For strands, the minimum length determined as per the ACI code would vary between 11 d for the wood-concrete and 10 d for the reference concrete (corresponding to 51 mm and 43 mm, respectively). The recommended EN 10080:2005 [17] length of 5 d (23 mm) is clearly insufficient in this case, aggravated by the fact that it is not a single wire of 4.5 mm but a two-wire strand of 4.5 mm in total. Carvalho et al. [34] confirm that, for diameters up to 10 mm, 5 d is considered small and suggests an anchorage length of 10 d. The bond length indicated in ASTM A1081M-21 [18] (approximately 400 mm) seems to ensure a sufficient bond length for strands of this type, since a bigger length is more representative and includes the repeatability of the pitch of the strand (Figure 5.17).

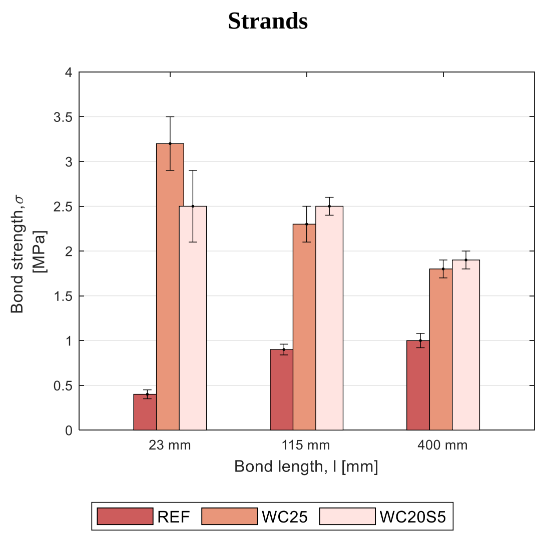


Figure 5.17: Correlation between bond strength and bond length of strands.

The load-slip plots of the strands are different from those obtained for ordinary reinforcement. In this case, the bond mechanisms are mainly adhesion and friction. After reaching the maximum bonding load, the plot softened immediately, especially for small bl values (23 mm and 115 mm), where the strand exhibits a load-slip behaviour more like that of a single wire than a strand. The load/slip plots for a bl of 400 mm (Figure 5.16) exhibit different behaviour; the adopted bl value (3.5 times the pitch) is apparently enough for the wedge effect provided by the strand shape. This behaviour does not reflect an increase in the bond strength.

The bond resistance is significantly higher than for the reference mix, regardless of the wood-concrete composite and the bond length. As for the ordinary reinforcement, at first there was no slip between the steel and the concrete for relatively higher loads in the case of wood-concrete composites. Again, the incorporation of wood appears to create a better mechanical interaction between the steel and concrete by increasing the friction as a resistance mechanism. In the vicinity of the strands, this effect probably increases the stick-slip phenomenon up to the limit of wood shear strength (2.0 MPa - Compressive strength class of C18 according to EN 338:2003 [35]). The bond resistance values and mean and standard deviation for the strands are presented in Table 5.6.

Table 5.6: Maximum load [N] and bond strength [MPa] of strands and mean and standard deviation

ϕ4.5	**REF**		**WC25**		**WC20S5**	
	Load	**Stress**	**Load**	**Stress**	**Load**	**Stress**
bl of 23 mm	131 ± 15	0.4 ± 0.05	1049 ± 81	3.2 ± 0.3	802 ± 132	2.5 ± 0.4
bl of 115 mm	1438 ± 93	0.9 ± 0.06	3801 ± 319	2.3 ± 0.2	4024 ± 240	2.5 ± 0.1
bl of 400 mm	5584 ± 465	1.0 ± 0.08	10329 ± 685	1.8 ± 0.1	10449 ± 414	1.9 ± 0.1

To evaluate the possible creep effect additional tests were performed. The strain was maintained for small loads for the 120-h test period for the reference and the wood-concrete composites (Figure 5.18).

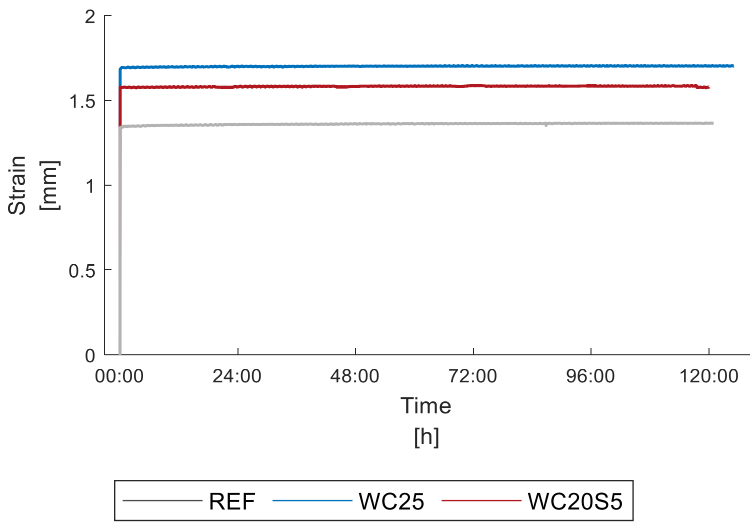


Figure 5.18: Strain recorded during the creep tests.

The possible existence of internal micro defects in the concrete at the wood-cement interface and the reduction of compressive strength (relative to the reference mix) appears not to contribute to enhance the creep phenomenon for the applied load.

5.5. Structural applications

5.5.1. Fabrication of linear structural elements (beams and columns)

Beams and columns were made and tested to assess the feasibility of using these composites for structural applications.

Two beams, 2.40 m long, were produced with ordinary reinforcement (ϕ6 and ϕ10) from each mix (REF, WC25 and WC20S5) and subjected to 3 point-bending at 28 days. These beams were cast in moulds, vibrated, and demoulded after a week.

Three columns, 3.0 m tall and reinforced with prestressing wire strands (ϕ4.5) were also produced with each mix (REF, WC25 and WC20S5). In this case, it was necessary to develop a system to apply the prestress load. This system, illustrated in Figures 5.19 and 5.20, uses a steel beam approximately 13 m in length to support the formwork of the columns, all aligned. The steel beam enables the mooring of the strands at one end and anchors the hydraulic jacks at the other. Each hydraulic jack pulls two strands, allowing the force to be the same on each strand. The force is specified by means of a pressure gauge on the hydraulic jacks. That load was specified based on the tensile strength of the strands previously determined in Section 2.2 - 60% of the $F_{p0.1\%}$ (15.3 kN). The mix was cast in moulds, with the strands stretched. The columns were also vibrated, the strands were cut at 7 days, and the elements demoulded. Two of each set were tested for 3-point bending and one for fatigue under bending conditions at 28 days. Table 5.7 gives the details of the structural elements constructed.

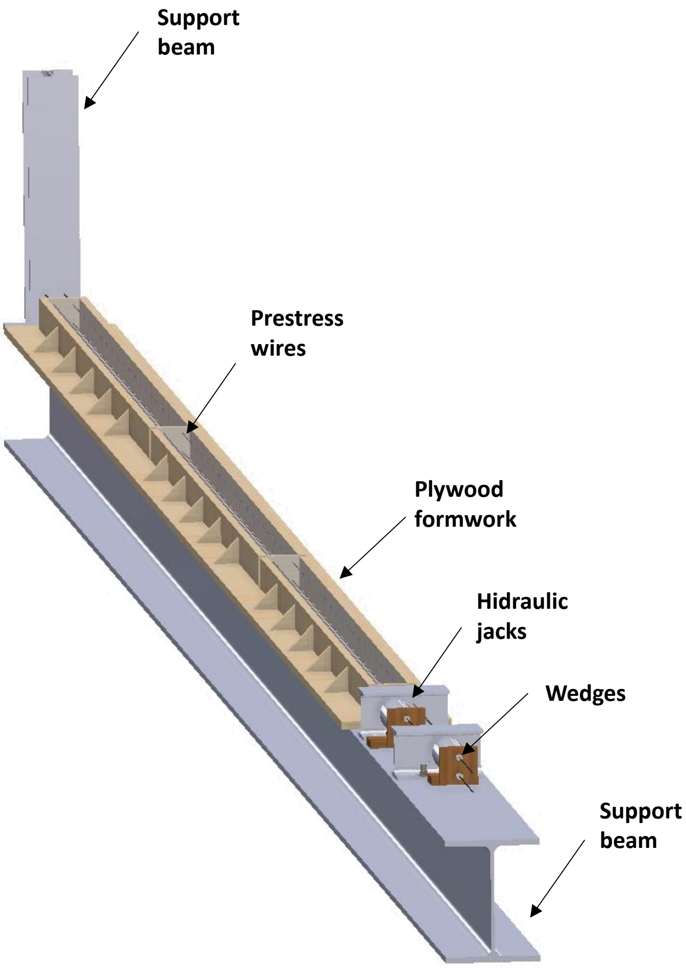
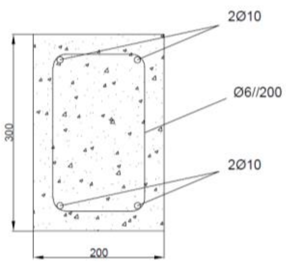
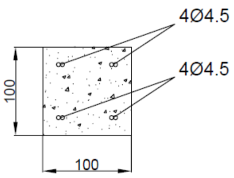


Figure 5.19: Column production set-up.

