Petri Sormunen

ECODESIGN OF CONSTRUCTION AND DEMOLITION WASTE-DERIVED THERMOPLASTIC COMPOSITES

ACTA UNIVERSITATIS LAPPEENRANTAENSIS 942

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Abstract

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The use of recycled materials in composites has been studied since the 1990s. Research has traditionally focused on technical properties, as well as the recyclability of materials. How these composites should be used or selected for new applications is usually left open. This information gap, together with the challenges associated with the reuse of recycled materials, make their selection difficult for the designer.

This dissertation focuses on the factors influencing the material selection process of composite material made from construction and demolition waste (CDW). The technical properties, cost-effectiveness, carbon footprint and their compatibility with ecodesign principles were investigated. It combines aspects of design, materials science, production economics, and waste management to form an overall picture of these materials from the perspective of the designer and, in part, the processor.

The processing of construction waste plastic, wood, mineral wool, and gypsum into composites is possible. At the product component level, the main supporting ecodesign criteria for CDW composites is the use of recycled material and avoided global warming impact if virgin plastics are replaced. Ecodesign criteria, such as the use of lower energy content materials, renewable materials, and recyclable materials work against composites. The challenges of using CDW are related to the safety, relatively low reinforcement properties, and quality variance of end-of-life materials caused by their life cycle and local conditions of the built environment. The designer should compare the processing cost, environmental issues, production and the properties carefully to fully benefit from adaptation of novel material.

Keywords: ecodesign, circular economy, product design, construction waste, composite

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Most importantly I thank my wife Marina and my firstborn son Leo for their love. To my family in Finland and Italy: kiitos and grazie!

Petri Sormunen
November 2020
Lappeenranta, Finland

Contents

List of publications

This dissertation is based on the following papers. The rights have been granted by publishers to include the papers in the dissertation. They are referred to in the text by their numerals.

I. Sormunen, P., and Kärki, T. (2019). Recycled construction and demolition waste as a possible source of materials for composite manufacturing. *Journal of Building Engineering*, 24.

II. Sormunen, P., and Kärki, T. (2019). Compression-Molded Thermoplastic Composites Entirely Made of Recycled Materials. *Sustainability*, 11(3), 631.

III. Sormunen, P., and Kärki, T. (2019). Promoting and Demoting Factors of Ecodesign Methodologies for The Application of Recycled Construction Waste: A Case Study of a Composite Product. *Urban Science*, 3(4).

IV. Sormunen, P., Deviatkin, I., Horttanainen, M., and Kärki, T. (2020). An evaluation of thermoplastic composite fillers derived from construction and demolition waste based on their economic and environmental characteristics. *Journal of Cleaner Production*, published 18th of November 2020.

Author’s contribution

Publication I: Recycled construction and demolition waste as a possible source of materials for composite manufacturing.

The first author, Petri Sormunen, conducted the study and analysis of the results and prepared the first draft of the paper. The second author, Timo Kärki, contributed by supervising the project and commenting on the draft before submission of the paper.

Publication II: Compression-Molded Thermoplastic Composites Entirely Made of Recycled Materials.

The first author, Petri Sormunen, designed the tooling, produced the samples, tested the materials, performed the analysis and investigation part and prepared the paper. The second author, Professor Timo Kärki, supervised the project and contributed to the methodology selection.

Publication III: Promoting and Demoting Factors of Ecodesign Methodologies for The Application of Recycled Construction Waste: A Case Study of a Composite Product.

The first author, Petri Sormunen, generated the idea and methodology of the paper. He conducted the study and analysis of the results and prepared the first draft of the paper. The second author, Timo Kärki, contributed by supervising the project and commenting on the draft before submission of the paper.

Publication IV: An evaluation of thermoplastic composite fillers derived from construction and demolition waste based on their economic and environmental characteristics.

The first author, Petri Sormunen, generated the idea for the research based on a discussion with Professor Timo Kärki. The first author formulated the research aims and prepared the economic analysis of the filler materials and prepared the first draft of the paper. The second author, Dr. Ivan Deviatkin, chose the research method for the environmental characteristics evaluation and conducted the LCA study. Professor Timo Kärki and Professor Mika Horttanainen commented on the draft of the paper before submission.

Nomenclature

In the present work, variables and constants are denoted using *slanted style*, vectors are denoted using **bold regular style**, and abbreviations are denoted using regular style.

Greek alphabet

ρ	rho, density
σ	sigma, in this study used for tensile strength

Abbreviations

CAD	Computer-aided design
CBR	Case-based reasoning
CDW	Construction and demolition waste
CO_2	Carbon dioxide
DfE	Design for environment
DfX	Design for X
EC	European Commission
EQFD	Environmental quality function deployment
EU	European Union
FRC	Fiber reinforced composites
GF	Glass fiber (numbers after the letters designate the fill rate)
GWP	Global warming potential (GWP100 is used throughout this paper)
HDPE	High-density polyethylene
IPCC	Intergovernmental Panel on Climate Change
ISO	International Organization for Standardization
LCA	Life cycle analysis
LEED	Leadership in Energy and Environmental Design
MW	Mineral wool
MWB	Mineral wool, by product (numbers after the letters designate the fill rate)
MWR	Mineral wool, recycled (numbers after the letters designate the fill rate)
NFF	Natural fiber, fine flour (numbers after the letters designate the fill rate)
NFR	Natural fiber, rough flour (numbers after the letters designate the fill rate)
PB	Partition board (gypsum) (numbers after the letters designate the fill rate)
PE	Polyethylene
PP	Polypropylene
QFD	Quality function deployment
REF	Reference material recycled HDPE
ROM	Rule-of-mixture
r-PE	Recycled high-density polyethylene
SC	Stone cut waste (soapstone)
SCI	Specular Component Included
SEM	Scanning electron microscopy

TOPSIS	Technique for Order of Preference by Similarity to Ideal Solution
TRIZ	Russian acronym for the ‘Theory of Inventive Problem Solving‘
UV	Ultraviolet radiation
WPC	Wood plastic composite

Units

E	Young’s modulus (Elastic modulus)	
GPa	Gigapascal	(1000 $N \cdot mm^{-2}$)
kg	Kilogram	
kJ	Kilojoule	
J	Joule	($kg \cdot m^{2} \cdot s^{-2}$)
*L	Lightness of material in CIE-LAB coordinate system	
µm	Micrometer	
m	Meter	(1000 mm)
mm	Millimeter	
MPa	Megapascal	($N \cdot mm^{-2}$)
N	Newton	($kg \cdot m \cdot s^{-2}$)
Pa	Pascal	($N \cdot m^{-2}$)
s	Second	

1 Introduction

Global population growth and urbanization leads to continuous construction and reconstruction, but this does not happen without consequences. Building activities generate a large amount of waste which, in accordance with the principles of the circular economy, should be put back into use (Gálvez-Martos et al., 2018). The circular economy and sustainable construction have the potential to reduce urban carbon emissions, and create new jobs and opportunities to improve the quality of life of urban citizens (Ellen Macarthur Foundation, 2017). The holistic process of designing future zero-waste cities reconceptualizes waste as a valuable flow of material resource (Hannon and Zaman, 2018; Lehmann, 2012). The majority of demolition waste is composed of crushed concrete, masonry and mixed debris (Gálvez-Martos et al., 2018; Rechberger and Brunner, 2016; Silva et al., 2014), but also includes lighter fractions such as wood, plastics, gypsum, and mineral wool. These lighter fractions have previously been recognized and studied as potential fillers to use in thermoplastic composite manufacturing (Liikanen et al., 2019; Sommerhuber et al., 2016; Väntsi and Kärki, 2014a). It is shown that construction and demolition waste (CDW) recycling is sustainable from economic, environmental, and energy perspectives (Blengini, 2009; Coelho and de Brito, 2013; Nußholz et al., 2019). The potential benefits of CDW recycling are influenced by many site specifics, such as the type of material, transport distances, and the economic and political context (Ghisellini et al., 2018). The digital twin of a building can already be used to define what materials are inside the building and how they should be recycled (Akinade et al., 2015; Volk et al., 2014), but this technology has not yet reached its full potential (Honic et al., 2019). Using alternative, recycled, unconventional, and natural materials in new product manufacturing can help to fight resource depletion and improve material use efficiency (Allwood et al., 2011; Krausmann et al., 2009; Kylili and Fokaides, 2017).

The built environment is a key target in the European Commission’s policy for the circular economy. The full life cycle of buildings in Europe are responsible for half of all energy use, 40% of all greenhouse gas emissions, half of all raw material extraction and a third of all water use (Publications Office of the European Union, 2019). The European Union’s ambitious ‘A European Green Deal’ strategy aims for Europe to become the world’s first climate-neutral continent by 2050, will put major investments into better energy performance of buildings, and also calls for the design of buildings to be in line with the circular economy (European Commission, 2019). The use of recycled material is also supported by sustainable building rating systems such as Leadership in Energy and Environmental Design (LEED®), which awards points for recycled material content (Azhar et al., 2011). Sustainable construction takes ecological, economic, and social aspects into consideration. It produces energy- and material-efficient buildings with a long lifespan that are safe, healthy, comfortable, adaptable, easy to maintain, and retain their value. There is no agreement regarding criteria for building products or their materials that would determine their environmentally friendliness; therefore, some organizations are promoting green products based on a narrow range of attributes they specify as being important for this purpose (Kibert, 2016). To improve the end-of-life recycling rates and environmental friendliness of products, a consistent use of ecodesign practices is required, which includes taking into consideration the facilitation of repair, resale, product upgrades, modularity, remanufacturing, and component reuse (Haas et al., 2015).

Recycled material thermoplastic composite is a combined material where the recycled material can work as reinforcement, filler, or the matrix component. The use of recycled materials in composites could be a means to improve the usability of recyclates previously sent to landfill. Some authors have criticized the use of downgrading materials as they have the potential to increase the overall production, which partially reduces the environmental benefits (Zink and Geyer, 2017). Products in the construction sector offer a great opportunity to implement the strategies of eco and circular design, as the expected lifespan of a building is often planned for 50 years or more. The calculated environmental costs and benefits are distributed over the long lifespan, meaning that the design for sustainability should be inbuilt in the building product design. Recycled material thermoplastic composites have been used mainly in the wood plastic composites (WPC) sector, where the use of recycled material has been common for decades. These composites have been advertised as having green or ecological properties due to their recycled and renewable material content. Life-cycle assessment (LCA) studies have verified some of the claimed environmental benefits related to WPC products with recycled materials (Liikanen et al., 2019; Sommerhuber et al., 2017, 2015; Väntsi and Kärki, 2015). The range of WPC filler materials has been expanded by studies to also encompass construction and demolition waste (Keskisaari et al., 2016; Väntsi and Kärki, 2014a). Despite the environmental potential, economic benefits and technical feasibility, the use of recycled material thermoplastic composites has not expanded beyond traditional WPC decking applications. This is partly due to previously limited research on the quality, economic, and environmental impact of their application. The role of the designer who is responsible for potentially selecting the recycled material thermoplastic composites has not been studied before. This dissertation aims to find out how well the established ecodesign methodologies support the choice of recycled material thermoplastic composites in new product design.

The hypothesis is that the study of waste-derived composite material properties, cost, environmental impact, together with established ecodesign methodologies, can be used to identify the promoting and demoting factors in its use. The identification of these factors helps stakeholders to estimate the applicability of the recycled materials in their products.

1.1 Background, motivation, and aim for the study

The possibilities of construction products manufacturing with recycled materials become more interesting with ever-tightening legislation related to waste materials. According to Directive 2008/98/EC, member states are required to take action: '*by 2020, the preparing for re-use, recycling and other material recovery, including backfilling operations using* *waste to substitute other materials, of non-hazardous construction and demolition waste excluding naturally occurring material…shall be increased to a minimum of 70% by weight* (Directive 2008/98/EC, 2018). The change in waste legislation can also increase the gate costs of waste, which has long made it cheaper to landfill than to process into recycled materials. The most common construction and demolition waste materials are extracted soils, concrete, bricks, mortar, ceramics, glass, gypsum, metal, plastic, wood, and insulation materials such as mineral wools. The heavier recycled aggregate that constitutes a major part of CDW is used as land building material and sometimes as filler in concrete. The lighter source-separated fractions such as plastic, wood, mineral wool, and gypsum do not have established processes for material circulation. The mentioned lighter fractions could be used in processes such as extrusion, extrusion press, compression molding, and casting. These processes have traditionally used the same virgin materials that are now filling the landfills as waste or are burned for energy. Although the manufacturing processes and waste streams with developed separation systems exist, the majority of new construction products are still made using virgin materials. From a designer's viewpoint, many questions still arise regarding the design of products made with open-loop recycled materials relating to properties, long-term durability, costs, and environmental aspects. The uncertainty is especially fortified by the complex nature of composite materials compared to more homogenous counterparts.

Research questions and definition of research problems:

1. What types of composite materials have been made from the most common recycled construction waste materials?
2. What are the challenges in the use of thermoplastic composites made of recycled CDW materials and how have they been resolved?
3. Do established eco-design methods support the manufacture of composites made with recycled materials?
4. What are the properties of compression-molded thermoplastic composites made with recycled materials and how can they be used?
5. What is their potential for decreasing the environmental impacts of products and how much do they cost to process?

For the purposes of this study, the following definitions of 2008/98/EC shall apply.

1. *'Waste' means any substance or object that the holder discards or intends or is required to discard.*
2. *'Recovery' means any operation, the principal result of which is waste, serving a useful purpose by replacing other materials that would otherwise have been used to fulfil a particular function, or waste being prepared to fulfil that function*.
3. *'Recycling' means any recovery operation by which waste materials are reprocessed into products, materials, or substances, whether for the original or other purposes…but does not include energy recovery and the reprocessing into materials that are to be used as fuels or for backfilling operations*.

1.2 Scope and limitations of the thesis

The study is focused on what is termed open-loop recycling of a selected group of construction and demolition waste-derived materials into thermoplastic composite products. This means that fewer clean materials are used, and the quality of the materials is not fully known in advance. The closed loop recycling usually happens inside the existing product system, where the materials' source and quality can be easily controlled and it is also much easier to find interested buyers/users for the material. The study did not focus on the use of material selection software tools that could influence the decision process of a designer in practice, especially with less experienced designers.

This study did not include a behavioral study to investigate the attitudes of designers (Collado-Ruiz and Ostad-Ahmad-Ghorabi, 2010; MacDonald and She, 2015), companies (Prendeville et al., 2017; Short et al., 2012; van Hemel and Cramer, 2002), or customers (Tseng and Hung, 2013) towards the general utilization of ecodesign in the industry. The emphasis was to specifically analyze the application potential of construction waste-derived composites. The established ecodesign tools, design for sustainability and traditional product design process function as a framework of thought, through which the advantages and disadvantages of these materials are studied.

Usually the studies about recycled thermoplastic composite materials are processed by extrusion. This study used the compression molding processing method to create samples from which the properties were tested (Article II). The case study products in Article IV were assumed to be compression molded. In the ecodesign case study of Article III, the case study product was an extrudable profile.

2 State of the art

An organization usually decides on the most important environmental aspects to be taken into consideration in the design phase. The main strategic product-related environmental objectives according to ISO/TR 14062:2002 are conservation of resources, recycling, and energy recovery, the prevention of pollution, waste, and other impacts. These goals are essential parts of the life-cycle thinking of products (see Figure 1). The objectives of ecodesign practices are geared toward reducing the environmental impact while maintaining or improving the product's functionality. Therefore, virgin material replacement with recycled materials done in the right way is a particularly good strategy if it is possible. The end-of-life phase of a product is designed so that unnecessary waste is avoided, and the future waste treatment method is thought through beforehand. Although important, the environmental aspects are rarely the only reason to implement ecodesign strategies. Companies that look for tangible user benefits, have systematic life-cycle thinking, expand their market, and look for cost reductions are generally more successful with their eco-designed products (Plouffe et al., 2011).

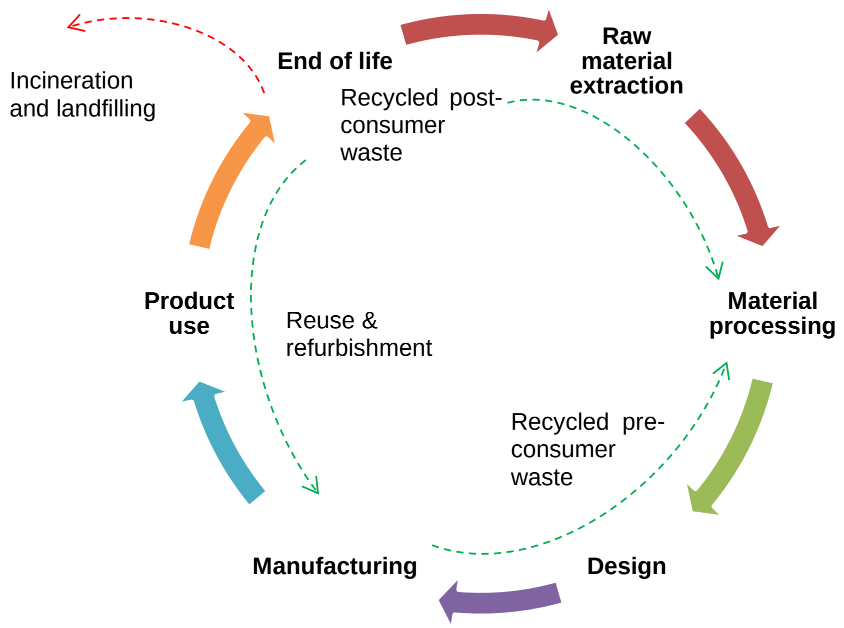

Figure 1. Life cycle thinking.

Many waste types that are generated in construction have recycling processes that require looping back into the same industries that generated the building component. This is the case with steel, glass, and gypsum products. Light materials such as wood, plastic, and mineral wool are an exception to this, as the recycled post-consumer waste is often incinerated or landfilled. Reuse means operation in which the product is not waste and is used again for the same purpose for which they were produced. Reuse is high in the EU waste treatment hierarchy, as can be seen in Figure 2, but it is a very limited strategy for CDW due to the high cost of manual disassembly, quality of deconstructed parts, lack of market, and the difficulty in meeting demand with the right material.

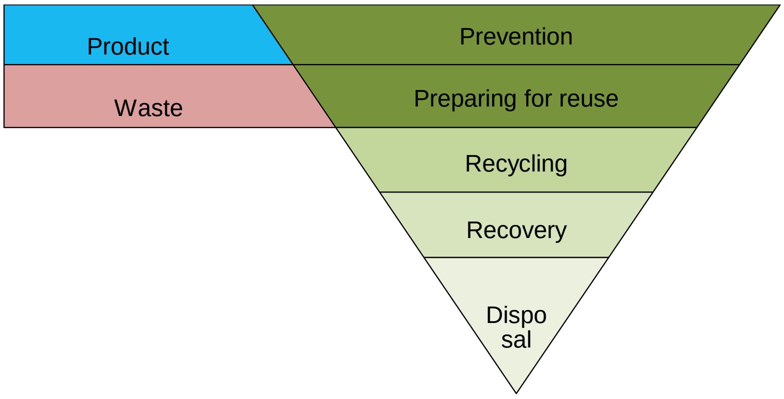

Figure 2. EU waste treatment hierarchy.