Table 5.7: Tests performed on the structural elements

Structural element	Tests
Ordinary reinforcement 	Bending
Prestressed strands 	Bending until failure Fatigue under bending conditions Bending until failure after fatigue

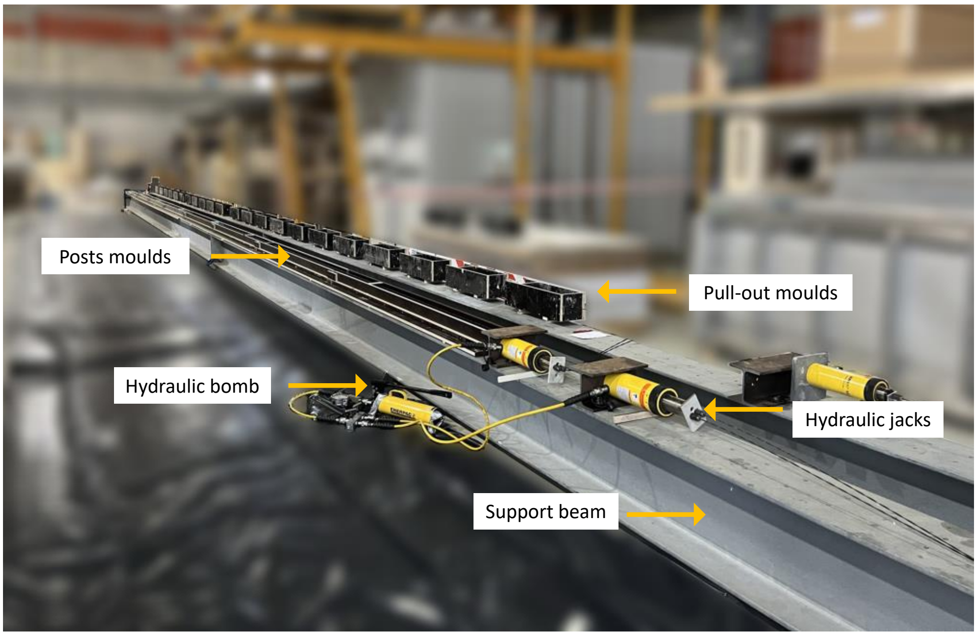


Figure 5.20: Columns and pull-out specimens prestress application.

5.5.2.Tests

Beams

The purpose of the 3-point bending test was to evaluate the force/displacement plot and the moment/curvature relation, observe the cracking phenomenon, and assess the crack pattern.

The beam was simply supported, with a span of 2.0 m between supports. The load was applied at the mid-span by an Instron hydraulic actuator model DYNSM1745 with a 250 kN load cell. The load was controlled by displacement, imposing a rate of 2 mm/s. Five HBM linear variable differential transformers (LVDTs), model K-WA were used. Three mounted to measure vertical displacements at the mid-point and quarter-points of the span (side A of the beam as illustrated in Figure 5.21). To determine the curvature, two horizontal LVDTs were placed on the opposite side of the beam in the central zone (side B, as shown in Figure 5.21).

Columns

The test follows the methodology of Annex B of EN 12839:2012[36], and the configuration was the same for both tests (static and dynamic). The specimen was fixed at one end and left free at the other as a cantilever. The free length of the specimens is 2.0 m. The load was applied perpendicularly to one side of the column in the middle of that span by means of a hydraulic actuator (the same as that used for the beams' bending test) with an HBM load cell of 5 kN model U9C, as illustrated in Figure 5.22.

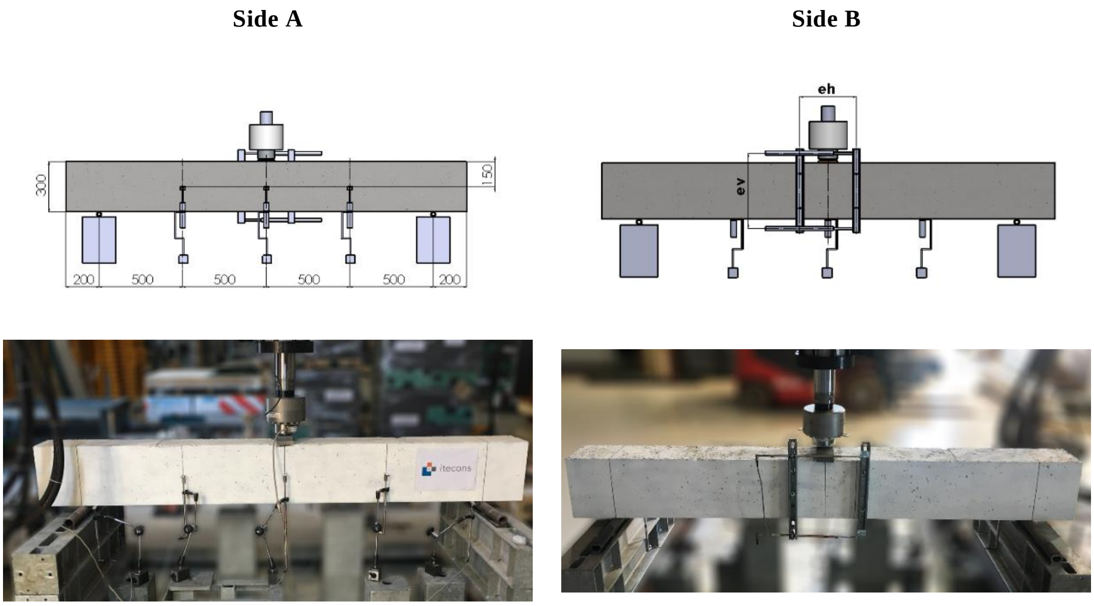


Figure 5.21: Scheme and photograph of the test set-up for bending the beams (dimensions in mm).

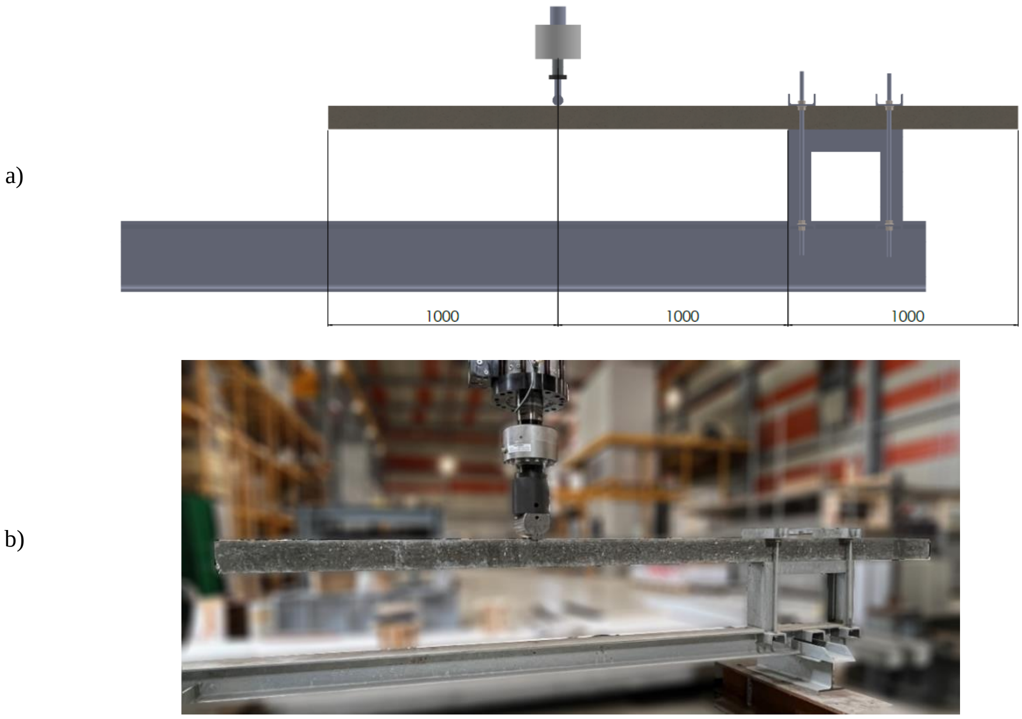


Figure 5.22: Test set-up for the bending tests of the columns (dimensions in mm): a) Scheme; b) Photograph.

In the bending tests until failure, the load was controlled by imposing a rate of 100 N/s. The displacement was also recorded during the test at the load application point. Two specimens of each set (mix) were loaded to failure.

In the bending fatigue tests, the load was applied dynamically with a frequency of 2 Hz, ranging from 750 N to 1000 N until 1 million cycles were reached. The load limits of 750 N and 1000 N correspond to 60% and 80% of the static load associated with the onset of the first crack, respectively.

5.5.3.Results

The experimental results are presented and discussed below, first for the beams and then for the prestressed specimens.

Beams

Figure 5.23 presents the bending test results: load/displacement and the moment/curvature graphics.

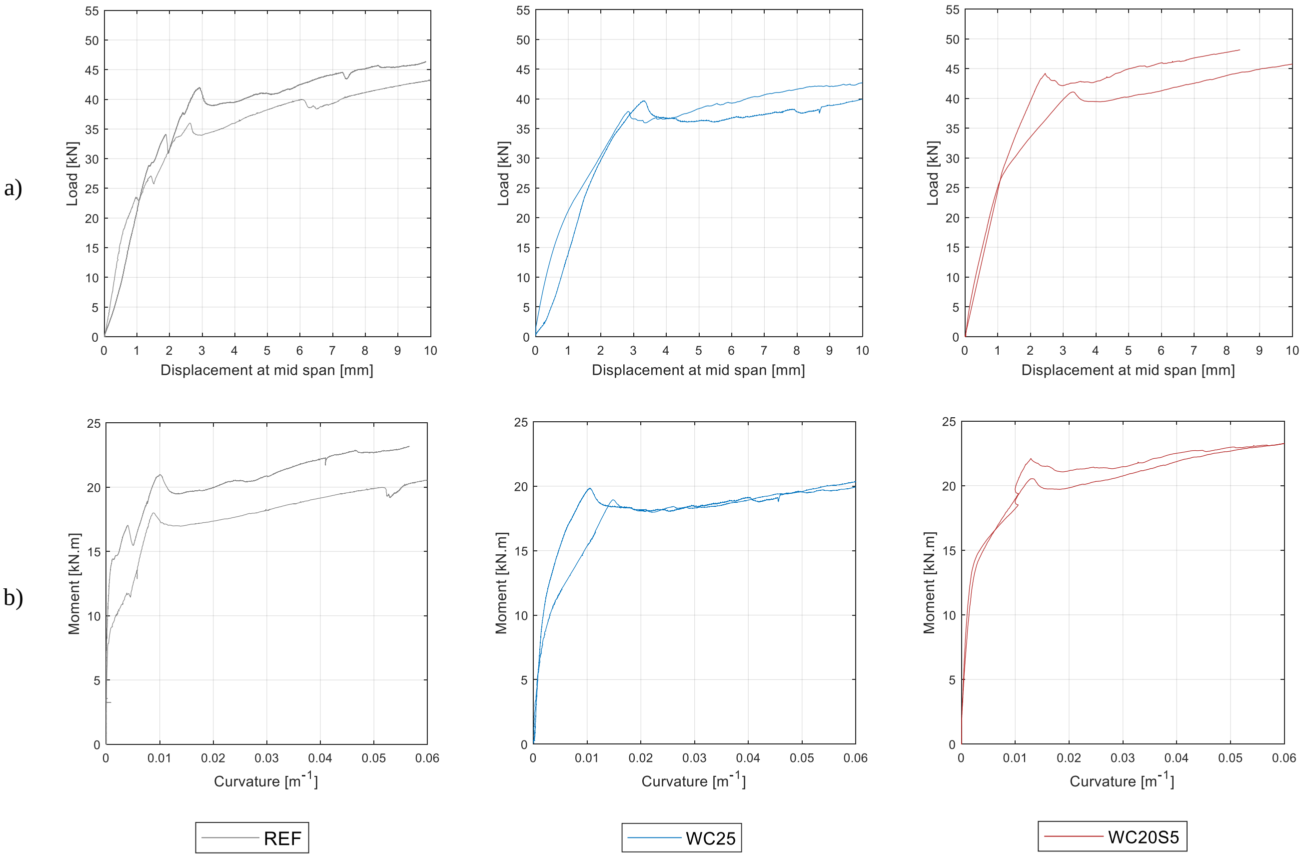


Figure 5.23: Bending results of the beams: a) Load/displacement at mid-span: b) Moment/curvature.

The moment at mid-span corresponds to the test load divided by two, and the registers of the horizontal LVDTs give the curvature, equation (5.2):

$$\left(\frac{\varepsilon_{lvdt\ sup}}{eh} + \frac{\varepsilon_{lvdt\ inf}}{eh}\right) \times \frac{1}{ev} \tag{5.2}$$

where $\varepsilon_{lvdt\ sup}$ and $\varepsilon_{lvdt\ inf}$ are the extensions recorded by the upper and lower horizontal LVDTs, respectively, and eh (0.3 m) and ev (0.4 m) are the distance (horizontal) between the fixed point of the horizontal LVDTs and the measuring point, and the vertical distance between the two LVDTs, respectively (Figure 5.21).

The stiffness, EI, was calculated from the slope of the beginning of moment/curvature figures (before cracking). The evaluation was done between 3 kN and 5 kN, and the correlation coefficient was always above 0.90. These results and the load/moment corresponding to the appearance of the first crack are presented in Table 5.8.

Table 5.8: Bending tests results (mean ± standard deviation) for the beams

Series	**Load at first crack [kN]**	**Moment at first crack [kN.m]**	**EI [kN.m^2]**
REF	26.0 ± 3.9	13 ± 1.95	27835 ± 4652
WC25	38.8 ± 1.3	19.4 ± 0.65	8544 ± 1534
WC20S5	42.6 ± 2.2	21.3 ± 1.1	5679 ± 1845

The bending stiffness of the reference mix is much higher than for the wood-concrete, which was expected since the modulus of elasticity of the reference concrete is much higher. Even between the wood-concrete composites, the modulus of elasticity of wood-concrete with sawdust is lower than that of the wood-concrete only with chips, which is also reflected in the bending stiffness obtained.

Figure 5.24 presents the crack pattern of the beams (one for each mix). In all cases, the first cracks appear in the middle section, where the bending moment is maximum. The reference specimens have always cracked before those incorporating wood (around 26.0 kN) and also shown more cracks than those with wood.

REF

WC25

WC20S5

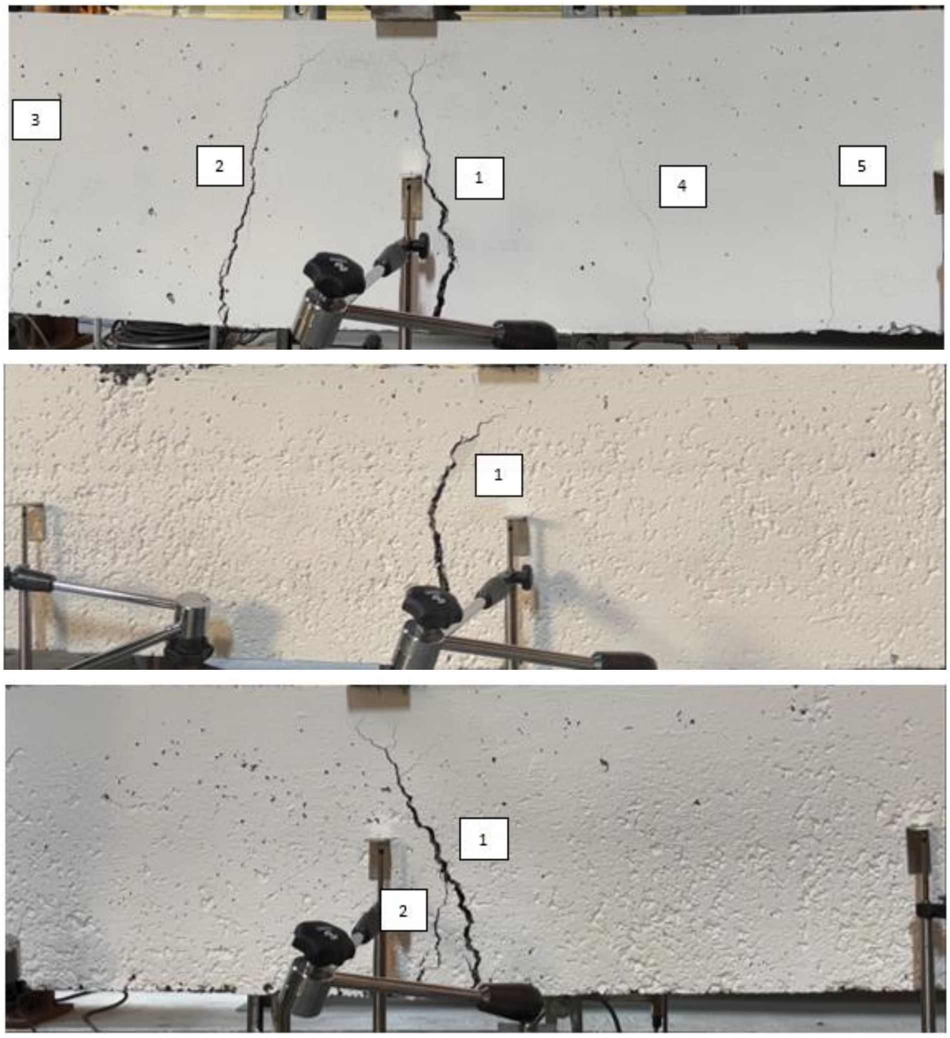


Figure 5.24: Crack development (pattern at the end of the test): REF crack 1 - 23 kN, crack 2 - 23 kN, crack 3 - 27 kN, crack 4 - 26 kN, crack 5 - 34 kN; WC25 crack 1 - 37 kN; WC20S5 crack 1 - 44 kN, crack 2 - 45 kN.