Eco-design, design for the environment (DfE) and sustainable design are terms that are understood as a development process that takes into account the complete life cycle and environmental aspects of a product at all stages of a process, striving for products that have the lowest possible environmental impact throughout their life cycles. These terms encompass tools to improve the eco-efficiency, health and safety, remanufacturing, recycling, source reduction, and waste minimization during the design phase and they are linked to life cycle assessment (Glavič and Lukman, 2007). Bovea and Pérez-Belis, (2012) studied the taxonomy of ecodesign methods and found three key factors for an ecodesign methodology, which were the early integration of environmental aspects into product design and development, a life cycle approach, and a multi-criteria approach to design. Van Hemel and Cramer, (2002) identified the ten most successful design for the environment principles, which included recycling and recyclability of materials, durability, use of recycled materials, low energy consumption, remanufacturing and refurbishing, the generation of less production waste, the use of clean production techniques, reduction in weight, clean materials, and efficient packaging. These environmental principles, combined with the functional product requirements, support the importance of the multi-criteria approach in design. A large variety of eco-design tools exist and they range from simple guidelines to complex and time-consuming quantitative tools. Rossi, Germani and Zamagni (2016) divided product-level ecodesign tools into distinct groups: Life Cycle Assessment- (LCA) and Computer-Aided Design- (CAD) integrated tools, diagram tools, checklists and guidelines, design for X approaches, methods for implementing the entire life cycle, innovation process and user-centered design for sustainability, and methods for integrating different existing tools. LCA tools require specific knowledge and considerable time and effort to be used effectively, and even the simplified LCA calculations require interpretation of results by trained professionals. LCA methods are also difficult to use in the design phase, where most of the environmental burden for the product is defined. CAD-integrated ecodesign tools are available in most commercial software solutions, they are easy to use but are highly simplified, and the sources behind the data sets used in the calculations lack transparency. Both LCA- and CAD-integrated tools can have high licensing prices, which limit their adaptation. Diagram tools are used to perform simplified environmental analysis through a mix of qualitative and quantitative data (Rossi et al., 2016). The diagram tools are easy to use but required experience for the user as arbitrary estimations need to be made. The qualitative nature of diagram tools can easily distort results because a larger group of materials cannot be easily compared. The checklist and guidelines are probably the most popular ecodesign tools for quickly evaluating the products' environmental profile. Usually these types of tools also provide suggestions on how to improve the design. Luttropp and Lagerstedt's (2006) Ten Golden Rules is one of the most famous examples of environmental design guidelines: it provides ten simple statements that are easy to use in daily design tasks to improve the sustainability of a product. Design for X (DfX) approaches are applied to improve a specific product characteristic related to the environment. Examples of DfX are Design of Disassembly, Design for Remanufacturing, Design for Recovery, and Design for Energy Efficiency (Rossi et al., 2016). Integrated ecodesign tools are a combination of environmental design aspects and product design methodologies, such as Quality Function Deployment (QFD) (Masui et al., 2003), TRIZ (Altshuller et al., 1997; Kobayashi, 2006), case-based reasoning (CBR) (Yang et al., 2012), or several tools in one, such as QFD, LCA, and TRIZ combined (Sakao, 2007). There is a wide variety of tools and the challenge is to select one that is suitable for the given case and the user. Eco-tool seeker was developed by Rousseaux et al., (2017) in order to help designers find suitable ecodesign methods considering the application and the complexity desired. The design of products has long been digital in nature, and the constant development of CAD tools is likely to make it ever more easier for designers to make quick evaluations of environmental impact based on product features and a very small amount of material and process-related data (Tao et al., 2017). Virtual prototyping can be used to numerically simulate use-phase energy efficiency of products (Landi et al., 2017). Currently the major challenges in the ecodesign field are the management and development of long-term strategic ways to integrate ecodesign activities into corporate strategy and existing new product development processes in the companies (Dekoninck et al., 2016).

Life Cycle Assessment (LCA) is standardized method that is used to quantify emissions and consumed resources, and their environmental impacts over the life cycle of the product. Two used standards for LCA are ISO 14040: 2006, which describes the principles and concepts, and ISO 14044: 2006, which has the requirements and guidelines. Usually the practical application of LCA happens through software tools, which can cause discrepancies in results due to differences in background datasets (Speck et al., 2015). The environmental performance of composite products has also been modeled by LCA and benchmarking them with traditional materials has been performed (Simões et al., 2012). The usefulness of LCA in comparing environmental performance is hard to replace, but it is a retrospective method as the LCA inventory only becomes usable in an embodiment or detailed design phase, thus making the LCA technique unsuitable for the early design decision-making process (Duflou and Dewulf, 2006). Today, many digital tools have also been developed for material design purposes, which help the designer to take the environmental, physical, mechanical, electrical, thermal, optical, and manufacturing process properties into consideration (Ramalhete et al., 2010).

The starting point of a material selection process is to define the function of the component. The functions of the component are then translated into objectives, usually in the form of minimizing or maximizing certain properties that the component is expected to have. Common objectives in plastic products design are minimum cost, minimum weight and maximum use temperature, while constraints could be qualitative such as feel, visual quality, etc. The objectives and functions are then turned into conditions or property limits that the component needs to meet. When the objectives and functions list is composed for thermoplastic materials, the following factors should be evaluated: targeted life span, temperature, environment, physical properties, mechanical properties, chemical properties, electrical properties, weight, dimensional tolerances and price (Biron, 2018a). The selection constraints can be complex when they are coupled with the product geometry. The use of calculated material indices can help to compare many properties in relation to each other and introduce visuality into the material selection process. The classic material selection process is described in Figure 3. The ranking of materials can be based on different types of numerical methods. Multicriteria analysis methods are regularly employed when numerous variables need to be processed simultaneously (Jahan et al., 2010; Wątróbski et al., 2019). The ranking methods can be paired with ecodesign methodologies that can direct the decision-making process by introducing weighting factors, which are usually defined by the targeted market group and the company strategy (Kobayashi, 2006; Mastura et al., 2018; Sakao, 2007). After the subset of materials is listed, the supporting information is applied to narrow down the choices. The supporting information can take place in the form of material data sheets and accessibility to it in the supply chain of the production (Ashby, 2017). The final material selection is done after the local conditions such, as the suitability for the available processing equipment, have been analyzed.

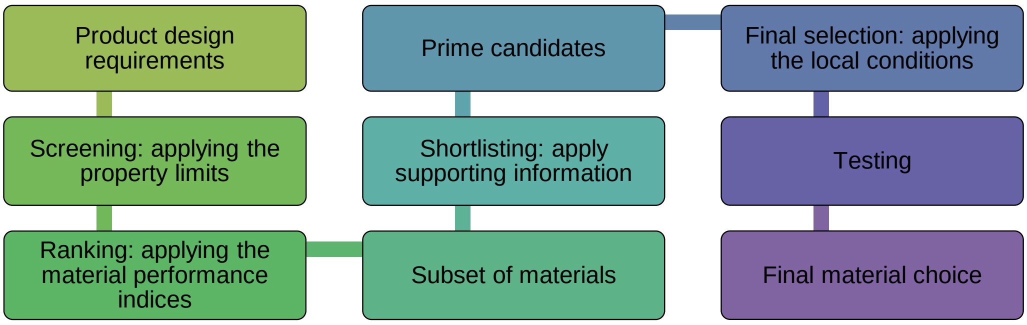

Figure 3. Material selection process in product development (Adapted from Ashby et al., (2004) and Jahan et al., (2010).

Thermoplastics are polymer materials which become moldable at a certain temperature and solidify after cooling. Unlike thermosets with irreversible molecular bonds, it is possible to remelt the thermoplastics and reshape them after solidification. Thermoplastic composites are a combination of a polymer matrix and reinforcement or filler. Typical thermoplastic reinforcements include glass and carbon fibers. Fillers are usually used when the product application makes it possible to drop the price of the plastic by the inclusion of cheaper material—usually a mineral such as talc or calcium carbonate. Mineral fillers improve the tensile modulus of thermoplastic but decrease tensile and impact strength. They increase the thermal conductivity and lower the thermal expansion of plastic. Mold shrinkage is also reduced, which can help the processing of accurate parts. Thermoplastic composites processing methods include injection molding, rotational molding, extrusion, vacuum molding, and compression molding (Yao et al., 2018). Extrusion and compression molding are the most commonly-used processing with recycled raw materials, due the varying properties of recycled material. Compression molding is typically used with a thermoplastic matrix with chopped fiber or randomly oriented or aligned fiber mats (Pickering et al., 2016). Quality compression molding processing requires control of viscosity, pressure, holding time, material, and geometry-related temperature (Balaji Thattaiparthasarathy et al., 2008; Barrera Betanzos et al., 2016; Ho et al., 2012). The prices of materials are continuously fluctuating and obtaining useful information about them for comparison purposes is difficult. Figure 4 presents an approximation for the price of plastics in comparison to some engineering material groups. Usually the cost of plastic materials are compared against weight, but also cost per volume, or cost linked to rigidity depending on the product application (Biron, 2018b).

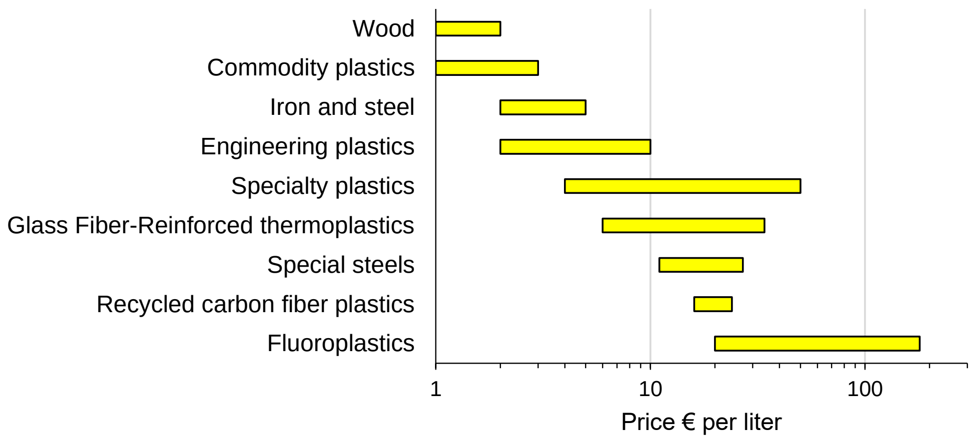

Figure 4. Approximate prices for a variety of materials (adapted from Biron (2018) and Barnes 2016).

Recycled material composites have been used mainly in the WPC sector, where the use of recycled material has been common for decades. WPC manufacturers have traditionally used recycled plastics and wood and it is common to have as high an amount of recycled materials as 95%. Early adopters of recycled materials had problems such as warping, rotting, splinters, and maintenance issues (Klyosov, 2007). These problems were not entirely related to the quality of materials, but there was still some negative influence due to the use of recycled materials. Nowadays, the main body of WPC extrusions is protected by a co-extruded layer providing resistance to fading, staining, scratching, and mold, thereby reducing some negative influences of the recycled bulk material. Figure 5 shows different types of reclaimed material sources for thermoplastic composites. The most common combinations are reclaimed carbon fiber with virgin thermoplastics and different types of WPC application based on natural fibers. The manufacturing of recycled material composites is done to reduce the costs and the carbon footprint of the product. The environmental benefits related to WPC products with recycled materials are based on the use of recycled plastic (Liikanen et al., 2019; Sommerhuber et al., 2017; Väntsi and Kärki, 2015). A high filler content decreases the relative environmental impacts gained by using recycled polymers. The transportation distance of waste has a major influence on the total energy consumption, costs, and environmental impacts of recycling strategies. The recycling of composites remains an economic, environmental, and technical challenge due to the interlinking of materials (Sormunen and Kärki, 2019a).

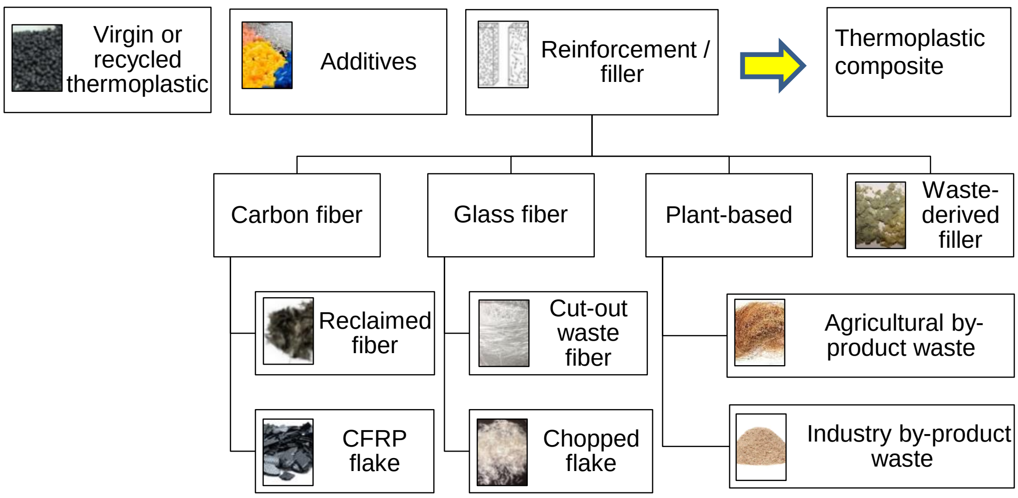

Figure 5. Different types of reclaimed material sources for thermoplastic composite reinforcement.

Table 1. Utilization criteria of recycled FRC material (adapted from Conroy et al. (2006)).

Utilization criteria	**Known problems**
The use of ground FRC should be beneficial to the product.	The reinforcing fibers tend to shorten in reprocessing, such as extrusion.
The material mixture should be synergistic.	Polymeric materials are usually incompatible with each other and the user should have know-how of compatibilizing mixed plastics.
Should not be reinforced with another material or made thicker due to inclusion of FRC.	The FRC should have sufficiently good properties to replace previously used materials. In practice this usually means some sort of downgrading solution.
Should not be disposed of as geotechnical fill.	Non-biodegradable plastic could harm the environment and living creatures.
Reuse method should be realistic in respect of the likely volumes of recyclates available.	The costs involved in remanufacturing are high due to labor intensity. Therefore, the retained value of the product should be relatively high for the take-back to make economic sense.
The reuse of FRC should not make the ultimate recycling of the product difficult.	Adding composite material components to structures made of highly recyclable materials such as metals would increase costs and hamper the end-of-life procedures of the original structure.
The product should not pose environmental or health and safety problems in use.	The regrinding of FRC could induce dangerous volatiles in the working environment, creating an occupational hazard (such as glass fiber dust).
Should not substitute for something which is made of more sustainable materials.	Replacement of virgin plastics is often calculated as an environmental benefit of recycled material composite, which does not take into consideration the fact that many homogenous plastics are easier to recycle and have established waste management practices, whereas composites do not.
The combination of ground FPC with some other waste materials should not divert this waste from an existing higher end reuse chain.	This would mean that ground FPC can only be used in solutions that are not recyclable in other ways than incineration for energy. Likewise, only recycled plastics should be used for the matrix.
The product should have a suitably long service life.	Product-specific testing is required for recyclates.
The product should be cost effective.	The replacement of virgin material with recycled material can usually only happen in situations where there is a decrease in manufacturing costs. The final costs are difficult to estimate due to little industry experience.

Perry et al. (2012) suggested three guidelines to implement during the design phase for better recycling of fiber reinforced composites (FRC) dismantling, matrix-fiber separation and material recognition before and after recycling. Their study also presented the generation of evolution for the composite where the successive product life cycles move from the most demanding mechanical structural solutions towards less demanding ones, such as those for leisure and sports. The product life evolutions approach could also be referred to as designing for downcycling, where eventually the product becomes waste; this phenomenon is also called ‘environmental burden shifting’ by some authors (Djuric Ilic et al., 2018). Pimenta and Pinho (2011) presented possible applications for recycled carbon fiber reinforced polymers depending on the recycling process and the composite manufacturing process, and the automotive and leisure and sports industries were mentioned as potential markets for the material. Carbon fiber composites are often made using a thermoset matrix, which makes them very difficult to recycle, as the crosslinking of polymers prevents remelting the material, but in the case of thermoplastic composites the reprocessing of the material is much more flexible (Conroy et al., 2006). Remelting and remolding of thermoplastic composites is possible (Yang et al., 2012) and is often offered as a potential solution for recycling, but it is unclear how the collection would happen in practice with lower value composites, as these materials are not widely collected or separated and therefore the volumes of mixed composite waste would not promote special systems to tackle the problem. Local waste collection systems exist for carbon fiber-reinforced plastics in the aerospace and automotive industries (Black, 2017; Francis, 2019; Vo Dong et al., 2018). Therefore, the recycling of composites is a challenge both with thermoplastics and thermosets. Conroy, Halliwell, and Reynolds (2006) suggested certain criteria to be met for the utilization of fiber-reinforced waste in product manufacturing to be economically and technically viable. For further information, see the commentary in Table 1.

Reuse is high in the European Union waste treatment hierarchy, but the composites are usually designed for very particular applications in mind, and it is debatable how practical the reuse of such products would be. Designers and builders have a duty to be sure of the structural integrity, and materials whose strength and condition is unknown cannot be reused. The composites are also more economical to produce than to reuse if labor-intensive inspection, cleaning, decontamination, refurbishing, or repair is needed. Currently relevant recycling methods for composites are pyrolysis, mechanical recycling, thermoforming, solvolysis, and dissolution (Cousins et al., 2019). Pyrolysis can be used to recover fiber from thermoset or thermoplastic composites, but the process can degrade the recovered glass fibers due to high temperatures (Oliveux et al., 2015). Mechanical recycling consists of crushing, grinding, or shredding the composite into smaller fractions, after which they can be used as filler or reinforcement in new composites. Solvolysis and dissolution are chemical treatments used to degrade the resin of the composite to get intact fibers. Solvolysis has attracted commercial interest for the recovery of carbon fibers (Oliveux et al., 2015).

3 Methods

Table 2. Research methods used in this study.

Article	Materials	Methods	Standards
I	The published studies about composites made of construction and demolition waste material.	A literature review	-
II	Recycled HDPE, wood, mineral wool, glass fiber, plasterboard, soapstone cutting waste, maleated polypropylene and processing additive.	Compression molding of samples and measurement of properties including mechanical, heat built-up, moisture resistance, and color.	ISO 527-1, EN 317:1993, EN15534-1:2014, Commission Internationale de l'Eclairage L*a*b color system.
III	Published properties of recycled material composites. Case study product was used demonstrate the recycled composite materials in selection process.	EcoTool Seeker (Rousseaux et al., 2017), Environmental Quality Function Deployment (with Voice of Customer questionnaire) and TOPSIS for materials selection.	-
IV	Materials from article II. Three case study products.	Evaluation of economic and environmental characteristics of recycled material composites in variety of dimensioning tasks. LCA calculation of carbon footprint. LCA study was conducted with GaBi software (version 9.0.0.42, DP service pack 38) (thinkstep AG, 2019).	The climate change impacts were assessed following the standards SFS-EN ISO 14040, 2006, SFS-EN ISO 14044, 2006), as well as SFS-EN ISO 14067, 2018).

Article I focused on a literature review of the potential of CDW materials in composite manufacturing as filler, reinforcement, or as matrix. The literature study was used to estimate the effects of recycling on the material, economic, and environmental impacts of recycled materials in composites and the processing aspects. The review aimed to identify papers pertaining to composites made with the following materials: thermoplastics, wood, paper and cardboard, metals, glass, gypsum, mineral wool, and inert materials, including concrete, ceramics, and stone.

Article II studied the mechanical, moisture resistance, and heat build-up properties of compression-molded high-density polyethylene (HDPE) composites filled with recycled wood fiber (fine flour (NFF), rough flour (NFR), glass fiber (GF), mineral wool (recycled (MWR), processing by-product (MWB), gypsum plasterboard (PB), and soapstone stone-cut waste (SC) particles by empirical testing, in order to evaluate the effect of recycled low-cost fillers on the recycled plastic. The materials were processed according to the procedure shown in Figure 6 into the composition described in Table 3.

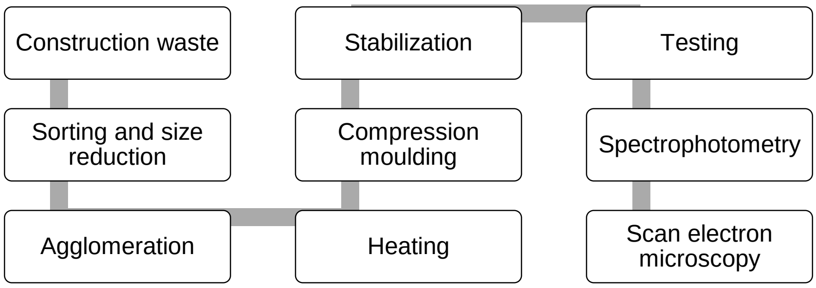

Figure 6. Processing of samples.

Table 3. Composition of the composites used in the study. The marked percentage of material is by weight.

Composite	Poly-ethylene	Wood fiber	Glass fiber	Mineral wool	Plaster-board	Stone cut waste	Coupling agent	Processing aid
r-HDPE (REF)	94%	-	-	-	-	-	3%	3%
NFF40	54%	40%	-	-	-	-	3%	3%
NFF60	34%	60%	-	-	-	-	3%	3%
NFR40	54%	40%	-	-	-	-	3%	3%
NFR60	34%	60%	-	-	-	-	3%	3%
GF40	54%	-	40%	-	-	-	3%	3%
GF60	34%	-	60%	-	-	-	3%	3%
MW40	54%	-	-	40%	-	-	3%	3%
MW60	34%	-	-	60%	-	-	3%	3%
PB40	54%	-	-	-	40%	-	3%	3%
PB60	34%	-	-	-	60%	-	3%	3%
SC40	54%	-	-	-	-	40%	3%	3%
SC60	34%	-	-	-	-	60%	3%	3%

Article III had the goal of finding repeating patterns from the studied ecodesign methodologies, which affect the chances of recycled composites materials being chosen. A case study product was designed through which the material selection process would be conducted (see Figure 7). Two methods were chosen as the framework of the study: Environmental Quality Function Deployment (EQFD) (Masui et al., 2003; Sakao, 2007) for the environmental criteria and weightings and Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) for numerical material comparison (Jahan et al., 2016). The case study was used to understand the factors influencing the materials selection process in a functional context, where the material properties and characteristics of the product are taken into consideration. The EFQD analysis was complemented with a 'Voice of the Customer' structured interview. The respondents were experts working closely with underfloor heating business-to-business customers in a Finnish company that manufactures and sells heating and cooling solutions. A House of Quality table was developed from the Voice of the Customer questionnaire results and the customer requirements were translated into metrics, of which the dependencies of requirements were cross-checked, and the technical importance ratings and relative weights were calculated.

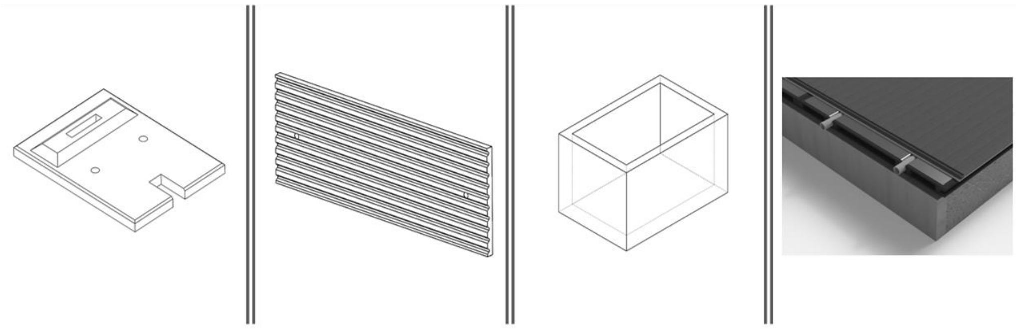

Figure 7. Case study applications used in Article III and Article IV. Starting from left: mass-related solution (20 kg), property-related solution 400 x 1000 mm, volume-related solution 564 cm^3 product, and underfloor heating platform (article III).

Article IV studied the economic and climate change impacts of construction waste-derived fillers. The study is conducted using the most promising materials identified previously in Article II. The costs are calculated for the production phase including preproduction activities: labor wages, and energy and material consumption. The expenditure related to capital costs, such as machinery and tooling, as well as maintenance of equipment, were not calculated as they were estimated to be similar regardless of the filler used. The range of the costs was calculated for each recipe based on the lower and upper boundaries of the expected cost. The cost calculation is influenced by the variation in material density and unit costs. The estimates assume that the capacity of the tooling is fully used and the production is continuous. The climate change impacts were characterized using the characterization factors developed by the Intergovernmental

Panel on Climate Change (IPCC, 2014) and implemented in GaBi software as ‘IPCC AR5 GWP 100, excl. biogenic carbon.’ The results are calculated using carbon dioxide (CO_2) as an impact category indicator, thus giving the results in kilograms of carbon dioxide equivalents (kg CO_2-eq.).

4 Results and discussion

4.1 Recycled material composites from CDW and their challenges

The literature review of academic research concerning CDW fraction use in composites recognized two main types thermoplastic and gypsum-based composites. The other light CDW fractions – wood, mineral wool, and paper – were used as filler materials. The suggested applications for thermoplastic composites were typical WPC and plastic tiles. Producing building materials from recycled materials is especially practiced in Africa. The compression-molded and casted gypsum composites were typically made into tiles. The weak bonding of used filler material to the composite matrix is a common problem. In general, the prediction of interface characteristics of the composite is difficult because of the random orientation of post-processed recycled fibers and fillers. The visual appearance, tactile texture, and odor are rarely reported in the studies, but we can assume that the quality and mixing of waste has a big influence on this. The raw material quality should conform to the set product standards set by the user and the respective authorities interested in the end-of-waste legislation-related activity. Therefore, the recycled materials should be monitored carefully for the possible entry of contaminants that might enter to the material batches. Potential emissions of volatile organic compounds from CDW materials are difficult to predict because of numerous additives used in the construction industry. Health risks could be controlled by using source-separated materials of known origin and composition.

The interface characteristics of WPC have been improved by using compatibilizers (Adhikary et al., 2008a; Chaharmahali et al., 2008; Englund and Villechevrolle, 2011; Poletto et al., 2011; Renner et al., 2010). Studies show that composites that utilized paper and cardboard waste had inferior mechanical properties compared to ones with wood fibers (Grigoriou, 2003; Lykidis et al., 2012). Gypsum is not affected by recycling and it has been used in combination with thermoplastics (del Rio Merino et al., 2019; Pedreño-Rojas et al., 2019; Ramos and Mendes, 2014; Vidales Barriguete et al., 2018), paper fibers (Carvalho et al., 2008), rubber (Adamopoulos et al., 2015; Jiménez Rivero et al., 2014), and mineral wool (Piñeiro et al., 2015). The aim of using recycled gypsum composites has usually been to create tiles. Mineral wool is a waste that substantially consumes landfill space and is currently without any considerable reuse possibilities (Kinnunen et al., 2017; Väntsi and Kärki, 2014b). The challenges of utilizing MW waste are related to its high porosity and bonding to the composite matrix (Keskisaari et al., 2016; Väntsi and Kärki, 2014a). The problems caused by porosity of MW might be resolved by grinding MW waste into powder.

The research in the field of recycled material composites is primarily focused on technical properties without the estimation of the economic and environmental effects of production. The applicability of studies could benefit from the inclusion of economic and environmental estimates, as presented by Keskisaari and Kärki, (2018), Rajendran et al., (2012) and Sommerhuber, Welling and Krause, (2015).

4.2 Mechanical properties of recycled material composites

4.2.1 Density

The measured densities of the compression-molded composites are presented in Figure 8. The measured densities did not always follow the rule-of-mixture (ROM) (see Article IV for more details) in all the composites. The largest deviation from ROM was in the composites with 60% by weight filler content. The suspected cause of the difference between ROM and measured was the lack of hot melt mixing in the processing phase (Sormunen and Kärki, 2019b). This study uses the measured density in the calculation of property index values. Section 4.4 Economic and environmental impacts uses the ROM range density range to evaluate the processing cost and average ROM for the evaluation of global warming potential. The primary reason for using commercial fillers in polyolefins is to enhance stiffness, heat distortion temperature, creep, and opacity with the penalty of increased cost compared to unfilled polymer (Dufton, 1998). This study concentrated on a few of the above mentioned aspects of fillers, but in addition the waste-derived fillers can provide a recycling route to previously landfilled materials. The recycled commodity polyolefins HDPE and PP are usually used with fillers (talc, calcium carbonate, or titanium dioxide) and additives (antioxidants and ultraviolet stabilizers) to improve the quality of plastics (Gu et al., 2017).

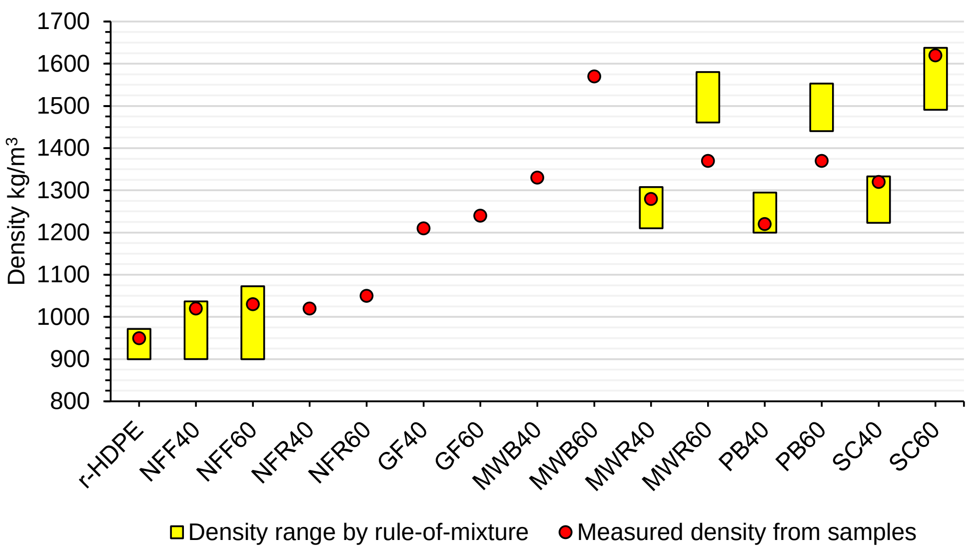

Figure 8. Density of studied composite formulations.

4.2.2 Tensile strength

The tensile strength decreased with the addition of filler material compared to fully plastic REF due to weak interphase adhesion in the filler interface. See Figure 9.

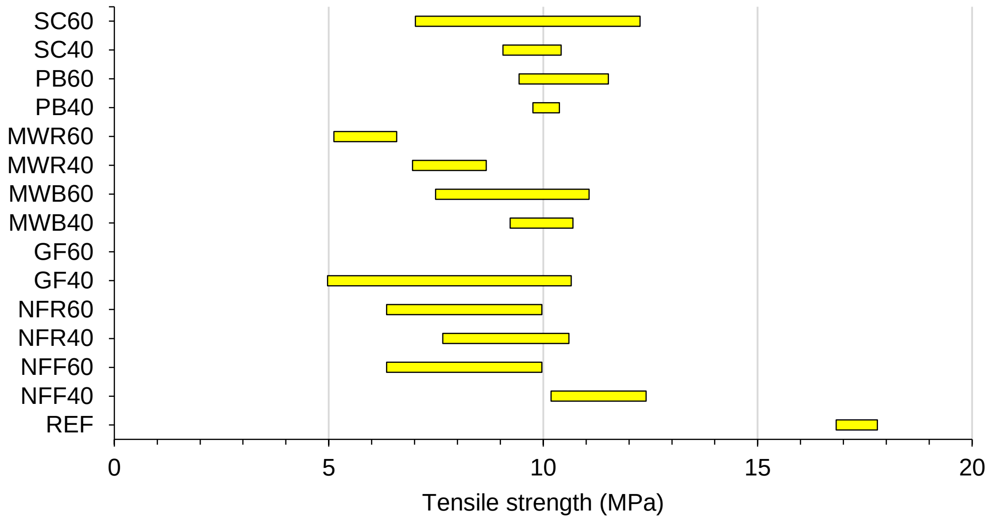

Figure 9. Tensile strength of composites.

The tensile strengths of the compression-molded wood plastic composite samples were significantly below the previously reported values by Bouafif et al. (2009) and Sommerhuber, Welling and Krause (2015). The composite NFF40 had 18% higher tensile strength than the composite NFR40, which would seem to suggest a negative influence from using larger wood particles. However, the wood plastic composite samples with a 60% fill rate demonstrated the opposite effect, and the NFF60 had 18% smaller tensile strength compared with NFR60. This seems to be in conflict with previous reports where the increased fiber size and fiber ratio has improved both the modulus of elasticity and maximum strength, although in these studies the fiber size has previously been significantly smaller (Bouafif et al., 2009; Migneault et al., 2009). Wood plastic composite samples NFR40, NFR60, NFF40 and NFF60 all had high variance in results. In the NFF60 with 20 mesh natural fiber filling of 60%, the deviation in results was over 30% of the average. The measured densities in NFR40, NFR60, NFF40, and NFF60 were close to each other despite the different fill rate, and while NFF60 composite samples were the heaviest, NFR60 performed better both in strength and in the modulus. The agglomerate heating method and low 24.3 MPa mold pressure might also have affected the results of the tensile strength negatively in composites with a high natural fiber content. The mineral-filled composites performed slightly better as a group compared to the fiber-filled composites; an exception to this are the samples MWR40 and MWR60. The difference in results between recycled and by-product mineral wool composites

MWB40 and MWB60 might be in the non-hardened resin component in the by-product material. The composites with by-product mineral wool filling tensile properties are close to the previously reported 9.00 MPa with a recycled HDPE matrix and 40% rock wool filling (Bredikhin and Kadykova, 2016). Wood plastic composites with 40% fiber fill have previously had significantly higher tensile strengths (Migneault et al., 2015). Similarly, there was a significant variance in the results of glass fiber composite GF40 with 40% filling. While processing the GF60 tensile strength and elastic modulus samples, the matrix was not able to hold the material together and they broke during demolding. In this study, the cut glass fiber also reduced significantly in size. In a study conducted in the same laboratory (Turku and Kärki, 2014), the glass fiber was agglomerated with the same method, and the size of processed glass fibers ranged from 20 to 460 µm, with a mean size of about 100 µm. Processing is known to affect the fiber length and distribution, and likewise, anisotropic particle fillers cleave and experience considerable delamination in processing (Móczó and Pukánszky, 2008). In both natural and glass fiber composites, the aggregation of fibers created weak spots in the matrix leading to crack propagation. In general, the mineral fillers with a small particle size performed better in the tensile strength test, which suggests better dispersion in the matrix than with the fiber fillers. The tensile strength of mineral wool composites MWR and MWB ranged between 5.85-9.96 MPa. The lowest result was with MWR60 and the highest with MWB40. Both MWB samples performed better than the samples with post-consumer recycled mineral wool. This could be due to the reinforcing effect of the non-hardened resin in by-product mineral wool, which was activated in the processing of the composite. The materials with the least variation in the mineral-filled composites group were the samples with recycled gypsum PB40 and PB60, and a good dispersion into the matrix is visible in the SEM analysis. The tensile strength SC40 and SC60 were similar, but there was greater variation in the results of SC60, which is probably caused by the higher local concentrations of soapstone in the mixture with a 60% fill rate.

4.2.3 Impact resistance

The impact resistance of polymers depends on geometry, the mode of loading, the load application rate, the loading environment, and polymer properties such as chain length, packing, chemical arrangement units in the polymer chain, alignment, and bonding forces. Therefore, the strength is the sum of properties that contribute to the dissipation of energy (Perkins, 1999). The effects of a high fill rate on the Charpy impact strength of the recycled plastic were significant. Figure 10 shows the range of test results for 12 samples for each composite type. The impact strength decreased in composite with 60% by weight filler content. There was an exception with the soapstone filling, as seen in SC40 and SC60, where the impact strength was higher with a 60% fill rate. Compared to the reference material REF, the drop in impact strength was on average 90%, as Figure 6 shows. Glass fiber GF40 had the highest impact strength of the measured composites. The relatively high result with GF40 was surprising, as it was the most difficult material to process and the fibers had become shorter in the agglomeration phase. According to previous studies, the high impact test results with glass fiber thermoplastic composites have attributed to strong interaction between the silanol groups of the glass surface and the anhydride group of the coupling agent (Xanthos, 2005; Yi-Hua Cui, 2009). The standard deviation in GF40 results was the highest of all tested materials, which was likely caused by the agglomeration phase where the fibers were broken into random lengths and clustered heavily together, creating discontinuities and porosity in the thermoplastic matrix. This same reason might be the cause of the higher results in GF40, as the clustering of fibers also created zones where the tough thermoplastic was the dominant material. This seems to be supported by the SEM; see Figure 13. The mixing effect was not as strong in the glass fiber composite with a higher fill rate GF60, which could be related to the plastic zones being smaller with a higher glass fiber content. The use of rough or fine saw flour did not seem to have a significant effect on the impact resistance properties in the wood plastic composite samples NFR40 and NFF40 with a 40% fill rate. Both of the particle types decreased the impact strength compared to unfilled REF, which is in line with the previous studies (Migneault et al., 2014; Sommerhuber et al., 2015). The composite NFF60 with fine wood flour performed better than the sample with rough wood flour NFR60. The variance in the impact strength was higher in samples with a 60% fill rate. Without the bonding effect of the plastic matrix, the high aggregation of fillers leads to insufficient homogeneity, rigidity, and low impact strength, and the aggregated particles act as crack initiation sites in impact (Móczó and Pukánszky, 2008). The mineral wool composites with recycled raw material MWR40 and MWR60 had higher impact strength than the MWB40 and MWB60 made of by-product mineral wool, this could be due to more fibrous particles in the filler see Figure 13. The composite PB40 performed well in impact testing with a small variation in results, but as the gypsum content was increased, the results dropped as in other tested samples of PB60.

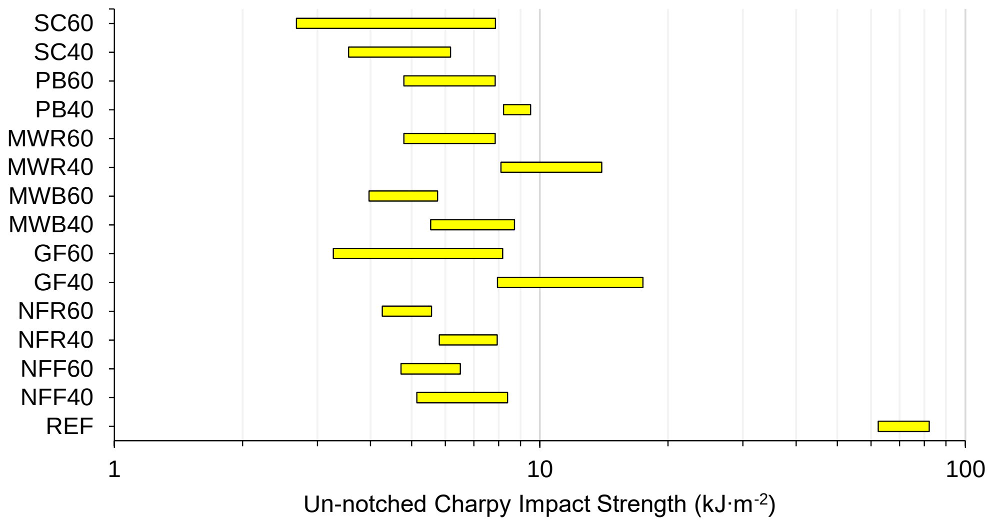

Figure 10. Charpy impact strength (kJ/m^2) of tested composites.