<u>*Columns*</u>

The registered load displacement plots of the columns are shown in Figure 5.25. Table 5.9 presents the failure loads. The reference columns showed higher load failure. However, both reference specimens cracked before failure for a lower load (1223 N and 1421 N). This same behaviour was found in the beams, thus corroborating the potential of the specimens incorporating wood to resist cracking.

During the fatigue in bending, the reference mix and the WC25 specimens cracked in the maximum moment zone at 172 800 and 518 400 cycles, respectively. The WC20S5 specimen did not present visible cracks at the end of the 1 000 000 cycles due to its lower modulus of elasticity. After that, the specimen was taken to failure, and the test result is presented in Figure 5.25

The failure load was 1889 N, 14% less than the mean of the bending tests.

Figure 5.26 shows a photograph of the crack.

Table 5.9: Bending tests results of the columns

Series	Test	Maximum load [N]
REF	Test nº1	2410
	Test nº2	2806
	Mean ± std	2608 ± 280
WC25	Test nº1	2253
	Test nº2	1679
	Mean ± std	1966 ± 406
WC20S5	Test nº1	2260
	Test nº2	2141
	Mean ± std	2200 ± 84

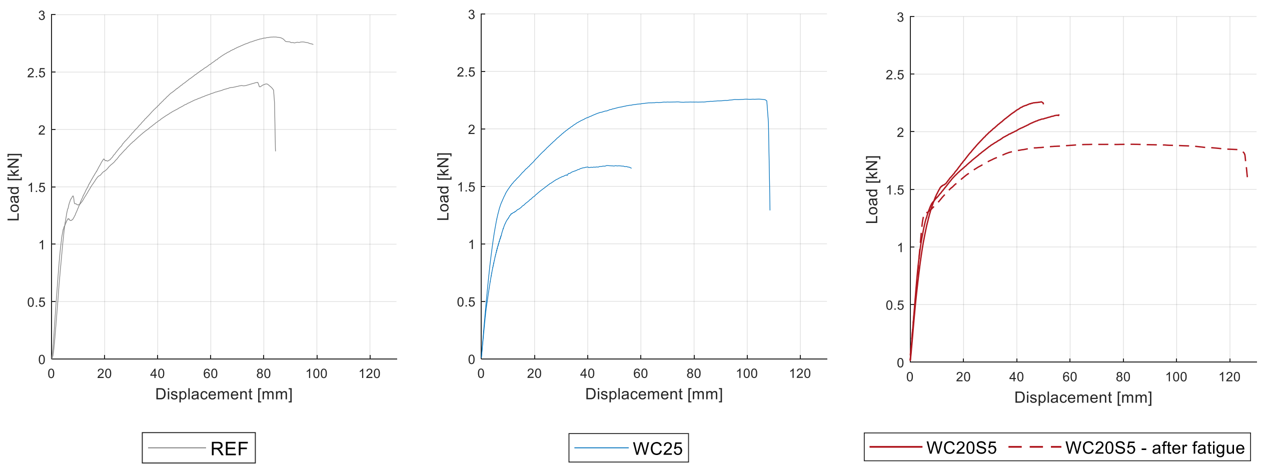


Figure 5.25: Load/displacement registered during the bending tests, original (solid line), after fatigue (dashed).

REF

WC25

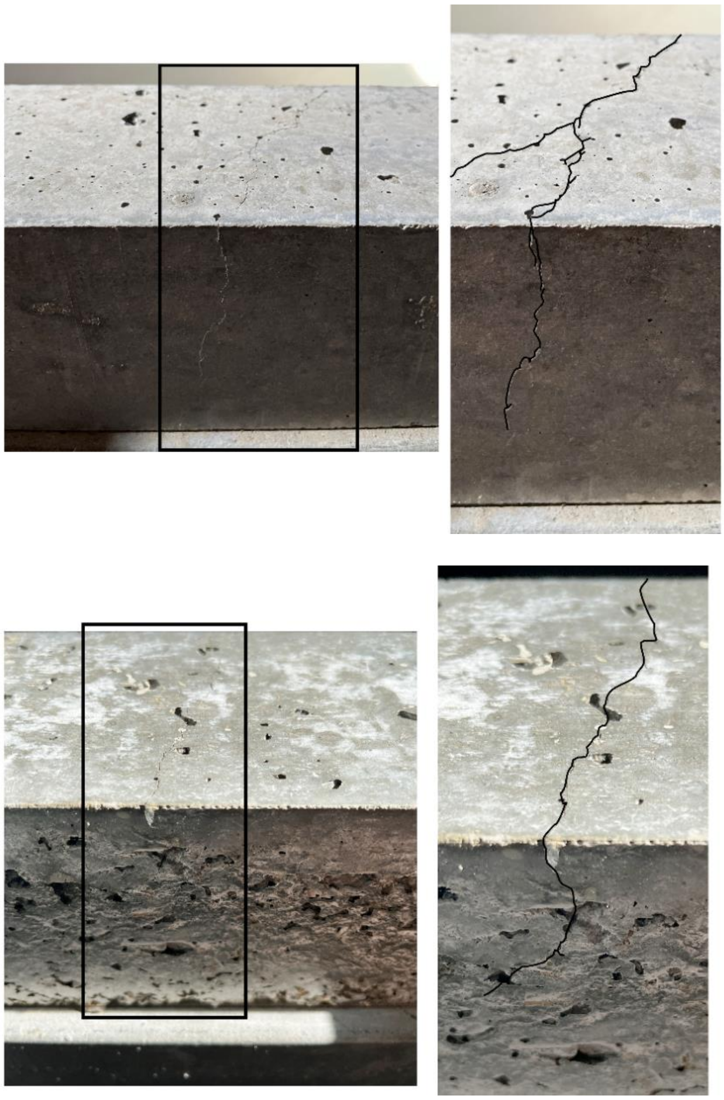


Figure 5.26: Close-up of the cracks after the bending fatigue test.

The prefabrication of structural elements of concrete containing wood waste could be a possible application of these composites. The European standard EN 13369:2018 [37] outlines the general common requirements applicable to many precast concrete products manufactured in a factory environment. Regarding the strength class of concrete, it indicates a minimum strength of C20/25 for reinforced precast concrete products and C30/37 for prestressed precast concrete products, which corresponds to a minimum characteristic cube strength (150 mm edge length) of 25 and 37 MPa, respectively, which the present composites fulfil.

This standard is also common for other normative references of precast concrete products. For instance, the EN 12839:2012 Precast concrete products – Elements for fences [36] was followed for the bending tests performed on the columns. Based on the requirements stated in the standard, the columns constructed and tested fulfil the mechanical requirements to be used as elements for mesh or wire fences (Table 6 of EN 12839:2012 [36]). Other requirements, such as water absorption limits, were also met.

5.6. Conclusions

The present chapter is intended to encourage a more widespread application of wood waste concrete mixes by investigating the steel-concrete bond behaviour. Two composites containing wood chips and wood chips plus sawdust were studied. Some major conclusions can be drawn from the experimental work:

Characterisation of wood concrete composites (four w/c ratios):

- The w/c of 0.45 leads to higher compressive strength and does not negatively affect the water absorption of the composites;
- Density and compressive strength steadily decrease with increasing w/c ratio;
- The modulus of elasticity decreases with increasing w/c ratio;
- The static value of the modulus of elasticity obtained experimentally was substantially lower than the dynamic value;
- The equation given in standard BS 8110-2:1985 [30] was used to estimate Young's modulus using the dynamic value, and the estimated value is in accordance with the measured static modulus;
- The bending stiffness (obtained through bending tests) is in accordance with the experimentally determined values of modulus of elasticity (static or dynamic). The modulus of elasticity determination seems to be a simple way to compare different concrete mixes (especially when incorporated aggregates that are less stiff than mineral ones) without building big structural reinforcement elements, like beams.