4.2.4 Elastic modulus

The addition of mineral and fiber fillers increased the tensile modulus of recycled HDPE in all samples except in PB40; see Figure 9. The standard deviation in samples NFR60, NFF60, GF40, and MWR60 was high due to the clustering of particulates to high concentrations in the tensile specimens. Also, the tensile modulus of MWR40 was quite close to the REF material. Mineral wool by-products MWB40 and MWB60 performed better than recycled mineral wool, probably due to the activated non-hardened resin in the by-product component. Wood plastic composites NFR40 and NFF40 had smaller variance in results than the other fiber composites due to the good dispersion of wood particles into the plastic matrix and the effect of the compatibilizer. Composites filled with by-product mineral wool (MWB40 and MWB60), gypsum PB40 and PB60 and soapstone SC40 and SC60 all showed small variation in the results because of their good dispersion in the matrix. The particulate and fiber filling increased the stiffness of the composites apart from the sample PB40. A great deal of variation is visible in the tensile modulus of NFR60, NFF60, GF40, and MWR60. A common factor for all of these is the large amount of porosity revealed by the SEM analysis. Both GF40 and MWR60 exhibit heavy clustering of small fibers without proper adhesion to the matrix, which explains the variation in the tensile modulus.

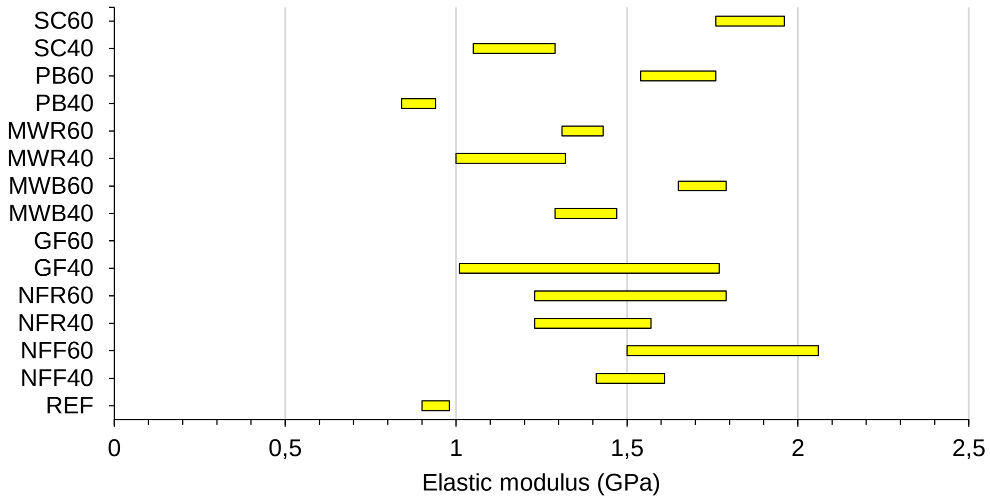

Figure 11. Elastic modulus of composites.

4.2.5 Hardness

Hardness is the degree of permanent deformation of a material under an applied force. Figure 12 displays the results for the measured Brinell hardness. There was a small increase in the Brinell hardness in composites MWR60, PB60, and SC60 compared with the REF material.

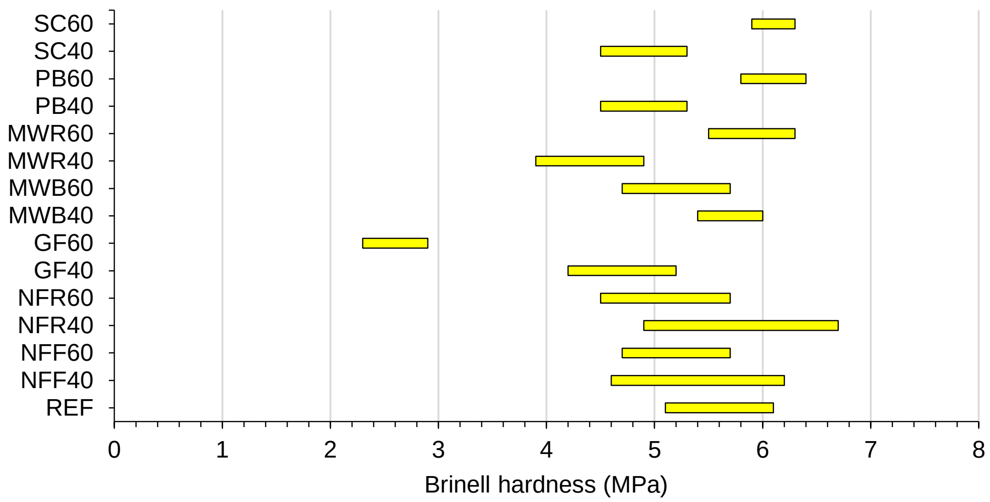

Figure 12. Brinell hardness of composites.

In a previous study, the addition of mineral wool (40%-wt) to recycled HDPE increased the Brinell hardness by 37% (Bredikhin and Kadykova, 2016). Another study reported that composites with 20%, 30%, and 40% of recycled mineral wool had 10.5%, 16.5%, and 20.6% lower Brinell hardness, respectively, than the wood-plastic composite reference (Väntsi and Kärki, 2014a). The smaller content of the filler and better interfacial adhesion of particles to the polymer matrix was used to explain the greater hardness in the lower filler content (Väntsi and Kärki, 2014a). Here, the filling effect of mineral wool lowered the Brinell hardness in MWR40 by 16% and in MWB60 by 7%. However, in the MWB40 and MWR60 samples, the hardness increased by 1% and 7%, respectively. The results seem to indicate that the influence of mineral wool filling on hardness is not completely predictable with high fill rate; this could be due to variation of particle dispersion in the agglomeration phase. The highest hardness value was obtained in the SC60 composite; it had the least amount of variation in results. This is surprising, as soapstone mainly consists of talc, which has a lower Mohs hardness than gypsum or silicon dioxide, which is one of the main components in mineral wool (Kappel, 2011). Likewise, the composite SC40 had a significantly lower hardness than SC60 and REF, which could be due to bad dispersion not creating highly packed zones of mineral material. Composites that had natural fiber filling demonstrated elastic behavior and spring-back, which explains the rather high values for hardness compared with the composites with mineral fillers. The spring-back effect is a common problem in the hardness measurement of elastic materials. Both glass fiber samples GF40 and GF60 had the poorest results for hardness due to their soft fiber bundles on the surface of the material that yielded during the indentation test. The GF60 samples had a 1-mm layer of loose and soft fiber material, indicating a strong bundling effect in short glass fibers. Previously, when glass fiber has been added as reinforcement to a wood plastic composite, a small increase in hardness has been reported (Turku and Kärki, 2014). However, earlier studies used only 10% of glass fiber, which dispersed more homogenously into the matrix and did not create soft fiber bundles. The hardness for wood plastic composite samples NFF40, NFF60, NFR40, and NFR60 was lower than in the REF material, probably because of the wood fibers close to the surface that gave way under pressure. When taking into consideration the increase in density and loss of the spring-back effect in unmixed plastic, it seems that waste-derived fillers are not advantageous for hardening the recycled HDPE. The reference material HDPE is better protected from permanent deformation by its uncompromised elasticity.

4.2.6 Topography of fracture mechanisms

The scanning electronic microscopy (SEM) can be used to analyze the topography of the broken tensile strength samples to determine fracture mechanisms and the dispersion of filler materials in the matrix. Figure 13 displays the SEM images for selected specimens. The broken surface of the unfilled REF material shows small impurities. It is unlikely that these small particles would have had a major effect on the mechanical properties, as they seem to be just on the surface of the material. Bits of unmelted plastic of different colors were visible on the surface of processed HDPE samples. Small quantities of impurities are often carried to the plastic material from the recycling process. In the wood plastic composite samples NFF and NFR, the wood fibers seem to have been clustered in parts of the broken surface; the concentrations of wood without the plastic matrix are weak points in the composite. Signs of fiber pullouts are visible in parts of the wood plastic composite. Debonding and fiber pullouts are dominant deformation processes when adhesion between the fiber and the matrix is poor (Móczó and Pukánszky, 2008). The GF40 sample shows a small amount of plastic material on the glass fiber surface suggesting weak bonding between the matrix and the fiber. The scanning electron microscopy shows the heavy clustering of glass fibers, which has probably impeded the flow of plastic during molding, likely causing the relatively high variation in the GF40 tensile strength results. Surprisingly, the impact strength results of GF40 were the second highest after REF. The glass fiber samples GF40 and GF60 both had volumetrically high fill rates, and it is likely that with a smaller fill rate, the matrix would have a more heterogeneous structure and better processing quality. In the PB60, the gypsum particulates have dispersed well into the material, which is also demonstrated by the smaller deviation in the test results for mechanical properties in the samples. The gypsum filler in PB40 and PB60 displays clean surfaces without plastic to create proper adhesion at the breakage points. The porosity and dislocation of the particulates from the matrix can be seen in the fracture scans of SC40 and SC60, but more in SC60. The large deviation in the tensile strength results of SC60 samples is related to the strong cavity formation around the soapstone particles. The fiber surface in MWR40 is clean of plastic material, suggesting weak bonding of the filler to the thermoplastic matrix. The recycled mineral wool composite MWR60 microscopy shows clumping of fiber and particle-type fractions, which has worked as discontinuity in the composite matrix leading to crack propagation. In the by-product mineral wool composites MWB40 and MWB60, the broken surfaces of the composite samples show the dislocations of the filler from the matrix. The matrix in both MWB40 and MWB60 shows signs of tearing as a result of stretching; there are also grooves that show signs of fiber pull-outs. The strength of the particulate-filled composite depends strongly on the stress transfer between the filler and the matrix (Fu et al., 2008). The void content and their shape, size, and location affect the mechanical properties and mechanisms, leading to mechanical failure stress/strain concentration effects (Mehdikhani et al., 2018). The presence of both resin and interlaminar voids is verified in the SEM of broken tensile samples. The influence of high porosity is most clearly seen in the soapstone-filled composites SC40 and SC60. Both SC40 and SC60 had high variance in impact and tensile strength properties, while PB40 and PB60 had little porosity and small variance. The lack of heating in the mold adversely affected the properties of the composite as the trapped air did not have enough time to move through the channel before the solidification of material.

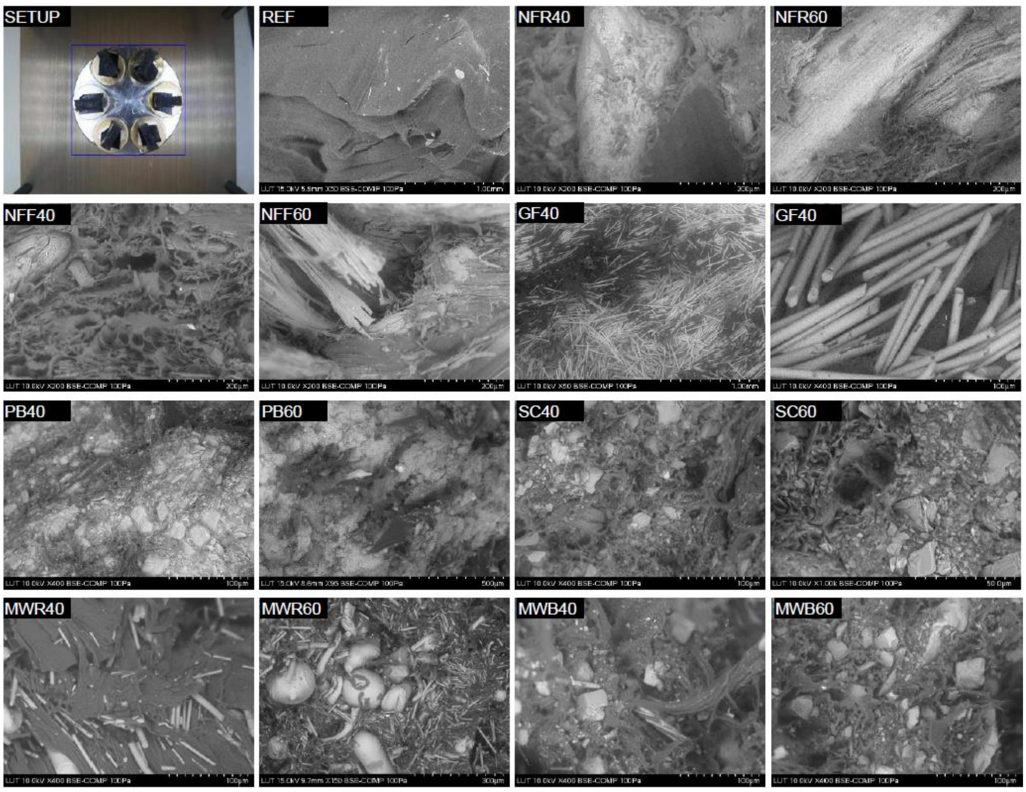

Figure 13. Scanning electron microscopy of broken tensile sample surfaces.

4.3 Physical properties

4.3.1 Moisture absorption and thickness swelling

The results of the moisture absorption and thickness swelling test over an immersion time of 28 days are shown in Figure 14. The reference material REF did not absorb water during the immersion time of 28 days. The wood plastic composites NFR60 and NFF60 absorbed approximately 13% by weight of water during the test period. The difference in performance between the 40% and 60% wood fiber mixture was considerable, as the NFR40 and NFF40 absorbed 5% by weight of water. The thickness swelling in wood plastic composites NFR60 and NFF60 was 4%, while the NFR40 and NFF40 had only 1%. The fiber mesh size had only a minimal effect on the moisture absorption, as also shown in previous studies (Bouafif et al., 2009). It is notable that the wood plastic composite samples with fine and rough flour size had significantly smaller thickness swelling than reported previously for compression-molded wood plastics (Kazemi Najafi et al., 2008). This can be attributed to the used coupling agent maleic anhydride modified polyethylene, which has been shown to improve the water absorption resistance of wood plastic composites (Adhikary et al., 2008b). The weather endurance properties of the composites were strongly affected by the exposure to UV light. WPC composite formulations with a wood component should be stabilized to decrease its degradation in open-air environments (Fabiyi et al., 2008). The glass fiber 60% composite GF60 absorbed 10% by weight of water during the immersion, performing worse than the hydrophilic wood plastic composites NFR40 and NFF40. In both of the glass fiber compositions, the poor surface quality, lack of plastic film on the surface, clustering of fibers and weak bonding formed pathways for the water to enter into the composite, increasing the water absorption to a relatively high level considering the hydrophobicity of the materials used. The poor quality of the glass fiber samples was also evident in the thickness swelling measurement, as the material was separated from the samples during the immersion period. The water absorption and thickness swelling of the particle-based composites was negligible. The highest value for thickness swelling in particle-filled composites was only approximately 1% in the MWR60 and PB60 composites. A small amount of filler material was separated during the immersion time, which would seem to suggest an incomplete covering of the particulates by the matrix on the surface of the composite samples. This could be seen from the visible mineral particles in the water container after drying the tested samples. The better moisture resistance of mineral filler-based CDW composites suggests that if the mechanical properties or the increased weight are not a limiting factor, there could be a replacement of WPC applications with the mineral filler group.

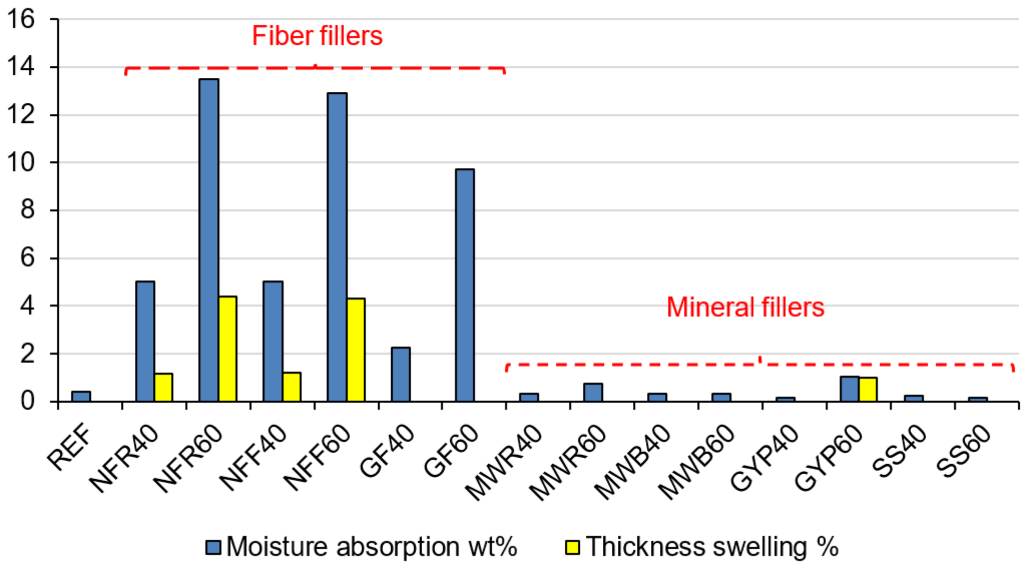

Figure 14. Moisture absorption and thickness swelling after 28 days of immersion in water.

4.3.2 Color measurements and heat build-up

Color has major impact on the heat built-up characteristics of products. CDW plastics, especially HDPE, is usually a darker color; for example, in their manufacturing, pipes are black due to the addition of 3–5% of carbon black in clear polyethylene. Jacket piping can also have clear colors such as yellow, red, or blue, depending on the product, but once these colors are mixed with other waste plastics, the color changes to darker hues. Carbon black is often added as a cheap additive to improve the UV protection of tubes. The rise in temperature in the composite material exposed to thermal radiation is related to the optical properties (Martikka et al., 2012). Table 4 presents the measured CIE L*, a*, and b* color values, with Specular Component Included (SCI) and Specular Component Excluded (SCE). The lightness *L stands for the darkest black at *L=0, and bright white at *L=100. The measured values for a* and b* represent the true neutral gray value at a*=0 and b*=0. The green color is represented at negative a* values and red at positive a* values. The b* negative values stand for blue and the positive b* values represent yellow. The composite CIE-LAB values were estimated using Colorizer. The black reference sample REF had an *L value of 25.20, while the results for the mineral-filled samples were in the range of 25.50–28.26. The exception to this was MWR60 with *L 32.61. For the wood plastic samples, the *L value ranged between 44.01 and 51.06, resulting in decreased heat build-up. The composites with the mineral fill rate of 40% increased the heat build-up by 4.5% compared with the reference material REF. The samples with a 60% mineral fill rate had no significant change in heat build-up compared with REF. The addition of wood fibers had on average a 10% decrease in heat build-up. The use of wood particles resulted in lighter colors than the black REF material. The results for wood plastic composite samples were close to previously reported ones with recycled materials (Sommerhuber et al., 2015). Both wood and glass fiber filling had the greatest impact on the optical properties compared with the reference material. The mineral-filled composites had low values for reflectance compared with wood plastic and glass fiber samples. This can lead to higher heat build-up values, as Figure 15 shows. The carbon black originally used to color the recycled sewer pipe plastic had the greatest influence on the optical properties of the composite. The addition of mineral and fiber fillers, however, decreased the reflectance of the plastic, giving it a duller appearance. The filler particulate size could also have affected the results of the color measurements, as the wood fibers were several times larger than any of the other filler type particles that were milled into dust in the agglomerating stage. The importance of color depends on the application and market trends; therefore, the effect of filler on the visual look of the product should be assessed case by case. The selected thermoplastic matrix has the most influence on the color of the product. Usually this means that recycled plastic products are darker than what is possible with virgin materials. The restrictions due to recycled plastic can have an influence on packaging applications in particular. In outdoor conditions the colors of WPCs lighten in the first eight months, after which they start to become darker due to mildew, mold, or dirt that gathers on the surface of the part (Fabiyi et al., 2008). Heat built-up is not a common method to estimate the thermal properties of materials. It is however a useful method in the case of waste-derived composites, as they are often recommended to be used in outdoor building applications such as decking and cladding. A difference of just a few degrees Celsius can be significant to feel, if the product is in direct contact with humans. It can also influence the weather resistance of cladding components. As expected, the composites with natural fiber filling have the smallest heat built-up of the studied group. Comparing the results to a previous study by Martikka et al., (2012) the heat-built up of soapstone samples is 10 °C higher. In their study the samples had a fill rate of 20%-wt and included 40% of wood fiber. The use of colorless virgin plastic and the wood filling in their study can also explain the difference.