Bond resistance:

- For ordinary reinforcement, the incorporation of wood appears to create a better mechanical interaction by increasing the friction component as a resistance mechanism. For the reference specimens, the slip between the bar and concrete happens for lower loads;
- Higher bond strengths were obtained for the reference specimens without wood waste due to their substantially higher compressive strength. This difference is more significant for ϕ10 specimens than for ϕ6 ones;
- Pull-out tests show that ACI 318-19 [33] is suitable for estimating the minimum bond length for these composites. The author suggests that test methodologies do not only consider the reinforcement length to define the bond length, but the compressive strength of the concrete should also be considered (previously determined);

- The bond length indicated in ASTM A1081M-21[18] (approximately 400 mm) seems to ensure a good enough bond length to test strands/concrete bond. The dimension of the specimens could be an inconvenience, however;
- In the case of strands, results show that the incorporation of wood has a positive effect on bond strength, thereby demonstrating the suitability of this kind of composite for structural purposes, particularly prefabricated prestressed elements, beams, and columns;
- Stretching the strands during cast and cure appears to be a feasible solution to overcome the fact that if the strand is not perfectly straight this could influence the results;
- The potential creep effect due to the incorporation of wood was evaluated. Results show that incorporating wood does not enhance the creep for a load corresponding to 50% of the mean results of the pull-out test.

Bending tests of full-scale elements:

- In bending tests, the reference concrete cracked under lower loads than the composites with wood and presented much higher bending stiffness than the wood-concrete composites;
- Columns made from the three mixes were submitted to fatigue in bending. The reference mix and the WC25 specimens cracked before reaching the end of the test (1 000 000 cycles). The WC20S5 specimen did not exhibit visible cracks at the end of the test, which demonstrates a better behaviour under dynamic load conditions.

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Appendix

ACI-318-19 [33] code length development equation (SI-metric stress in MPa)

$$l_d = \frac{f_y}{1.1\lambda\sqrt{f_c^{'}}} \frac{\psi_t \psi_e \psi_s}{\left(\frac{c_b + K_{tr}}{d_b}\right)} d_b \qquad \text{(A1)}$$

Where:

λ - the lightweight factor, (λ=1.0 for normal weight concrete);

ψ_t - factor used to modify development length for casting location in tension, (1.0 for bottom bars);

ψ_e - factor used to modify development length based on reinforcement coating, (1.0 for non-coated bars);

ψ_s - factor used to modify development length based on reinforcement size, (0.8 for bars or wires with a diameter less than 19 mm);

K_{tr} - transverse reinforcement index;

c_b - concrete cover (lesser of: (a) the distance from centre of a bar or wire to nearest concrete surface, and (b) one-half of the centre-to-centre spacing of bars or wires being developed, mm);

d_b - nominal diameter of bar, wire, or prestressing strand, mm;

$f_c^{'}$ - specified compressive strength of concrete, MPa;

f_y - specified yield strength, MPa.

Development length equation parameters.

	$l_d d_b$ (mm)	l_d (mm)	f_y (MPa)	$f_c^{'}$ (MPa)	ψ_e	ψ_s	ψ_t	d_b (mm)	c_b (mm)	K_{tr}
Wood concrete	$5d_b$	28	646	38	1	0.8	1	6.0	97.00	0
	$8d_b$	81	656	38	1	0.8	1	10.0	95.00	0
	$11d_b$	51	2086	38	1	0.8	1	4.5	97.75	0
REF	$4d_b$	24	646	53	1	0.8	1	6.0	97.00	0
	$7d_b$	69	656	53	1	0.8	1	10.0	95.00	0
	$10d_b$	43	2086	53	1	0.8	1	4.5	97.75	0

CHAPTER 6

ENVIRONMENTAL PERFORMANCE

6.1. Introduction

The construction industry is increasingly driven by the urgent need to address environmental challenges, combat pollution from construction activities, and avoid overconsumption of non-renewable resources [1–3]. Achieving environmental sustainability has become paramount for numerous construction projects, including the United Nations Sustainable Development Goals [4]. Environmental sustainability within the construction sector is vital in preserving natural resources, mitigating climate change, minimizing environmental impact, and ensuring healthy indoor environments. The construction industry can actively contribute to a greener and more sustainable future by adopting sustainable practices.

A key component of this environmental transformation is the widespread adoption of a circular economy approach [5]. This approach entails a shift from linear processes, towards an economy that strives to preserve the value of resources, materials, and products for as long as possible. The primary objective is to enhance the value of end-of-life products, materials, and by-products by integrating them into new production processes. There has been a notable increase in efforts to explore the potential utilization of agricultural and forest waste in the creation of construction materials and products [6,7]. Cement is the concrete constituent responsible for the highest amount of energy use and emissions. For that reason, the partial substitution of cement with bio-based wastes, particularly in the form of ashes, has been raising interest in the last years few [8–

10]. Nevertheless, the use of agricultural wastes or by-products as aggregates has also been studied from an environmental point of view [11–16]. Among these waste materials, wood waste [17] shows significant promise. Caldas et al. [18] assessed the environmental impacts of various bio-concrete mixes incorporating bamboo, rice husk, and wood shavings. They found that wood shavings made the most substantial contribution to carbon saving among these bio-based alternatives. They can be sourced as virgin wood waste or as wood waste treated with preservatives to safeguard against biological degradation. Raw wood waste typically originates from sawmills, while chemically treated wood waste is commonly sourced from railways, construction, fencing posts, bridges, and urban furniture.

The possible uses for these wastes have become a research topic [17,19–21]. Farjana et al. [22] studied the sustainable circular economy pathways for waste of engineered wood management (MDF and particleboard). They found that the production phase is more impactful towards the environment than end-of-life management. Material recovery is favoured over energy recovery for most of the impact categories. Compared to landfill and material recovery, the main conditioning with energy recovery lies in the potential toxicity impacts. Hussain and Poon [19] evaluated various alternative strategies for wood waste management focusing on environmental performance. They concluded that the utilization of wood waste could be explored through different scenarios depending on the waste quality. High-quality wood waste could be prioritized for particleboard production, whereas wood waste of lower quality could be effectively utilized for cement-bonded composites or energy generation. Nevertheless, the life cycle assessment (LCA) results clearly show that landfilling wood waste represents the most detrimental practice.

LCA can also be an important tool in decision-making. For instance, Caldas et al. [23] evaluated the environmental impacts of workable wood bio-concrete mixes composed of wood shavings, Portland cement, and supplementary cementitious materials (SCMs). The environmental feasibility of reducing the cement content in the mixes with SCMs replacement was assessed, and their environmental impacts were evaluated concerning mechanical performance (the functional unit was compressive strength). By assessing the most favourable mix concerning the trade-off between environmental impacts and compressive strength, the study also explores potential strategies for attaining carbon neutrality by adjusting the content of wood shavings in concrete. The authors found that negative global warming potential (GWP) values could be achieved for non-structural bio-concrete mixes that blend wood shavings with 50% CEM replacement with SCMs. Additionally, they identified wood chips as the most advantageous option for improving global impact categories.

In this work, a LCA analysis was performed to assess the environmental performance of construction elements, namely the posts studied in the previous chapter. The objective of this study was to compare selected solutions that utilize contaminated wood waste, in addition to two reference cases (posts made of only concrete or only wood). The main focus was to analyse the potential environmental implications associated with the incorporation of wood chips and sawdust in posts made of concrete. A life cycle model was developed based on prototyping data and bibliographic sources. The inventory elements with the greatest contribution to the different impact categories were identified, and their performance was compared.

The chapter is divided into two main sections: the description of LCA analysis (section 6.2) and the presentation and discussion of results (section 6.3). The final remarks are summarized in the conclusions section (6.4).

6.2. Life cycle assessment

Life cycle assessment is a methodology that allows the quantification and assessment of aspects and potential environmental impacts throughout the life cycle of a product, building or service, from the extraction of raw materials to its end of life, through the creation of inflows and outflows of mass and energy [24]. This tool is based on an analysis of systems where the processes are part of a chain of subsystems that exchange inputs and outputs among themselves [25], thus allowing to identify the most critical processes or inventory elements.

6.2.1. Life cycle evaluation methodology

LCA methodology is defined by four distinct phases: Definition of purpose and scope: this step involves identifying the objectives, the system boundaries (what stages of the life cycle will be included), and the functional unit (the unit of measure for the product or service); Life cycle inventory: in this phase, data is collected from various sources on all inputs (e.g., raw materials, energy) and outputs (e.g., emissions, waste) associated with each stage of the product's life cycle; Life cycle impact assessment: the collected inventory data is evaluated to assess its potential environmental impacts by quantifying the effects of the inputs and outputs on different categories; Life cycle interpretation: finally those results are interpreted to understand the significance of the identified environmental impacts [24]. This methodology intends to evaluate the environmental impacts of products and services on the environment and human health, using the international standards for environmental management ISO 14040:2006 [26] and ISO 14044:2006 [24]. The European standard EN 15804:2012+A1:2013 [27] also covers the product category of construction products.

6.2.2.Definition of objective and scope

The main objective of the LCA study was to quantitatively assess the environmental performance of the posts examined in the previous chapter and compare them with two references. The life cycle model of the solutions was developed considering the stages of raw material extraction, processing, transport to the factory, and production, while excluding subsequent phases (a cradle-to-gate - A1-A3 life cycle model).

The declared unit for this study was defined as a single post measuring 2 meters in height, with a diameter ranging from 6 cm. In the development of this study, whenever available, all data referring to the production and prototyping of the posts were considered. To model the material inputs, their composition was considered based on technical sheets and data provided by TOSCCA. Concerning transport, the impacts associated with the combustion of diesel were considered, with the impacts of infrastructure being excluded from the scope of this study, namely vehicle manufacturing and maintenance. For the electricity used in the product stage, the study adopted the energy mix of Portugal in 2018 (*Electricity low voltage, PT production mix*) from the *Ecoinvent v3.8* database.

The study focused on four solutions, including two reference options: the wood reference (REF-W) and the concrete reference (REF-C). Additionally, two solutions were studied using previously examined concrete mixes - one incorporating chips and sawdust (WC25S20) and the other utilizing only chips (WC25).

6.2.3. Life cycle inventory

The inventory data, whenever possible, was based on actual data provided by TOSCCA on existing products on the market and LNEC specifications. Since the new posts incorporating chips and sawdust were produced in a semi-industrial context, some of the data regarding the posts production were estimated based on prototyping processes. Bibliographic sources and the *Ecoinvent v 3.8* databases were also used to complement missing data or to compare and validate existing data. Table 6.1 shows the inventory for the product stage [A1-A3] of the posts.

Table 6.1: Inventory data for the product stage (A1-A3) of a 2 m post

			Unit	REF-1	REF-2	WC20S5	WC25
Product stage *(Inputs)*	**Raw materials**	Pine wood	kg	1.09E+01	-	-	-
		Wood treatment	kg	2.21E-01	-	-	-
		Portland cement	kg	-	2.49E+00	2.49E+00	2.49E+00
		Sand	kg	-	4.29E+00	2.13E+00	2.30E+00
		Gravel	kg	-	7.10E+00	6.41E+00	4.48E-00
		Wood waste chips	kg	-	-	3.55E-01	4.44E-01
		Wood waste sawdust	kg	-	-	7.37E-02	-
		Strand	kg	-	3.94E-01	3.94E-01	3.94E-01
		Superplasticiser	kg		-	3.88E-02	3.88E-02
	Water	Tap water	l	2.37E+00	1.01E+00	1.01E+00	1.01E+00
		Rainwater	l	7.83E+00	-	-	-
	Energy	Electricity	kWh	2.88E-01	1.35E-02	1.35E-02	1.35E-02
		Diesel	kWh	7.70E-01	-	-	-
Product stage *(Outputs)*	**Gas emissions**	Water vapour	kg	-	4.26E-01	4.26E-01	4.26E-01
	Wastes	Concrete	kg	-	1.35E+00	1.35E+00	1.35E+00
		Treated pine wood	kg	3.18E-01	-	-	-

6.2.4.Life cycle impact assessment

In the life cycle impact assessment (LCIA) phase, the CML method - IA version 4.7 (Leiden University), from August 2016, was used with a midpoint approach to evaluate the environmental profile in terms of the impact categories mentioned in EN 15804:2012+A1:2013 [27]: abiotic depletion potential (ADP-elements and ADP-fossil resources), GWP, ozone layer depletion potential (ODP), photochemical oxidation potential (POCP), acidification potential (AP) and eutrophication potential (EP).

The LCIA results of the present study are potential impacts and do not predict final impacts by category (endpoint) but intermediate impacts (midpoint). Table 6.2 presents the potential environmental impacts of the product stage [A1-A3] of the posts under analysis.

Table 6.2: Potential environmental impacts of the posts for the product stage (A1-A3).

Post	ADP - elements [kg Sb eq]	ADP - fossil resources [MJ]	GWP [kg CO_2 eq]	ODP [kg CFC^{-11} eq]	POCP [kg C_2H_4 eq]	AP [kg SO_2 eq]	EP [kg $(PO_4)^{3-}$eq]
REF-W	3.35E-05	9.23 E+00	-1.82 E+01	1.03E-07	5.28 E-04	5.10 E-03	2.04 E-03
REF-C	4.04E-06	1.58 E+01	2.91 E+00	1.10 E-07	5.08 E-04	6.97 E-03	1.04 E-03
WC20S5	4.08E-06	1.66 E+01	2.83 E+00	1.06 E-07	5.16 E-04	6.94 E-03	2.59 E-03
WC25	4.08E-06	1.63 E+01	2.94 E+00	1.04 E-07	5.11 E-04	6.84 E-03	2.56 E-03

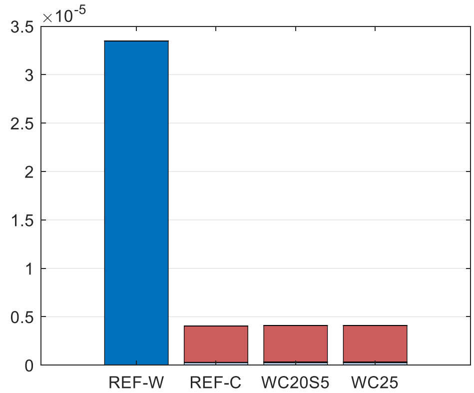
6.3. Results and discussion

Figure 6.1 summarises the contribution of each inventory element to the environmental impact categories for the different types of posts. Through the analysis of Figure 6.1, it becomes evident that wood a significantly contribute to several impact categories in the wooden post (REF-W). Specifically, wood contributes approximately 43% to ADP - fossil resources, 50% to Ozone Layer Depletion Potential, and 77% to POCP. Interestingly, for the GWP category, the wood used in posts production yields a negative impact (benefit) due to carbon storage throughout its life cycle until final disposal. Regarding the Acidification Potential (AP) category, wood treatment and diesel consumption are the most influential inventory elements.

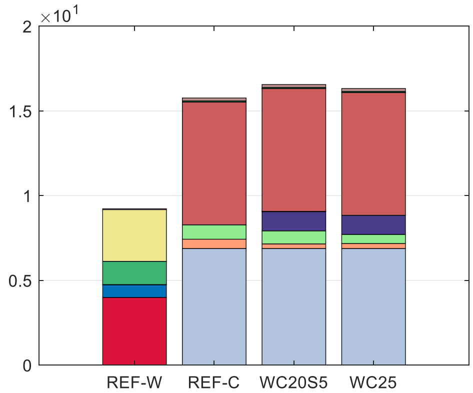
On the other hand, for the concrete posts (REF-C, WC20S5, and WC25), steel wire emerges as the primary contributor to most impact categories, accounting for approximately 93% to 92% of the DRA (elements), 44% to 46% of ADP (fossil resources), around 70% of POCP, and 35% to 52% of EP. Additionally, cement assumes a larger role in the remaining categories. Notably, the WC20S5 post shows that sawdust contributes negatively to the GWP category, owing to carbon storage throughout its life cycle until final disposal.

When considering a comparative evaluation among the analysed posts, it becomes evident that the conventional concrete post (REF-C) post performs poorly across all impact categories, except for the ADP category (elements). Conversely, the REF-W post exhibits the worst performance for the ADP category (elements) due using the chemical product Korasit in wood treatment. The concrete post with 25% chips (WC25) generally demonstrates better performance across most categories when compared to both the conventional concrete post (REF-C) and the concrete post with 5% incorporation of sawdust (WC20S5).