Table 4. CIE L*, a* and b* color coordinates of the studied composites.

	REF	NFR40	NFR60	NFF40	NFF60	GF40	GF60	MWR40	MWR60	MWB40	MWB60	PB40	PB60	SC40	SC60
SCI															
L*=	25.2	44.0	51.1	43.9	48.1	36.8	38.0	27.8	32.6	27.0	25.9	25.4	25.5	28.5	28.3
a*=	0.0	2.4	2.1	1.3	1.2	0.0	0.4	-0.2	-0.3	-0.2	-0.1	-0.2	-0.2	-0.3	-0.1
b*=	-0.3	12.4	13.2	9.4	10.2	0.4	2.7	3.3	5.9	0.9	-0.4	-0.7	0.0	-0.3	-0.3

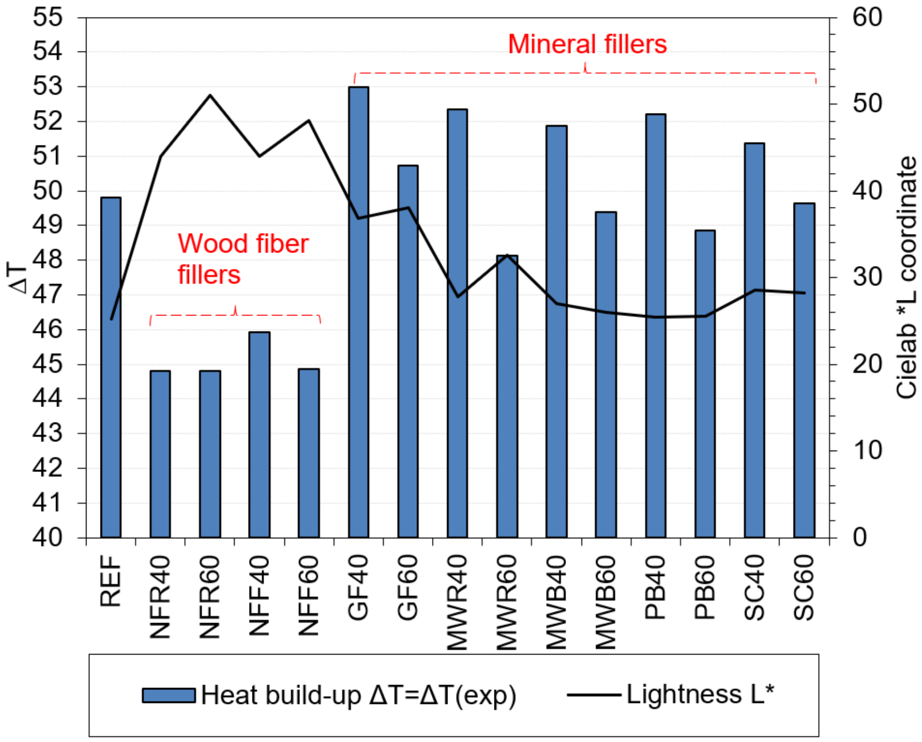

Figure 15. Heat build-up of the studied composites.

4.4 Economic and environmental impacts

The total costs (C_T) and impact on climate change for composites manufacturing are presented in Figure 16. The use of waste-derived filler material decreases the total cost of filled plastic (€ per kilogram). Figure 16 also shows the global warming potential that takes into consideration the potential substitution of plastic HDPE products on the market with waste-derived composites. Therefore, more than half of the avoided impact originates from the replacement of plastic products made of virgin HDPE. The lowest avoided impact of 1790 kg CO_2-eq. per ton of composite originates in the composite NFF60. For the purposes of cost calculation, we estimated that both wood flour types fine (NFF) and rough (NFR) have roughly the same environmental impact and processing costs; therefore, the two wood plastic composite types are discussed using only the acronyms NFF40 and NFF60 in Chapter 4.4. Similarly with mineral wool composite in the following sections only acronym MWR is used. If no plastic was replaced, then the cumulative impact in the scenario NFF60 would be 140 kg CO_2-eq. per ton, the only scenario with induced impact if the substitution of plastic products was not considered. This means from the design point of view that the new product should contribute to a replacement of thermoplastic use, or more specifically the matrix material of the composite in question. An interesting paradigm is the open loop recycling of material to make composites that need to have very narrowed-down applications (almost closed loop). When the composite is replacing a material such as wood, the avoided impact is much smaller. It is questionable whether this condition is in accordance with the principle of ecodesign (not to make products that are harder to recycle). The use of wood filler decreases the cost of the r-PE plastic on average by 12.9% in NFF40 and 19.1% in NFF60. The material with the highest costs, namely r-HDPE, had also higher avoided impacts of 3.17 kg CO_2-eq per kilogram of composite. As the costs of the recipes decrease, e.g., in the case of NFF40 and NFF60, the avoided impacts increase to 1.79...2.25 kg CO_2-eq. The decrease in cost compared to r-HDPE is 21.5% in MWR40, 19.9% in PB40, and 15.9% in SC40. The drop in cost compared to r-HDPE further increases with higher filler rates to 31.4% in MWR60, 29.3% in PB60, and 24.7% in SC60. Mineral-based composites of equal filler rate have a similar total cost despite the differences in material cost. The avoided climate change impacts do not vary significantly between mineral composites of equal filler rate.

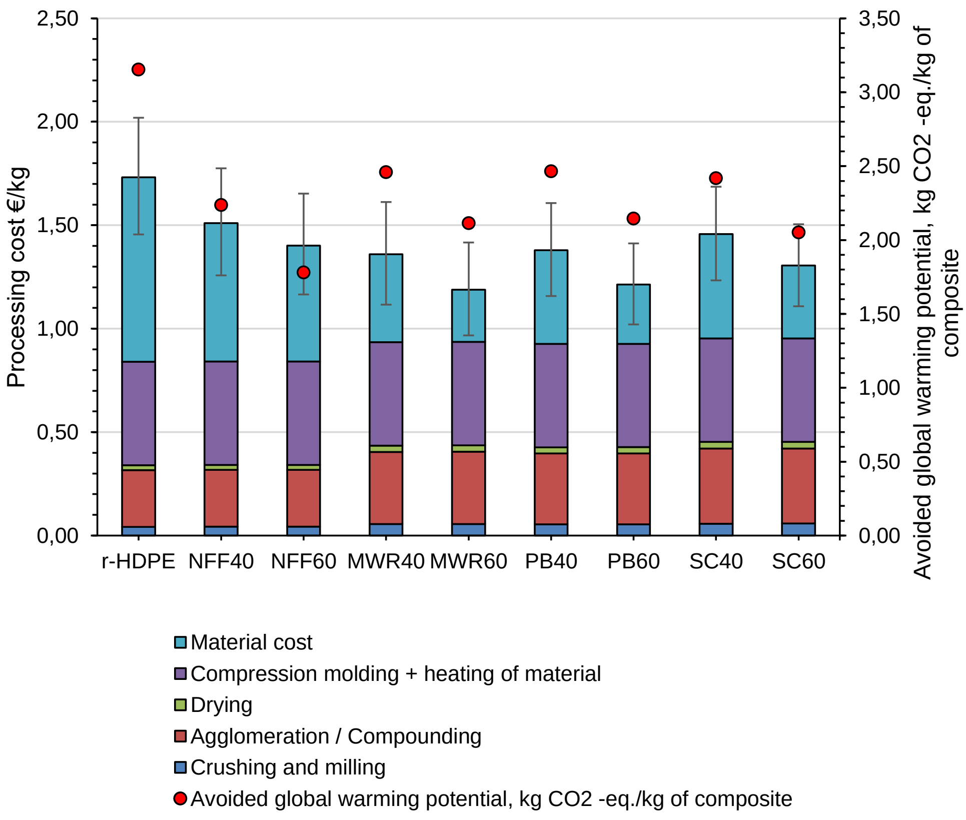

Figure 16. Total cost (€/kg) of compression-molded composite material and division of processing costs. Tolerance bar shows the variance in total cost.

Figure 17 shows the price per product unit (m^3) for different composites. Almost all polymer parts produced are sold on a volume basis; therefore, it is better to use the volume price basis in raw material calculations. As a result, the actual bulk polymer price of filled polyolefin is higher than the volume price of virgin unfilled polymer (Dufton, 1998). When the elastic modulus is taken into consideration, the total cost of a product unit decreases in relation to the property improvement. Likewise, when the strength of the material is the determining factor ,the unfilled plastic performs better than the composites with filler. This is why property improvement should always be taken into consideration in the product dimensioning to gain the cost advantage of waste filler materials. The processing of plastic parts requires increased cycle times as their thickness or volume increases, due to longer required cooling times before part removal from the mold. Decreasing the volume also lowers processing costs. The limiting factor in this is the processing method, as compression molding can only be used with form plates with a thickness of 1-10 mm (Biron, 2013), but extrusion would provide more chances of using the property improvement as hollow profiles are possible. As far as production economics are concerned, it is recommended to use composites with a 60% fill rate when the technical characteristics of the product application allow it. The reported technical properties for PB40 seem to be the exception to the trend with higher costs than r-HDPE, and this could be explained by problems in processing (Sormunen and Kärki, 2019b). If the replacement of material is done on a 1:1 basis, there is no expected cost advantage in mineral composites due to expensive pre-processing activities.

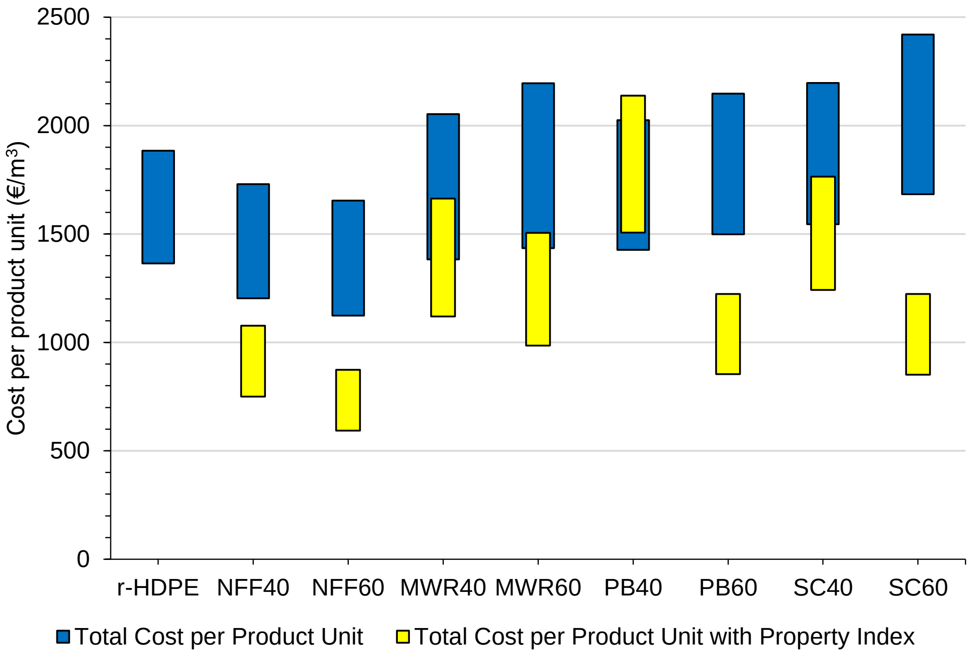

Figure 17. The cost per product unit (m^3) of compression-molded material with property index values.

Volume-based application has a set of space that the application needs to fill. In this case the lower total cost per kilogram of mineral waste-based composites offers no benefit as the material properties cannot be taken into consideration. In the volume-based application, the total avoided impacts on climate change per product are higher in the mineral waste-filled composites; this is due to a higher mass of the product with mineral waste-based composites. The comparison of composites in a volume-based product example is shown in Figure 18. The cheapest solution is achieved with NFF60.

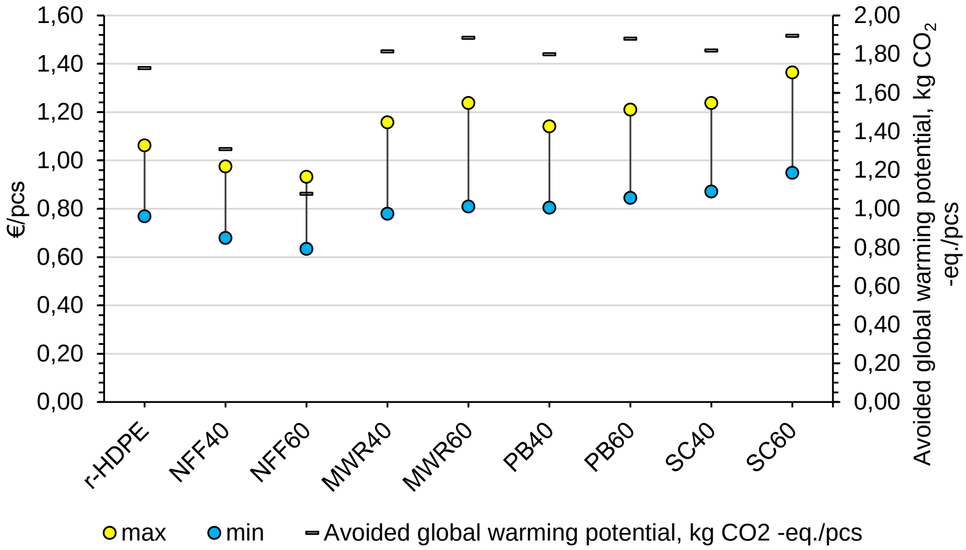

Figure 18. Example of a volume-based application (564 cm^3) unit costs.

A mass-related solution presents an application where a product needs to have certain weight. Lower C_T favors mineral fillers over r-HDPE. From a climate change point of view, the product design favors unfilled plastic because of the high avoided impact per kilogram of recycled HDPE. The comparison of composites in the mass-based product example is shown in Figure 19. Note that the mineral-filled composites need 40% less material volume to achieve the 20 kg mass.

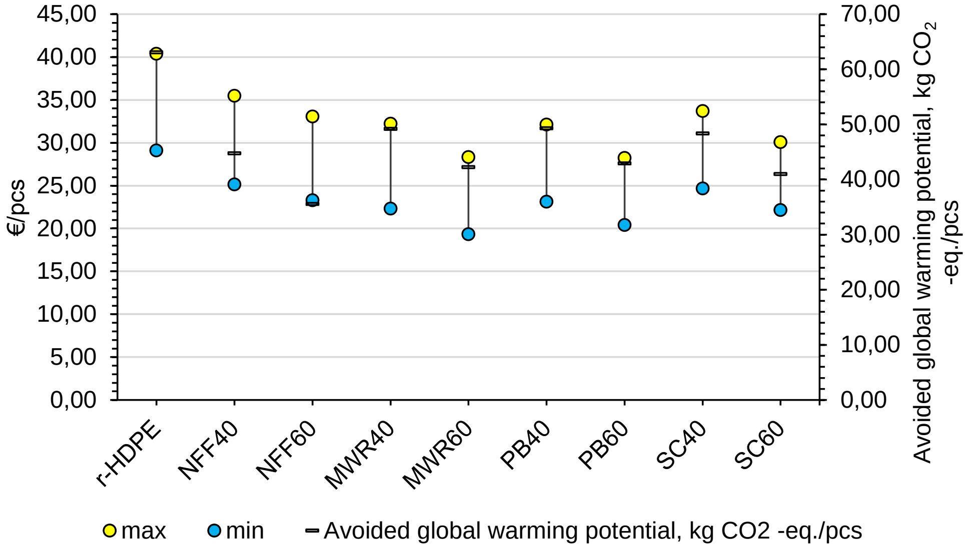

Figure 19. Example of mass- (20 kg) based product unit costs.

In the last example a property optimized profile has been calculated. Here the property index is used to take the properties of composite into consideration in material usage. The height of the profile can be optimized while keeping the needed surface area. Wood fiber filled composite NFF60 is the cheapest solution of the studied materials for this product. The comparison of composites in property optimized product example is shown in Figure 20.

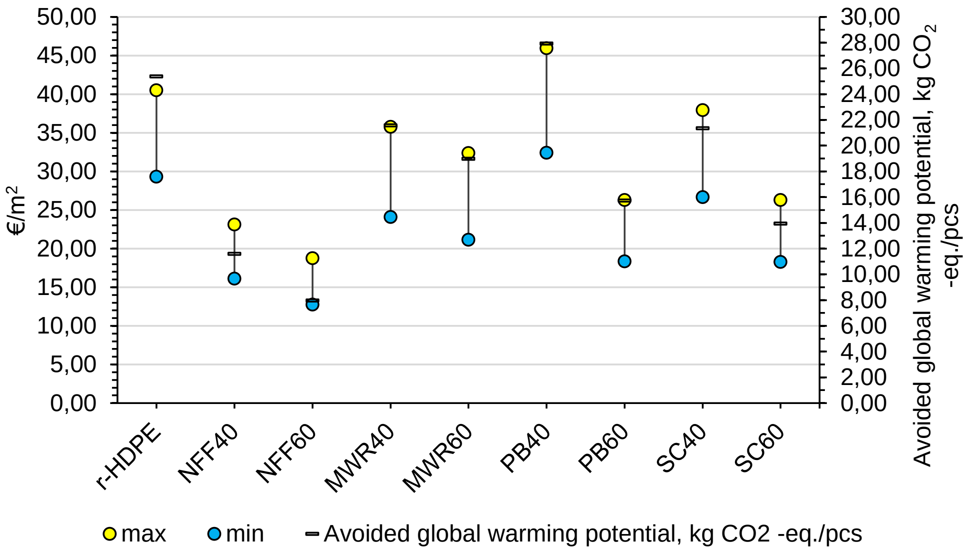

Figure 20. Example of property-optimized profile (0.4 x 1.0 m) costs per m^2.

A more accurate product cost calculation can be done by taking into consideration the geometry complexity of a part from which production time and tooling costs are estimated (Hagnell and Åkermo, 2015). The volume of production has a great influence on the product cost, especially if complex tooling is involved. The manufacturing cost in compression molding also depends significantly on the used material heating method, whether it is isothermal (heating the tool and the surrounding area) or non-isothermal (heating the material directly, for example with an IR oven) (Pantelakis et al., 2009). The application of novelty materials also requires practice, and low series production is more likely to suffer from a high proportion of rejects and disruptions in processing before acceptable quality is achieved. It is also probable that the processing cost variates between different waste fillers in its subprocesses like heating, tool closing time, cooling time, inspection and dimensional stability control. The composite agglomerate from recycled materials vary as follows: recycled HDPE €1.1–1.5/kg, NFF40 €0.9–1.2/kg, NFF60 €0.8–1.1/kg, MWR40 €0.7–1.1/kg, MWR60 €0.5–0.90/kg, PB40 €0.8–1.1/kg, PB60 €0.6–0.9/kg, SC40 €0.8–1.1/kg, and SC60 €0.7–1.0/kg. Reprocessing recycled clean CDW wood has a potential for a more economical fiber source, as commercial WPC granulates prices range between €1.00–4.00/kg (Dammer et al., 2013). The price of composite agglomerates was near to the virgin polyethylene prices of €0.9–1.2/kg. At the time of writing, the petrochemical-based WPCs have started to face competition from bio-based polymer matrix composites with polylactic acid (Dammer et al., 2013; Friedrich, 2018), 2018), although they are still more expensive than typical WPC granulates. Polylactic acid costs €2.0/kg, polybutylene adipate terephthalate €3.5/kg, polytrimethylene terephthalate and bio-polybutylene succinate €4/kg and polyhydroxyalkanoate €5/kg (Oever et al., 2017). So far the cost calculation for composites in academic studies have been quite rare, although lower costs are almost always mentioned as incentives for their use. Gu et al. (2016) used performance-material cost analysis to evaluate the use of injection molded recycled polypropylene composites and found them to cost 50% less than the ones with virgin polypropylene. In a paper by Keskisaari and Kärki, (2018) the composite manufacturing cost with waste fillers comprised approximately 50% material and 50% processing. Their paper did not evaluate the influence of material density on processing, but the range of total cost was close to the one in this study, i.e., €0.9–1.2/kg. The processing cost was higher in this study compared to the studies of Gu et al. (2016) & Keskisaari and Kärki (2018), which is explained by the more efficient processing methods of extrusion and injection molding.

Benefiting fully from filler materials requires optimization of product structure, taking into consideration the reinforcement ability of the filler. This is often not possible as products usually have volumetric requirements. The structure optimization is limited by the processing issues and it is not always possible to decrease wall strength according to property improvement. Products that can benefit the most from a better stiffness-density ratio are profiles where used material volume can be affected by changing the cross-section. However, this strategy is not usually possible if the part is compression-molded. The variance in the cost and quality of recycled material can negate the cost-effectiveness of implementation. The results present extreme cases where the material weight and the material price are either highest or lowest. The material price is the most important factor and the processing changes little due to variance in material weight.

4.5 Ecodesign and recycled material composites

The main benefit of using a holistic ecodesign approach such as EQFD combined with multiple criteria analysis is that it helps the designer to examine the environmental benefits in relation to functional design for better designs. Methods such as EQFD that take the voice of the customer into consideration throughout the development process are a good way to incorporate sustainability in the design process while keeping the market demands at the center of attention. The promoting factor in favor of recycled material composites in EQFD is the rate of recycled material but biodegradability, recyclability, and the mixing of material favor the homogenous virgin materials. The case is a bit different in ecodesign methodologies that are designed for sustainability improvements. The Ecodesign Strategy Wheel has eight categories related to sustainable design: the selection of low-impact materials, reduction of materials usage, optimization of production techniques, optimization of distribution systems (or logistics), reduction of impact during use, optimization of initial lifetime, and optimization of end-of-life systems (van Hemel and Cramer, 2002). Most of these can promote recycled material composite use, which can be low-impact materials if they are compared to many virgin plastics, as shown earlier in Figure 16, but not when compared to wood materials (Liikanen et al., 2019). The recycled material composite can reduce the amount of used material if we compare with commodity plastics such as unfilled HDPE or PP, as shown in Figure 20. For the optimization of distribution system purposes, there is no obvious promoting or demoting factors, as the use of composites does not always decrease the mass of a product or packaging. Conversely, the recyclable materials criteria found in most ecodesign methodologies can work against the goal, as the main contender materials are renewable wood and easily recyclable plastics. At the product innovation level of the Ecodesign Strategy Wheel, the alternative production techniques can in some cases support composite products, as some plastics production techniques are available that would not be with plain wood, and this might enable the manufacturing of shapes that contribute to a lower weight for the designed product. The use of recycled material increases the production steps, as the materials need to be pretreated before use, and this in turn reduces the potential environmental benefits gained from the use of recycled materials. At the product system level, the product and business-level design of composite can improve the reusability of the composite, for example in the form of take-back business model usage. Taking into consideration the long lifetime of construction sector products, the take-back system is not often realistic. Also, remanufacturing and refurbishing options are not viable as there is no substantial circulation of products in the system to keep the required option alive. The optimization of initial lifetime is the main reason that WPC products exist, as their endurance in outdoor applications compared to wood is the main reason for their popularity. The freedom of form with plastics processing enables the innovative use of shapes for a modular product structure that is easy to mount and disassemble, like in the case study product in Article III. The Ten Golden Rules by Luttropp and Lagerstedt

(2006) is generic advice for merging environmental aspects into product development. The rules function as general guidelines for development, and it is encouraged to modify the rules list according to the studied case at hand using the most relevant ones. The Ten Golden Rules have a similar emphasis as the earlier work on ecodesign but clearly advices not to use blended materials. As we have already established, the main material groups that recycled material composites compete with are wood and thermoplastics. TOPSIS and other multiple criteria analysis methods can further promote the recycled material composites if the technical criteria properties are higher than in the base plastic material of the composite matrix. In addition to the promoting criteria that were concluded in the case study, economic and environmental benefits can also be attributed to recycled material composites in two particular cases if additional mass is required or the increased stiffness of the composite can be utilized; see Figure 19 and Figure 20. This is however to be checked separately each time, as most of the time a certain volume of the part is fixed, and this can lead to increased costs in composite with the assumption that the price of the material and the processing is related to the specific density of the material. Multiple criteria analysis methods work quite well with recycled materials as the variation in properties is somewhat taken into consideration when the numbers are compared with the target, as the documentation should be checked after the final group of materials has been received as a result of the analysis. The customer preferences and functionality of the product mostly guide the product design, and even as the ecodesign criteria are incorporated in the design process, their relative strength in decision-making can remain small. Checklist methods can be rapidly compared to numerical analyses such as the EQFD ranking method, but this can also be deceitful as is it possible to compile them without taking a closer look at the handbook data. The use of ecodesign methodologies requires a great deal of information, which requires a more comprehensive approach from the designer.

4.6 Practical implications for the designer

Sustainable product design is a hot topic today and the use of ecodesign methodologies has been suggested to help designers in selecting greener materials. When estimating the suitability for design, recycled materials present a practical difficulty, which is the lack of design values. This puts the designer in an uncomfortable place in terms of responsibility. The properties are in turn easy to acquire with commercial virgin materials from the supplier data sheets. The data sheet in turn is the supplier’s declaration of its product (material), which the designers are inclined to trust; this is a connection that is hard to obtain with academic papers. A variety of studies have been conducted about recycled and other sustainable materials in composites. The focus has been on material properties testing and they often suffer from not going to the application level, which in turn could provide more credibility for their potential. In the case of insufficient information, the data extracted from handbooks and online databases can be used to estimate the results, but it does not provide a feeling of security for the designer as the material providers are not supplying this ‘hypothetical’ material. The results of the material tests depend on several factors such as material quality, pretreatment, processing equipment used, processing parameters, the interface compatibility of the matrix and the filler, the mechanical effect between reinforcement and the matrix, know-how of the tester, and so on. In studies, it is common to process the material with laboratory equipment, which might cause differences compared to industry-level volume-producing equipment. It is difficult to get a clear picture of the potential challenges caused by novelty materials when they are transferred to the production environment.

One obvious difference is that the recycled hybrid or composite materials are not available in the materials data banks, so just looking through the data banks or handbooks will never give the designer these materials as options. Therefore, it is quite natural to assume that the recycled composite materials solutions will be adapted only in those fields that are able to use composite mixtures that are very similar to the ones used in the industry, such as wood-plastic composites. Besides the properties, there are other more pressing issues when considering the adaptation of recycled material. The company needs to consider the sourcing of the material in a deep manner at an early stage of the product design, which affects the attractiveness of these potentially sustainability and cost effectiveness-improving materials.

Transportation distance has often been mentioned as a significant factor in terms of whether recycled material is ecological or not. It also has a great effect on how cost efficient it is to use them for processing factories. The gap where the price advantage in composites can be reached depends on the relative price of the virgin matrix and filler material. Product design can be used to influence manufacturing costs, which in turn can decrease or increase the price advantage gap. The factors affecting the additional costs have been addressed by Sommerhuber, Welling and Krause (2015), in the WRAP project, (2002), and by Hestin, Faninger and Milios (2015). A company willing to get involved in processing recycled material composites should be situated close to the recycled material suppliers. This makes the situation difficult for a designer, whose primary role is to design a product with materials that meet the functional requirements and that are suitable for the available supply chain. If the new design of a product were to apply the principle of 'circular material,' then the designer requires extensive information about the future uses of the applied material. The designer should also be aware of the gap where the cost and ecological advantages of the total system can be achieved.

In recent years, the safety of building materials has been a hot topic. Safety issues are also a cause for concern for some people because of the lack of studies about the potential emissions from the recycled material. There is still a lot of work to do in the field of health and safety, and the variety of different materials makes conducting comprehensive studies difficult. This is not an issue in practice, as the material supplier should be able to convince the buyer about safety issues and quality with product-specific testing procedures. The circular economy is increasing the knowledge requirements and widening the recycling business perspective to the field of material science. This transformation can prove to be difficult in industries, such as material handling plants and waste management, which now want to be reprocessors of plastics. The producer applying the recycled material can only collaborate with suppliers who are committed to the quality and supply reliability of the material. The suppliers play a key role in the search for new applications for these materials.

4.7 Advice for product design

The basic design aspects that a designer should know about with regard to the studied recycled material composites are summarized in Table 5. One should note that in addition to the studied properties in this study, the chemical composition and condition of the used recycled polymer type (He et al., 2015; Tsai et al., 2009) and filler materials also have an influence on the processing health and safety aspects of the materials. The safety aspect can be improved by using polymer and filler of controlled origin. The study by Félix, Domeño and Nerín (2013) examined the volatile compounds of WPC materials made with landfilled plastics and found no human safety compromising compounds. The processor, along with the material supplier, should make sure that safety during processing and while in use is ensured. Old recycled mineral wool filler would likely include urea-phenol-formaldehyde concentrations (Väntsi and Kärki, 2014b). Both phenol and formaldehyde are dangerous compounds that would be present in post-consumer mineral wool. In the case of gypsum waste filler, the recycled material should have stayed relatively dry to avoid dissolving into calcium and sulfate, causing problems with odor (Kijjanapanich et al., 2013).

Table 5. Design aspects of recycled material composites from CDW.

Design aspect	Commentary
Environmental aspects	Recycled material composite should replace a plastic product for it to have a positive environmental impact. One should be cautious of creating a parallel market with potentially more difficult materials to recycle.
Economic aspects	The potential economic advantages of utilizing post-consumer construction waste depend on the dimensioning and the end use of the product. One should always balance the potential benefit with the additional resources that the waste-derived material utilization requires. The volumetric price of unfilled recycled polymers is cheaper.
Mechanical properties	The use of construction waste-derived fillers does not increase the stiffness of the plastic matrix enough for it to have radically new applications outside the normal application of polyolefins. The modulus is at best similar to what is required in WPC solutions. Strength and impact strength are significantly reduced compared to base plastic, which limits the use in many cases.
Physical properties	The use of mineral fillers increased the heat built-up compared to WPC solution and recycled HDPE. The natural fiber fillers increase moisture absorption and thickness swelling of the base matrix material.
Sensory perceptions	As it is likely that recycled plastic is of a darker color, it is likely that mineral fillers form visibly lighter areas on the surface. The smell of the composite depends on the quality of the used material, here organic content should be

	minimized that is often present in post-consumer plastic waste. The sensory properties can be improved by surfacing the material, for example by co-extrusion or by using additives (which is limited due to increase in processing cost).

The potential application sectors in which the studied composite types could be considered based on the study are summarized in Table 6. The traditional WPC solutions such as decking and cladding are good options. A recent study by Basalp et al., (2020) suggested the manufacturing of furniture and packing for food products from a recycled material WPC. Recycled CDW wood and plastics can be used to make products for this sector. There is also decades of studies behind WPC materials, which helps a producer in considering these applications. The mineral filler composites could be used to make components for a polymer decking system, which is where their better moisture resistance compared to wood should be used. Composites with mineral fillers are not good for making decking components that are in direct contact with people because of higher heat-built-up compared to WPC solutions; see Figure 15. Pallets and packaging are possible solutions for the studied materials. A study by Soury et al. (2009) demonstrated a design optimization of a logistics pallet made with WPC material. Their study used mass and deflection as parameters to obtain the best I-profile shape for the pallet beams. Beams and profiles require extrusion processing to be used. The composites with mineral filler could be used instead of WPC as there would not be a similar risk of insects and mildew due to organic wood. The elastic modulus of the WPC in the study by Soury et al. (2009) is comparable to that tested in this study; see Figure 11. Elastic modulus of composites. The packaging of consumer goods is difficult for waste composites due to hygiene and their appearance. Sound barriers are potential applications for waste-derived WPCs as there is vibration damping effect in adding wood filler to polyolefin, as the material modulus increases (Santoni et al., 2018). Sound barriers are often used next to highways and are subjected to sunlight and weather but can be quite rough-looking. The composites with mineral fillers could resist moisture more effectively than their WPC counterparts. Casing and containers that are typical polyethylene applications are not particularly good for composites, as the volume filling parts are cheaper to produce with unfilled or foamed polymers in high-speed processing machinery. It is better to make profiles with extrusion, but compression molding can be applied in some cases when more complex geometry and smaller dimensions are needed.

Table 6. Potential applications of CDW-derived composite materials.

Application	Commentary
Decking, tiles, cladding	Mechanical properties are comparable to WPC solution, especially when proper compatibilizers are used. Wood is best of the tested CDW-derived fillers for decking. Quality of the plastic and the used UV-protection are the most important factors when composites are made for outdoor building. Cladding could be a potential application for waste-derived composites once the fading and long-term endurance of elements is tested. Mineral-filled composites have better moisture resistance than WPC counterparts.
Pallets and packaging	Logistics applications are possible but should be designed for circulation in the same way as plastic pallets. Single-use-only packaging would be more detrimental to the environment than a wooden pallet. The limitations and variation that the recycled material places on hygienic and sensory properties limits use in consumer packaging solutions.
Sound barriers	Porous natural fibers and mineral fibers have good sound absorption properties. When compressed into plates with resin, the damping effect decreases. Natural fiber composites perform better at high frequencies (Zhu et al., 2014). The use of mineral fillers increase the stiffness of the plastic and increase the sound transmission loss in the plastic (Liang and Jiang, 2012).
Casing, covers and containers	Volume-based solutions are better with low density materials with a good strength-to-weight ratio. Composites with waste-derived fillers have significantly lower tensile and impact strength than their base polymer matrix, which are usually important properties in protective cover design.
Profiles	In most cases not an optimal thing to do with compression molding. With extrusion the effective utilization of recycled materials in composites is easier to do. Compression molding can however be useful to make fixing parts for profiles made with extrusion.

Ashby charts can be used to compare recycled material composites to other materials. When Young’s modulus (see Figure 21) and tensile strength (see Figure 22) are charted with the material densities, it is possible to evaluate the suitability and compare materials quickly. The recycled material composites fall within the polymer category and have similar properties with commodity plastics such as polyethylene and polypropylene. The position of CDW composites in the material chart demonstrates that although the material has higher Young’s modulus, it is still not high enough to radically change the range of applications from the mechanical property point of view. Also, relatively cheap foamed polymer materials have a wider range of construction material applications, especially when sandwich structures are utilized. Foamed polymers also have advanced manufacturing technologies available that help to reduce the costs of processing.

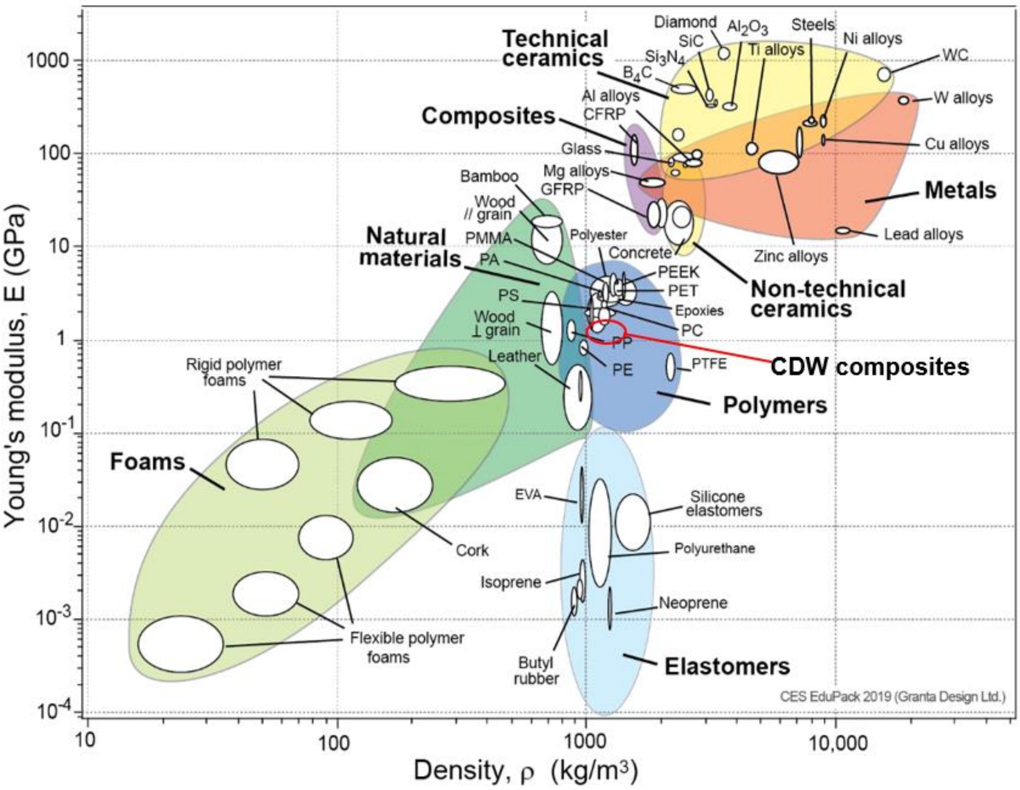

Figure 21. Ashby chart for Young's modulus (chart created using CES EduPack 2018, Granta Design Ltd.).