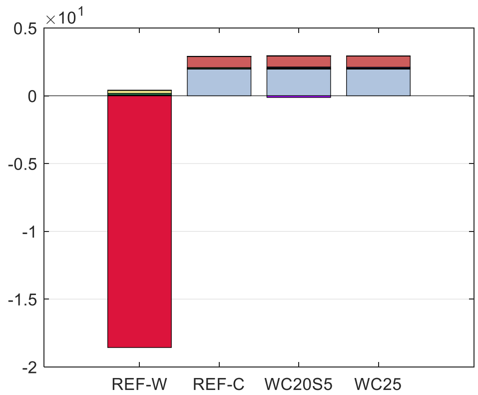
Abiotic Depletion Potential (ADP - elements) [kg Sb eq]



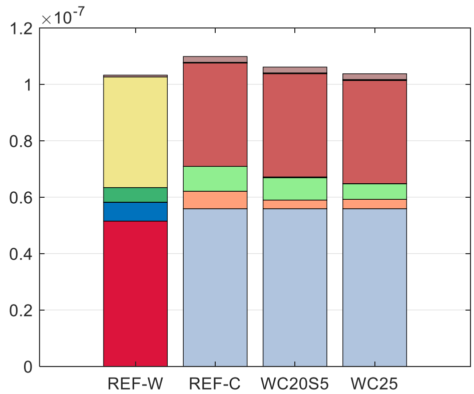
Abiotic Depletion Potential (ADP - fossil resources) [MJ]



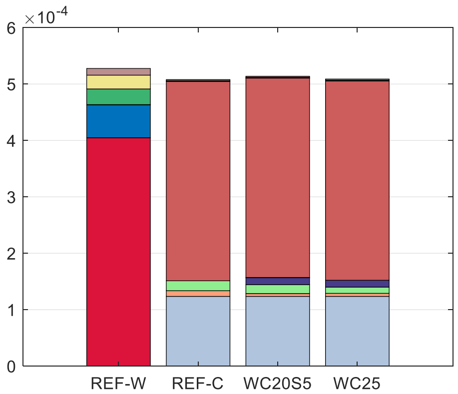
Global Warming Potential (GWP) [kg CO_2 eq]



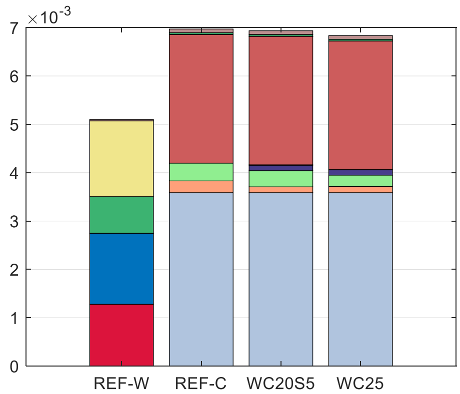
Ozone Layer Depletion Potential (ODP) [kg CFC-11 eq]



Photochemical Oxidation Potential (POCP) [kg C_2H_4 eq]



Acidification Potential (AP) [kg SO_2 eq]



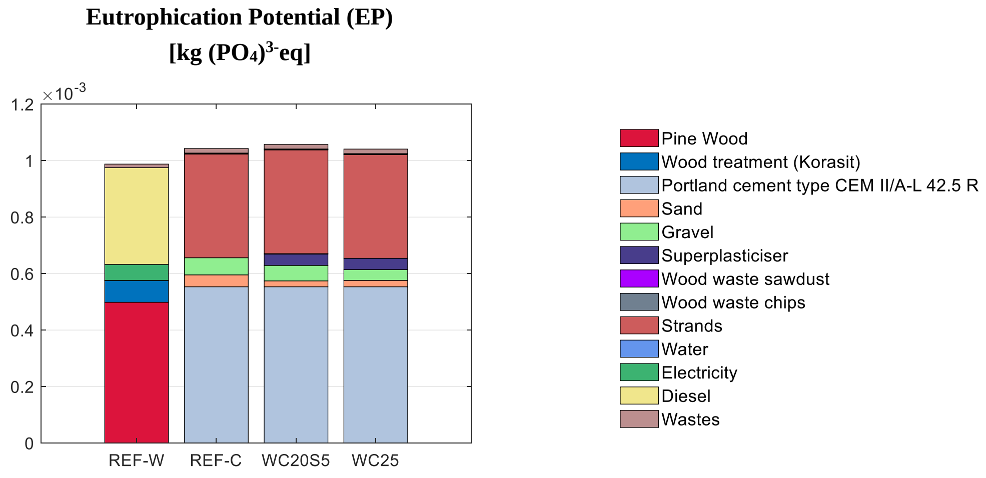


Figure 6.1: Comparative environmental assessment of the posts at production stage (A1-A3).

With the LCA study, it was observed that the REF-C presents the worst performance for all impact categories, except for the DRA category (elements), and that the concrete pole with 25% wood chips WC25 presents a slightly better performance for most categories, when compared to the conventional concrete post.

Fewer mineral resources consumed results in better environmental performance, even though this benefit is partially offset by the negative impact resulting from the necessity of using a superplasticizer.

The LCA analysis does not demonstrate a substantial environmental advantage in utilizing wood waste. Other studies found in the literature [23,28] refer that reducing the impact of these composites is difficult compared to common concrete without reducing cement content. Nevertheless, the LCA results also do not indicate any detrimental effects. The true environmental benefit of WC20S5 and WC25 posts, which lie in their ability to add value to waste materials, was not fully captured by the LCA analysis's boundaries. Incorporating wood waste, particularly those contaminated with chemicals, into new cement-based materials diverts them from their probable end-of-life destination - landfills.

Another important issue is the depletion of bulk resources that is avoided by wood waste aggregate substitution. Habert et al. [29] suggest that the indicators used to assess resource consumption in the impacts assessment of LCA could not be entirely suitable for the concrete industry. The reason lies in the fact that concrete constituents are typically not transported over long distances (because of the price per tonne of aggregates transportation), and the consequence is that the depletion occurs more locally, where the impact of mineral depletion is not so significant at a country level but much more relevant at the regional scale.

By incorporating these wood waste materials into sustainable construction solutions, the environmental burden associated with their disposal is certainly mitigated. This aspect may be taken into account in future LCA studies, highlighting the broader environmental implications and the value derived from diverting waste from landfill sites.

6.4. Conclusions

While the life cycle assessment (LCA) analysis does not demonstrate a substantial environmental advantage in utilizing wood waste, it does not indicate any detrimental effects. Additionally, it should be noted that the true environmental benefit of WC20S5 and WC25 posts, which lies in their ability to add value to waste materials, was not expected to be fully captured within the boundaries of the conducted LCA analysis. Incorporating wood waste, particularly those contaminated with chemicals, into new cement-based materials diverts them from their likely end-of-life destination (landfills). Thus, this practice contributes to reducing mineral aggregates consumption, and the environmental burden associated with waste disposal.

In addition to conducting an LCA study, reflecting on the economic feasibility of integrating waste materials into new solutions is important. The economic criterion is sometimes undervalued in academic contexts but is important in practical, real-world scenarios. The concept of a circular economy requires considering not only the environmental perspective but also the economic aspect. If a waste material is not economically viable, its production will unlikely be implemented in practice.

Since the posts being studied are not currently being produced, a Portuguese company that produces pre-fabricated elements with wood cement composites and other bio-based aggregates was consulted. According to this company, the cost of these wood chip aggregates would be similar to the natural mineral aggregates, although two concerns should be carefully considered. First, wood aggregates must be wet before integrating them into the mix. This company indicated that an irrigation system would be required for that. However, this additional equipment is not expected to add a relevant additional production cost.

The second concern is related to the curing time and consequent line of production occupation. These composites could take longer time to achieve the resistance needed to cut the wires and release the production line. According to the standard EN 13369:2018 [30], concrete shall have a minimum strength of 25 MPa (cubic specimens) at the transfer of the prestressing force. In the case of ordinary reinforcement, this does not comprise a concern. This additional time for the production occupation line leads to a lower production rate. Although, there are measures to diminish cure time, like adding setting accelerators or heating the production line, both options are associated with additional costs that should be evaluated. A life cycle cost should be interesting to evaluate how these additional details could influence the product's final cost. Nevertheless, this exercise could be difficult to perform and imprecise since the posts have not yet been fabricated in an industrial facility.

Concerning service life, concrete and wood posts for agriculture can be significantly different. The service life of wood posts chemically treated can reach 15 to 20 years, while those made of concrete are expected to keep their performance up to 50 years. However, the durability depends on several factors, such as wood specie and preservative treatment, in the case of the wood, cement content and type, water/cement ratio and rebar covering, in the case of concrete. Based on durability tests in Chapter 4, similar service life is expected for the new composites and the concrete reference. Indeed, the results of the artificial aging process revealed that wet-dry and freeze-thaw aging cycles hadn't a greater impact on compressive strength. Compressive strength remained above 30 MPa even after all the accelerated aging tests. Also, the water absorption of the hardened material was low, suggesting that the presence of wood content in the composites had minimal influence on this property, indicating that the material's resistance to water penetration remained high.

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CHAPTER 7

CONCLUSIONS AND FUTURE WORKS

7.1. Overview and final statements

Extensive research has been conducted in recent years to explore alternative aggregates in concrete. These alternative aggregates include recycled concrete aggregates, wastes, and by-products derived from natural and manufactured sources. Among these options, wood waste is a promising alternative aggregate that can partially or entirely replace traditional aggregates in concrete mixes for structural and non-structural use. However, despite its potential, the widespread adoption of wood waste as an aggregate in concrete is still limited. Wood waste is generated from various sources, and finding alternative uses to reduce pollution is essential. In Europe, there is a growing emphasis on recycling and the circular economy, making wood waste a valuable source of secondary raw materials. However, one significant challenge lies in the lower recycling rate of treated wood.