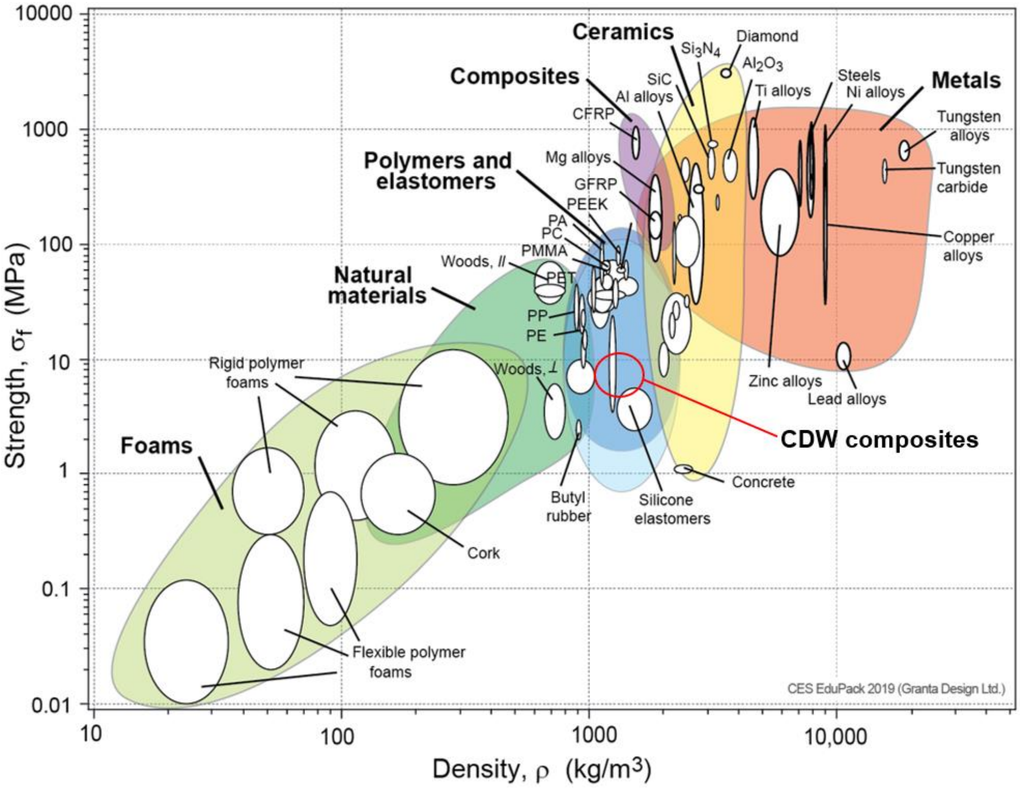

Figure 22. Ashby chart for Tensile strength (chart created using CES EduPack 2018, Granta Design Ltd.).

Figure 21 and Figure 22 help to visualize the recycled material composites in the big picture in the materials selection field. Figure 23 to Figure 26 help in the selection process for product design. The left side of the solution frontier line shows the preferable options for the compared parameters. For example, in Figure 23 solution SC60 is preferable to virgin PP, because of the higher Young's modulus and lower emissions of SC60 production. Note that there is a variation to all the plotted materials that represent material average values.

Figure 23 plots the Young's modulus and the GWP per liter of the studied composites with materials they are likely to compete against established by looking at the Ashby charts in Figure 21 and Figure 22. The optimal solution group can be seen in the left side of the solution frontier, assuming that these properties are good enough for the application under consideration. Wood seems to be the best material, taking into consideration the much lower emissions from material production compared to polymer solutions. Next are composites NFF60 and SC60.

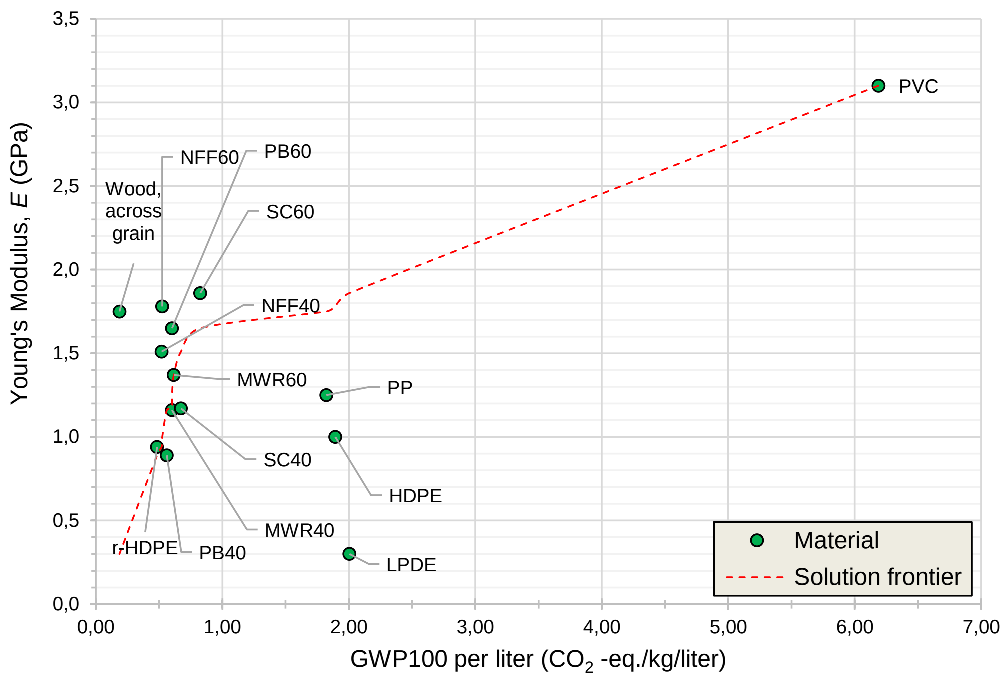

Figure 23. Global warming potential of production plotted with Young's modulus.

Figure 24 plots Young's modulus of materials with their cost per liter. The group of optimal solutions are the same as in the previous figure. Wood is still the best of the compared materials. The composite MWR60 slightly improves its standing due to its low cost. The next best solutions are NFF60 and SC60. The differences in mechanical properties are small and in practice using the cheaper solution is wiser. The mechanical properties can be improved by optimizing the use of compatibilizing agent.

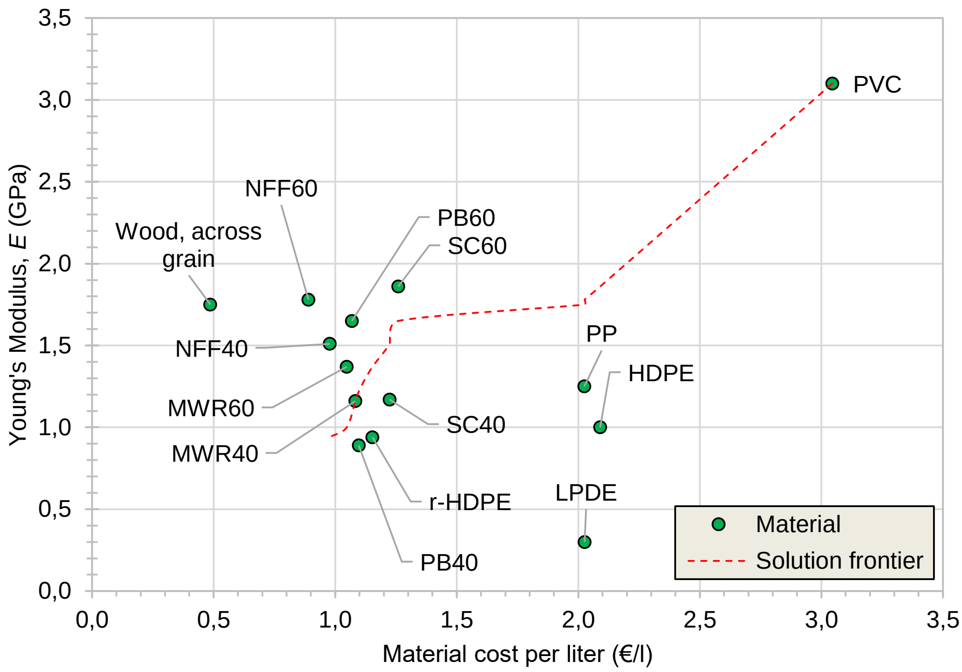

Figure 24. Material cost per liter plotted with Young's modulus.

Figure 25 plots the ultimate tensile strength of the studied materials with the measured moisture absorption. Not surprisingly the polymer should be left unfilled with waste filler if good strength is important for the application. The wood plastic composites NFF40 and NFF60 perform much more weakly compared to mineral filed composites, now that their hydrophilic properties are taken into consideration. SC60 is still on the left side of the solution frontier due to its good moisture resistance. Note that the composite materials close to 0% moisture absorption perform in practice the same way.

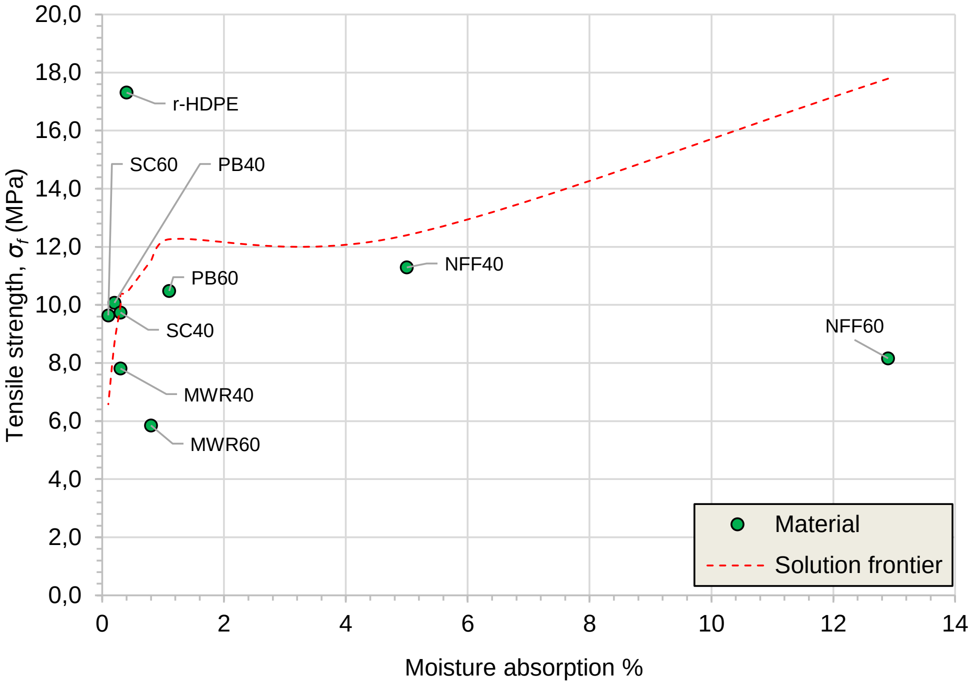

Figure 25. Moisture absorption plotted with ultimate tensile strength.

Figure 26 plots the Young's modulus and moisture absorption of the composites. When the stiffness of the material and moisture resistance are important, the best solution is SC60. SC60 has a higher modulus than NFF60 and is well resistant to water; however, it is much heavier than NFF60 and is significantly more expensive to produce. In our study the stone-cut waste was soapstone, which consists primarily of talc and magnesium carbonate in almost equal quantities. Lamellar mineral fillers such as talc are known to reinforce polyethylene, thus improving rigidity (Karrad et al., 1998). Magnesium carbonate and talc also are reported to improve the fire retardancy of polyethylene composites (Bellayer et al., 2011).

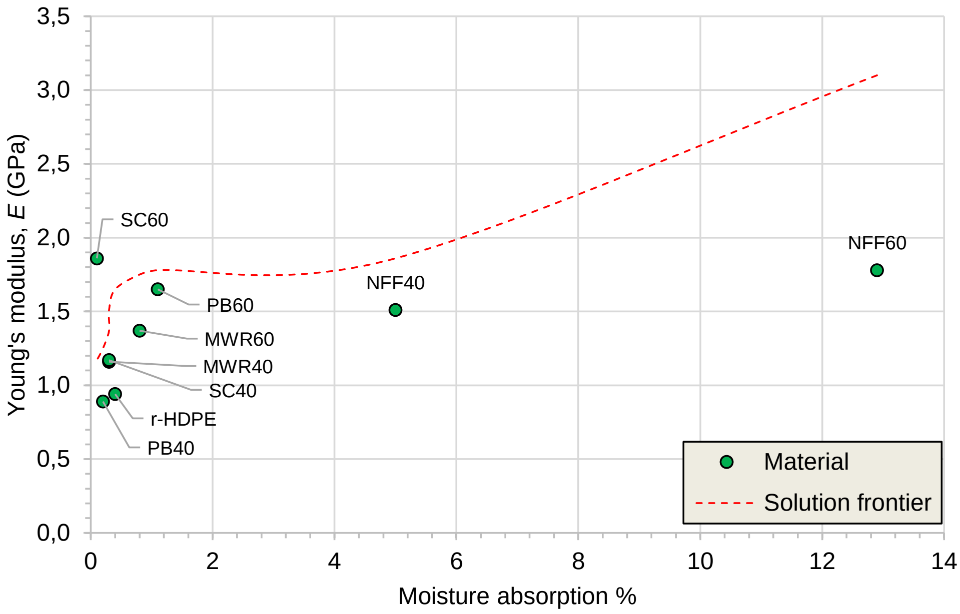

Figure 26. Moisture absorption plotted with Young's modulus.

5 Conclusions

This doctoral dissertation focuses on the factors affecting the material selection process of composite material made of recycled CDW materials. The technical properties, cost-effectiveness, carbon footprint, and compatibility with ecodesign principles of thermoplastic composites made from construction waste by compression molding were investigated. This work presents the first study in the design process for thermoplastic composites made from recycled construction and demolition waste materials. It combines aspects of engineering design, materials science, production economics, and waste management to form an overall picture of these materials from designer and partly processor perspectives. The results sections, which are intended for designers, help interested parties to quickly assess the suitability of materials for their product applications, taking into consideration the principles of ecodesign and more product specifics. Property measurements for compression-molded composites help to compare the differences between the manufacturing processes of plastic products, which for these materials means extrusion and compression molding. The materials are also mapped in a broader framework, which is usually forgotten in materials testing studies. This reminds us that materials are contesting between each other and for a novelty material to be successful, it should expand the material family with properties previously not accessible. The results can be generalized in many respects to thermoplastic composites filled with recycled post-consumer waste material. Composites made of recycled reinforcing fiber (such as carbon fiber) differ from those presented for their potential applications, properties, and processing cost.

In previous studies the lighter CDW materials such as wood, plastic, gypsum, and mineral wool have been made into composites with either plastic or gypsum matrix. Composites with commercial potential have been achieved by using recycled plastic and wood to make wood plastic composites. To some extent the thermoplastic composite properties suffer from the use of recycled material that has been modified by their life cycle and the recycling process. The challenges of using CDW are related to the safety and quality variance of end-of-life materials caused by the life cycle and local conditions of the built environment. Lighter CDW fractions require versatility from the recycling process and do not guarantee total purity of material. Impurities and sometimes the chemical content limit the use of waste material composites in food and water packaging, and many products in direct human contact. The technical challenges related to processing are for the most part the same as with virgin thermoplastic composites with reinforcement (interfaces, reinforcement dispersion, the force distribution mechanisms). Challenges in processing include the availability of material (especially good quality recycled plastic), degradation of plastic, agglomeration of filler material, heating costs, recycling costs and pre-processing costs, selecting the right additives, lack of experience of operators, quality control and material related variance, and health and safety issues. From the point of view of effective material circulation, it is best to use post-consumer waste fractions that do not have efficient closed loop recycling processes such as wood, plastic, and mineral wool.

At the product component level, the main supporting ecodesign criteria for composites is the use of recycled material and avoided global warming impact if virgin plastics are replaced. Ecodesign criteria, such as the use of lower energy content materials, renewable materials, and recyclable materials work against composites, as the main contenders are renewable wood and easily recyclable thermoplastics. The principles of ecodesign support the use of waste-derived composites when they can safely and cost efficiently use material that would otherwise end up in landfill.

The main reason for using cheap waste-derived fillers is to improve the stiffness of a commodity plastic such as PE or PP. A higher fill rate is advisable as it means better elastic modulus, ensuring that the density does not increase too much for the application. The recycled fillers improve the tensile modulus of the recycled HDPE but decrease impact strength, tensile strength, and elasticity. The composites with mineral fillers had better resistance to moisture compared to WPC samples, which would be beneficial in outdoor applications. The heat built-up in composites with mineral fillers was higher than in those with wood, which means that natural fibers are still a better option for producing decking products. Stone-cut waste (soapstone) filler was the best option for wood of the studied materials if the application requires stiffness and moisture resistance. The climate change impacts of producing 1 kg of composites ranged between 0.44–0.51 kg CO_2-eq. The environmental potential of composite manufacturing is significant when it replaces the use of virgin plastics. The economic potential of CDW composites depends on the type of product. In volume-based applications, recycled wood filler is the most efficient filler material of the studied group and it has lower cost than unfilled recycled polyethylene. In applications where mass is important, composites with 60% mineral filling (by weight) offer the most cost-efficient solution of the studied group; however, the decrease in cost is relatively small in comparison to wood filling. As a result, using wood filler is less risky for the manufacturer, as WPC solutions have a long use and production history.

The limitations of the study are related to the composite processing method and the cost calculation section of the study. The focus on the material properties achieved with one processing method is a slight limitation, as extrusion processing would often be better for the studied materials. The compatibilizing agent used was optimized for wood, and changing it to something more compatible with other waste fillers would improve the properties of those composites. The production economics sections focused only on the direct costs and did not consider the investments related to this type of production. These factors have an influence on the achievable properties and economic benefits of recycled material use.

Further studies are needed to better understand designer attitude, cultural bias, and behavior related to recycled materials. It would be useful to study in detail the investments needed for the manufacturer to use waste material to better understand production economics, and the possible business models between the recycler and user. The chemical coupling of different phases in the material have major effect in the composite properties, therefore, future work should include development of cost-effective coupling technology for the investigated materials.

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Appendix A: Additional tables

Table 7. References for benchmarked materials used in Figures 23–16

Material	Young's modulus	Tensile strength	Cost €/kg	GWP100 LCA Datasets
Wood	Ashby, (2017)			Finnish timber EPD
Polypropylene (PP)				DE: Polypropylene granulate (PP) mix ts
HDPE				RER: Polyethylene high density granulate (PE-HD) ELCD/PlasticsEurope <p-agg>
LPDE				RER: Polyethylene low density granulate (PE-LD) ELCD/PlasticsEurope <p-agg>

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Recycled construction and demolition waste as a possible source of materials for composite manufacturing

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ABSTRACT

Although the reuse of demolition wastes has been studied in recent years, their reuse in composites has not been thoroughly examined. This study aims to provide a comprehensive literature review pertaining to the possibilities of using recycled construction and demolition waste in composite manufacturing. This study is focused on investigating the use of recycled wood, paper, cardboard, metal, glass, mineral wool, gypsum, concrete, and ceramics as raw components for composite materials. The composition, contamination, degradation, and recycling of construction materials is discussed to explain potential challenges for composite material manufacturers. Most of the research relating to recycled construction and demolition materials have been conducted on thermoplastics combined with cellulose-based fibers. However, mineral wool and gypsum have also been utilized. The use of recycled materials as matrix, filler, or fiber tends to result in the production of materials with weaker mechanical properties compared with virgin materials. Entities who utilize construction and demolition waste should take into consideration possible contaminations so as to prevent the spread of harmful substances. Because investigations on the economics, carbon footprint, and practicality of production have been scarce, definitive conclusions on the potential use of recycled material composites cannot be made. It was found that the most promising recycled construction waste materials for composites were thermoplastics, mineral wool, gypsum, and wood.

1. Introduction

The current legislative pressure pertaining to waste materials in Europe reinforces the need for identifying new uses for previously discarded construction and demolitions wastes as recycled materials. Their use as components of composite materials could be a means to mitigate problems that arise when recycled materials with lower properties are used. Currently, construction and demolition waste (CDW) is among the largest in EU, estimated to be 25–30% of all generated wastes [1]. The EU waste directive 2008/98/EC requires member states to recycle 70% of their non-hazardous CDW as raw materials by 2020. However, the current recycling rate is only approximately 46% [2–4]. The expansion of end-user products and material markets remains as an ongoing challenge for marketers of recyclables. The challenges involved are those associated with inadequate information on recycled products, such as negative perceptions about them, their unexpectedly high cost compared with virgin materials, and considerably conflicting information on their availability, durability, qualities, and functionality [5,6]. Several reviews focused on CDW recycling and separation [7,8], availability [9–11], economics of recycling [12–14], life-cycle analysis [15,16], management [8,17], research trends [18,19], and benefits of circular economy [20,21] have been conducted. Additionally, although the reuse of CDW, especially in concrete [22,23], has been studied in recent years, material reuse in composites has not been comprehensively examined. New material uses for recyclates are needed to meet the objectives of recycling and reuse by 2020. Composites offer an opportunity to use and combine recyclates into products with new properties. The main aim of this review is to study the possibilities of using common construction and demolition waste materials in composite manufacturing. The composition, contamination, degradation and recycling of construction materials are discussed to explain potential challenges for composite material manufacturers.