This work began with the literature review presented in Chapter 2. This review thoroughly analysed concrete and cement composites that integrate various waste materials. These include recycled concrete waste, end-of-life manufactured materials (tyre rubber, plastic, and glass), and forest/agricultural waste (hemp, rice husk and wood). The aim was to gain comprehensive insights into utilizing these waste materials in concrete and cement composites. By examining existing studies, the review explored the impact of incorporating these waste materials on concrete's mechanical performance and physical properties. It also delved into the advantages and disadvantages associated with their use. Furthermore, examples of construction projects and products that have successfully integrated these alternative aggregates are provided, demonstrating their real-world applications, and encouraging their use.

Despite significant research investments, the current adoption of concrete or cement-based materials with waste integration remains relatively small. The review emphasized the importance of policies that promote environmental-friendly choices and enforce conservation regulations in driving the widespread adoption of these sustainable practices in the construction industry. The carbon footprint can be reduced by reusing waste materials, contributing to increased circularity, which is urgently needed. Therefore, to enhance sustainability and minimize environmental impact, political and economic incentives should be utilized to encourage the adoption of these eco-friendly materials in the construction sector.

In this context, this research focused on one of the reviewed wastes: wood - raw and treated end-of-life. In Chapter 3, wood waste from four different sources underwent thorough characterization to evaluate the presence of leaching substances and determine physical properties relevant to cement composite production. Initially, cement pastes were prepared with wood extractives, followed by wood particle-containing pastes, to assess the compatibility with Portland cement binder. The results indicated that the concentration of leaching substances varied significantly depending on the wood waste source, sometimes exceeding acceptance limits for inert or non-hazardous waste landfills. No significant chemicals were detected in the eluate of untreated wood, while eluates of ACQ (alkaline copper quaternary) and CCA (chromated copper arsenate)-treated wood revealed notable amounts of heavy metals. The eluate of creosote-treated wood contained relevant organic compounds. However, wood particles from ACQ and CCA sources posed low environmental risk due to the likely fixation of heavy metals in cement composites. In contrast, wood particles from creosote-treated posed a higher threat as the organic compounds were not expected to bind with cement matrices efficiently and, for that reason, were excluded from the upcoming research.

Following the characterization of wood waste and assessment of compatibility, an extensive experimental study to investigate the feasibility of incorporating wood chips and sawdust into concrete mixes was carried out and is presented in Chapter 4. Twelve mixes were formulated, incorporating different percentages of wood particles, and were subjected to comprehensive mechanical performance characterization (e.g. compressive strength, modulus of elasticity, and flexural strength). All mixes demonstrated a compressive strength at 28 days exceeding 30 MPa, indicating their suitability for structural applications. Based on the results, two mixes, besides a reference without wood, with optimized features were selected for all further work. The selected mixes were subjected to more experimental tests, including microstructural analysis and evaluation of relevant durability and hygrothermal properties. They also underwent a durability assessment, which revealed that their compressive strength remained above the predefined criteria of 25 MPa even after undergoing relevant artificial aging processes. The recorded hygrothermal properties also showed promising results when compared to the reference. Additional uses for wood wastes were explored with a focus on acoustic applications. Two variations of cement mixes, devoid of mineral aggregates, and two loose-laid materials were developed and tested as acoustical insulation layers for slabs, varying in thickness. The assessment of impact noise reduction caused by floor claddings revealed that the loose-laid material exhibited the highest level of insulation.

In Chapter 5, further experimental work was conducted on the selected mixes by varying the water-cement ratio to assess its impact. It was observed that a water-cement ratio of 0.45 resulted in higher compressive strength without adversely affecting the water absorption characteristics of the composites. The density, compressive strength, and modulus of elasticity were also evaluated for different w/c ratios. The core focus of Chapter 5 revolved around investigating the steel-concrete bond through pull-out tests. The tests were conducted on steel bars (ϕ6 and ϕ10) and two-wire strands (ϕ4.5) by adopting different bond lengths, 5 d (based on EN 10080:2005), the stranding pitch, and 400 mm (based on ASTM A1081M-21). The results revealed that incorporating wood in the composites improved mechanical interaction by enhancing the friction component as a resistance mechanism. In the case of the strands, regardless of the wood-concrete composites and bond length, the bond resistance significantly increased. Additionally, tests were carried out to evaluate potential creep effects. Specimens were subjected to a constant tensile load equivalent to 50% of the mean pull-out test results for 120 hours. The findings indicated that incorporating wood did not contribute to increasing creep under this load level.

Full-scale structural elements were constructed to assess the feasibility of using these composites in structural applications (beams and posts). Bending and bending plus fatigue tests were conducted to examine the behaviour under static and dynamic loads. It was concluded that the reference concrete without wood incorporation exhibited cracking at lower loads compared to the wood-concrete composites and demonstrated significantly higher bending stiffness than the wood-concrete composites. The wood-concrete composites incorporating sawdust withstood fatigue bending tests successfully without cracking, indicating their durability and resistance to cyclic loading.

The posts developed to assess the feasibility of using the developed composites in structural applications were studied regarding environmental performance. The final chapter involved a life cycle assessment study, incorporating data from prototypes and relevant bibliographic sources. The primary objective of the life cycle assessment (LCA) study was to quantitatively evaluate the environmental performance of the wood-concrete composite posts investigated in the previous chapter and compare them with two reference scenarios, a wood and a concrete post. The life cycle model for the assessment focused on the stages of raw material extraction, processing, transport to the factory, and production, following a cradle-to-gate model. The LCA results indicated that wood-incorporated concrete is in the same range as the concrete reference, showing that the environmental performance of products made by this composite type is almost unaffected. Moreover, it is important to note that the LCA methodology does not account for the fact that the wood waste used in these composites would likely be otherwise destined for landfill disposal if not for recycling. Considering the contaminated nature of the wood waste and the lack of viable recycling options, using wood waste in concrete composites offers significant environmental benefits by diverting the waste from landfills. The LCA results emphasize the importance of considering the overall context and potential alternatives when evaluating the sustainability of such innovative recycling options.

This doctoral thesis focused on developing construction elements utilizing wood waste cement composites. The thesis was structured around two main categories of specific objectives: the composite's development and characterisation, and the construction elements' design and study. Overall, the research addressed critical aspects related to wood waste cement composites. By focusing on the development and characterization of the composite and the design and study of construction elements, the study intends to contribute to the advancement of sustainable construction practices and promote the utilization of wood waste as a valuable resource in the industry.

7.2. Future works

This research could be considered an ongoing work since several aspects deserve further research for more in-depth knowledge. Therefore, the following future studies are suggested:

- Explore the feasibility of utilizing end-of-life wood from engineered wood products such as OSB (oriented strand board), MDF (medium density fiberboard), CLT (cross-laminated timber), LVL (laminated veneer lumber), and other wood materials that are challenging to recycle because of the presence of adhesives. Investigate the potential integration of these waste materials into cement composites by studying the influence of the remaining adhesives on wood waste-cement adhesion;

- Investigate the mechanical behaviour of the developed mixes by substituting different percentages of cement with wood waste ash, as research indicates that wood waste ash shows promising characteristics as a pozzolanic partial replacement material for cement. Furthermore, it is worthwhile to explore the use of other alternative greener cementitious binders to mitigate the environmental impact typically associated with cement production;
- Assess the energy absorption capacity of the developed composites. Investigate the impact strength characteristics of wood concrete composites to understand their behaviour and evaluate their performance for various potential applications;
- Investigate the long-term creep behaviour of these composites over extended durations;
- Explore the use of fibre-reinforced polymer (FRP) rebars with these types of composites; since, for structural applications, a comprehensive understanding of the influence of wood-concrete bonding on rebar-concrete adhesion is essential;
- Carry out numerical simulations to replicate and predict the behaviour of these composites, specifically concerning the steel-concrete interaction. This approach is essential as conducting experimental studies in this field can be costly and logistically challenging to execute;
- Conduct pull-out tests after fatigue tests, specifically after subjecting the specimens to cyclic loading within the elastic region. This sequential approach allows for the dynamic assessment of the pull-out behaviour;
- Investigate the possibility of integrating the developed composites into timber-concrete composites (TCC), which combine timber joists and a concrete slab to act compositely. Wood-cement compounds have significant potential for creating multifunctional structural elements that serve load-bearing purposes and provide thermal and acoustic insulation and thermal mass. The use of wood-cement composites in TCC can positively impact the eco-balance of buildings;
- Conduct detailed life cycle assessments (cradle to grave analysis) of concrete incorporating wood waste elements to evaluate their environmental impact throughout their entire life cycle comprehensively, including a life cycle costing.