2. Methodology

A literature review is a systematic, comprehensive, reproducible plan to identify, evaluate and synthesize the existing body of literature produced by researchers [24]. Thereafter, the review is followed by an in-depth analysis of the state of the art to identify topics for further

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study. This study focuses on a comprehensive literature review of the possibilities of using CDW materials in composite manufacturing as filler and reinforcement or as matrix. The methodology follows a narrative review structure [25]. The materials selected for further examination represent a substantial volume of waste resulting from demolition and construction activities around the world. The studied waste types are also often source separated on site. In order to discuss the potential of CDW in composites a literature research was carried out using the Google Scholar search engine and the databases ScienceDirect, Web of Science, Taylor & Francis, Research Gate and European Commission LIFE Programme. Supplementary reference material was used to estimate the effects of recycling on the materials, economics and environmental impacts of recycled materials in composites and the processing aspects. Boundaries of the literature review were established to identify the papers for further inspection. The validity of a selected literature was determined based on the analysis of the title, methods, materials, and abstract of the research paper, after which the non-relevant studies were excluded. Papers focusing on the use of recycled CDW aggregates in concrete were discussed only shortly as they have already been studied and reviewed extensively. Five criteria were prepared in order to establish whether a material was relevant to the study. The selected papers must satisfy at least one of the criteria or complement the discussion with further details:

i. This review aimed to identify papers pertaining to composites made with the following materials: thermoplastics, wood, paper and cardboard, metals, glass, gypsum, mineral wool, and inert materials, including concrete, ceramics, and stone. The manufacturing methods in the scope of this review were extrusion, molding and casting.
ii. Recycled materials could be present in the composite as matrix, fiber, or filler. At least one of the materials should be from the aforementioned list and applicable to CDW.
ii. The process on CDW recycling was discussed in order to explain the preprocessing requirements for recycled materials.
iv. The degradation of construction materials during their lifetime, environmental impact, and recycling process were considered to highlight potential challenges manufacturers of composites might encounter in their use of CDW recyclates.
v. This review is focused on what is commonly referred to as open-loop applications for recycled materials. In closed-loop applications, the use of each material is listed to show the competing applications for the same material.

The division of references used in this review can be seen in Fig. 1. The division of case studies by material is presented in Fig. 2. Data about the use of recycled thermoplastics and wood was plenty as wood plastic composites have been produced for a long time. As expected there was no data examples found of using recycled metals in composite extrusion, molding or casting. Glass material was often mentioned

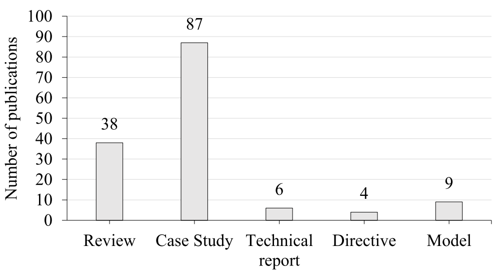

Fig. 1. Number of publications per type.

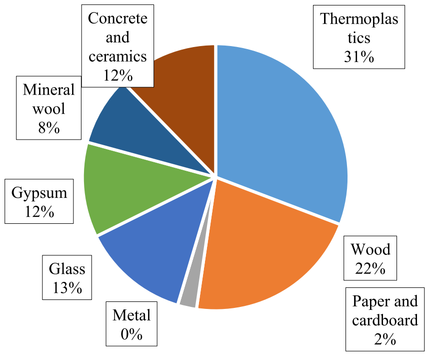

Fig. 2. Division of case studies by material.

when looking for CDW related studies, this due its use in the studies as filler for concrete. Similarly studies about using concrete and ceramic waste as filler for new concrete were found plenty but they were out of the scope of this study.

3. Construction and demolition waste

By volume, CDW consists of concrete, tiles, ceramics, wood, glass, plastics, bitumen, metals, stones and soil, dredging spoil, insulation materials, cardboard, gypsum-based products, electronics, and packaging materials [26]. Construction waste is regarded as containing lesser contaminants than materials from demolition activities do. Construction waste consists mainly of cut-outs, concrete molds, packaging, scrap, and unused materials [26]. Although construction waste has not been subjected to environmental conditions or bonded with other materials, this benefit is easily lost if separation is not performed on it (refer to the example in Fig. 3). Source separation is the best way to facilitate the entry of waste into recycling. Moreover, it is necessary step when the upcycling of waste would be possible, and contamination because of material mixing is not acceptable. Pre-demolition audits helps to identify CDW generated and implement proper deconstruction so as to improve the quality of materials for recycling [27]. The use of building information models (BIM) could improve the deconstruction process, recyclability, and reuse of materials in the future. Detailed data pertaining to installed components, including composition, physical properties, exact location, geometries, installation dates, occupancy history, hazardous material information, and potential recycling and disposal options could be inputted to BIM files [28,29]. The commonly source-separated CDW includes concrete, tile, flagstone and ceramics, gypsum-based products, untreated wood, metal, glass, plastics, paper, cardboard, and earth and mineral waste [30,31]. Hazardous waste are to be separated, as otherwise, they will contaminate non-hazardous materials. Prior to sending CDW to a material handling facility, it is usually stored outdoors in open spaces exposed to rain, snow, heat, cold, and dust from the surrounding work site and environment.

The typical procedure for CDW acceptance and processing in a material handling facility is presented in Fig. 4. The waste is evaluated and weighed upon arrival, and sorting and processing are performed with a variety of systems, depending on the material flow and designated use of the recycled waste. The volume of each waste fraction depends of the geographical location of the building, its architecture, construction culture, as well as the construction year of the building, considering that different construction materials were popular during certain periods of time. Table 1 summarizes the case studies presented in literature pertaining to amounts of waste materials from demolitions. Different types of inert materials, such as stones, concrete, mortar, tiles,

Fig. 3. Non-separated CDW in a material handling facility A) renovation waste and B) new building waste (with permission Ronkanen [32]).

and ceramics are emphatically represented in CDW because of their use in heavy structures.

4. Potential of CDW materials for composites

Composites are used to achieve properties, such as higher mechanical properties, environmental endurance, lighter weight, and maintenance-free use, which are otherwise unattainable with the use of singular materials [36]. In composites, the matrix material is combined with fiber or filler with the goal of improving the mechanical or other functional properties. The properties of a composite material depend on the details of its structure and adhesion between the fiber and matrix. The fiber length and orientation have a critical influence on the mechanical properties of composites [36,37]. After the required mechanical processing, fibers or particles available from recycled materials tend to be short, consequently, limiting their reinforcement properties. In the context of CDW materials, their use in composites could be a means to improve the usability of recyclates, whose properties alone are inferior to those of virgin materials. Composites from typical CDW materials are often produced by extrusion, molding, or casting. Thermoplastics and gypsum have been used as composite matrices. Material preparation methods involve the crushing and milling of recycled fractions into smaller particles (see the example in Fig. 5), and further processing of recyclates depends on the type of material (see Sections 4.3–4.10).

Despite legislative pressure for circular economies, the use of CDW as a material for new products is hindered by the vagueness surrounding the end-of-waste status, and the absence of harmonized standards and waste classifications. Without clear guidelines and procedures, waste management organizations have difficulties estimating the contamination grade of waste particles, making post-processing difficult [26]. The number of controllable variables increases when recyclates are used in production. The raw material quality should conform to a set of standards established by the user and respective authorities interested in activities under the end-of-waste legislation. Because hazardous contaminants should be blocked from processing, the origin and preprocessing of recyclates need to be monitored carefully. This is relevant for occupational health and safety reasons, as workers handling CDW could be subjected to risks otherwise confined only in the material handling facility [38,39].

Besides the effect on material properties as well as on possible emissions, the influence of recycled materials on odor and other sensory properties of the end-product should be tested by the manufacturer. The use of filler can have a significant impact on the visual look of the product see Fig. 6. Masking unpleasant odors originating from recycled raw materials is not always possible even with deodorizing agents. Consequently, the end uses of the composite product become restricted. The odor is dependent on the material composition, contamination, and processing temperatures. In some cases, the effect of the composite manufacturing process has reduced the concentration of volatile organic compounds (VOCs) [40].

Improving source separation, selective demolition, and recycling processes to extract purer materials, and developing testing methods and acceptance criteria for waste could reduce VOCs and odor-related problems. Mixing recyclates with virgin materials offers the possibility of raising material quality and is a common practice when recycling thermoplastics, metals, paper, and glass. The technical requirements set by the EU harmonized product standards are the same for products made of CDW and virgin materials [27]. A possible process for manufacturing composites containing CDW is presented in Fig. 7.

4.1. Potential environmental impacts of composites made of CDW materials

One of the main objectives in developing composites from recycled materials is to reduce the carbon footprint of products. Although technical properties of composites made of recycled materials have been studied over an extended period of time [41–48], reports on the life-cycle analysis of composites made of recycled materials are limited. Iacovidou et al. [49] conducted an extensive review of resource recovery from waste metrics measuring benefits and impacts in environmental, economic, social and technical dimensions. Unfortunately this type of methods are often not used in studies focusing in the technical aspects of recycled material use in composites. Generally the transportation distance for wastes has had a major influence on the total energy consumption, costs, and environmental impacts of recycling strategies [50,51]. In certain cases, the use of recycled plastics has improved the positive environmental impacts of the use of composites [52]. Väntsi et al. [53] studied the environmental impacts of the wood-plastic composite (WPC) made of recycled polypropylene and mineral wool (MW), comparing it with WPC products made of virgin plastic, wood, and glass fiber (GF). The MW performed environmentally better than GF in applications where properties obtainable by the use of MW are required. Sommerhuber et al. [54] assessed the life cycle stage of raw material supply and end-of-life pathways of WPC. Producing WPC from recycled wood and thermoplastic was ecologically a better alternative to production using virgin WPC. The environmental benefits

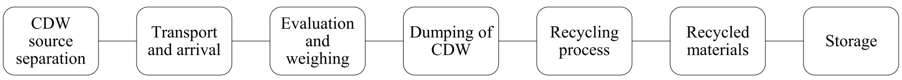

Fig. 4. Procedure for the acceptance and processing of CDW in a material handling facility (adapted from Silva et al. [11]).

Table 1
Case studies of waste generation in demolitions and renovation activities.

Type of building: Activity: Location: Wastes	Military camp Demolition[a] France % wt	Block of flats Demolition[b] Italy % wt	Housing building Renovation[c] Portugal % wt	Service building Renovation[c] Portugal % wt
Concrete, bricks, tiles, ceramics, mortar, stone and soil	70.91	91.56	92.43	90.19
Metals	3.26	3.73	0.81	1.44
Glass	0.59	0.10	0.18	0.13
Mineral wool	6.17	0.18	–	–
Gypsum-based waste	3.02	4.09	4.25	5.21
Plastic waste	0.48	0.24	0.03	0.24
Paper and cardboard	–	–	0.29	0.60
Wood	10.02	0.11	1.70	1.70
Other mixed materials	5.57	–	0.30	0.40

Some waste types in the studies were combined for the purpose of comparison
[a] Roussat et al. [33], some waste types combined.
[b] Blengini [34].
[c] Coelho and de Brito [35].

depend on the formulation of the composite and required waste processing methods. A high filler content in composites decreases the relative environmental impacts gained by using recycled polymers [52–54]. The recycling of composites remains as an economic, environmental, and technical challenge because of the interlinking of materials [54]. The use of locally sourced recycled material can have positive environmental and social impacts in countries with insufficient waste management practices. One example of this is the manufacturing of composite bricks from sand and plastic waste which otherwise would be abandoned in the street causing adverse impact on public health and environment [55].

4.2. Potential economic impacts of composites made of CDW materials

To the best knowledge of the author, there were only a few studies conducted on the potential economic impact of manufacturing composites with recycled materials. Coelho and de Brito [56] studied the economic viability of the CDW recycling plant, considering location, materials, technology, and economic impacts. However, their study did not cover economics on the part of the recycled material user. The economic benefits of recycled materials in composite manufacturing depend on the producers place in the supply chain and the required amount of material processing. The transportation distances of low-cost recyclates should be minimized, as otherwise, the cost structure of

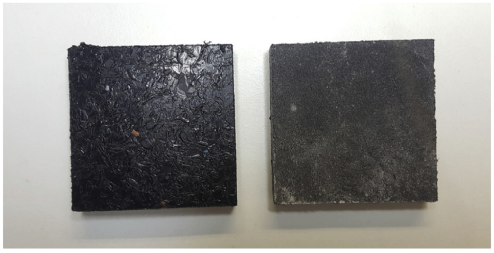

Fig. 6. Recycled gypsum powder is used to change color of the recycled plastic (LUT University).

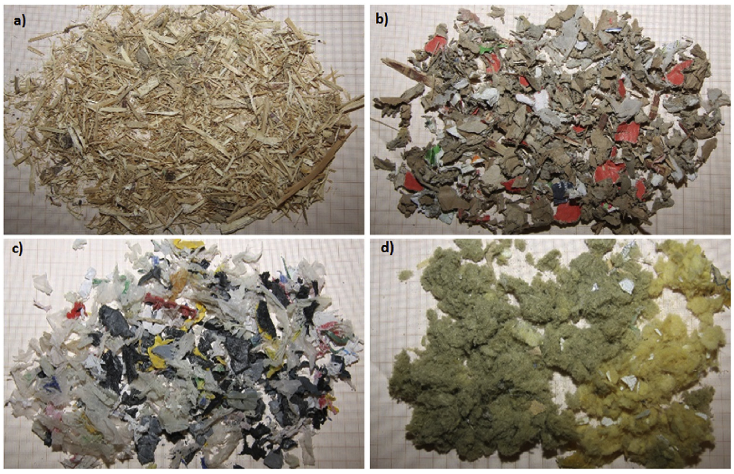

Fig. 5. Crushed CDW materials a) wood, b) cardboard, c) plastic and d) mineral wool. Notice the contamination of samples by other materials because of insufficient separation (with permission, Ronkanen [32]).

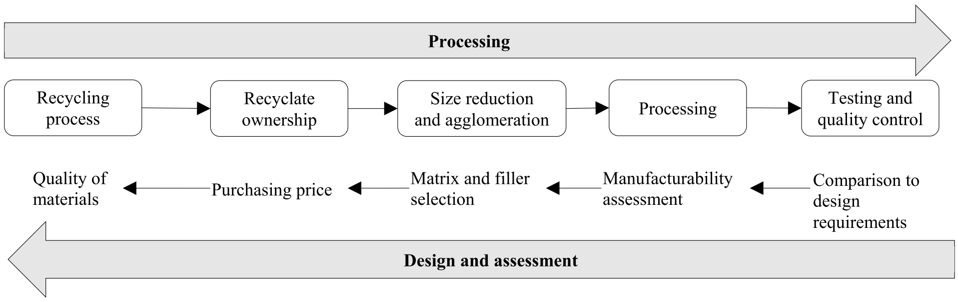

Fig. 7. Manufacturing process of composites from recycled construction and demolition waste.

products made from recycled materials might lose their major competitive advantage [5]. A study by Sommerhuber et al. [54] raised interesting potentials on the use of recyclates as replacements. The amount of the recycled thermoplastic produced yearly solely from post-consumer packaging in Germany could satisfy the need of the entire WPC production in that country. From the perspective of demand, the wood requirement in the WPC industry is only 1% of the material consumed by the wood-based panel industry. The additional processing of waste into a useable form, specifically sorting, grinding, drying, and sieving increases the end cost of an otherwise cheap material, but it does not necessarily have significant effect in the total manufacturing price [14]. The economic feasibility of using CDW in composites depend on the material for example the use of recycled wood in WPC is still questionable because of the small price difference between this material and competing products [54]. In the case of CDW, the processing cost consists of transportation, distance, sorting, quantity of waste generation in the area, economy of scale, price of raw materials, and tipping fees [13,57]. Additionally, the materials should undergo size reduction, cleaning, quality inspections, and agglomeration, which further increase the total cost. The relative quantities of the materials in the composite have an impact on the total price. Usually high filler content of recycled material decreases the material cost in thermoplastic composites, as the relatively expensive plastic is replaced [14]. The environmental and economic sustainability of implementing CDW can be summarized as the combination of the inclusion of the design stage, adoption of selective demolition strategies, building type, material type, building element type, location of the user from the construction site, scale of recycling plants, presence of markets, presence of secondary material resellers, secondary material quality, company business model, and economic and political contexts of investigated cases [20,21].

4.3. Recycled CDW thermoplastics for composites

The use of plastics sourced from landfills and material recovery facilities is uncommon compared to the use of cleaner industrial by-product plastics. Accordingly, the research on CDW plastics as raw materials for composite production is also scarce, although there should be fewer problematic organic residues in these materials than in municipal waste. The lack of knowledge on changes in the properties and quality of recycled plastics under different stages of degradation, mixing, and contamination is a major drawback on the use recycled polymers [58]. The construction sector has used plastics for a wide range of applications because of their durability, strength, corrosion resistance, low maintenance, and aesthetic finish. The typical products include profiles, coverings, insulation materials, cable sheeting, roofing, waterproof applications, composites, pipes, and ducts [59]. The common construction plastics include polyvinylchloride (PVC), expanded polystyrene (EPS), high-density polyethylene (HDPE), polypropylene (PP), low-density polyethylene (LDPE), polystyrene (PS), and others at 58, 9, 8, 4, 3, 1, and 17%, respectively [60]. Numerous additives and chemicals have been used in plastic production during the time that plastics have been adopted in the building sector, several of which are nowadays discerned to be harmful to people and the environment. These additives can eventually contaminate the products, where they might be harmful or banned altogether. The effects of recycling, degradation, and composition of plastics should be considered before reusing these materials (see Table 2).

Often the plastic material from a recycling plant is a mixture of homopolymers. Because of the technical limitations of recycling facilities, the structure of the products consisting of different plastics often make the full separation of these components practically impossible [69]. Fig. 8 shows the typical stages of the mechanical recycling of plastic. In the first stage, the plastic waste is shredded into small sizes for further processing. Washing the plastic with water or cyclone cleaning is required to separate the dirt. Usually, CDW plastics are

Table 2
Possible disadvantages of using recycled CDW plastics.

Thermoplastic	Common additives	Disadvantages	Sources
Polyethylene (LPDE, HDPE)	Colorants, flame retardants	PE and PP have similar densities, making mechanical separation difficult; Increased MFI.	[58,61]
Polypropylene (PP)	Antioxidants, colorants, flame retardants	Recycled PP has been shown to exhibit a greater crystallization rate and higher crystallinity than virgin PP, because of the chain scission in reprocessing; Increased MFI.	[58,61,62]
Polystyrene (PS/HIPS)	Colorants, flame retardants	Fire retardants might pose a risk of contaminating the other recycled plastic; Increased MFI.	[58,63]
Expanded polystyrene (EPS and XPS)	Flame retardants, colorants, blowing agents	Because of the low density of EPS products, the economic benefits of their recycling suffer due to high transportation costs; Expanded polystyrene breaks up easily during demolition and entangles with other wastes; The use of fire retardants pose a risk of contaminating other plastics in recycling.	[63,64]
PVC	Colorants, plasticizers, stabilizers, flame retardants, lubricants	Primary recycling is often not possible from post-consumer waste, because of hazardous additives in the PVC; Increased MFI.	[58,65–68]

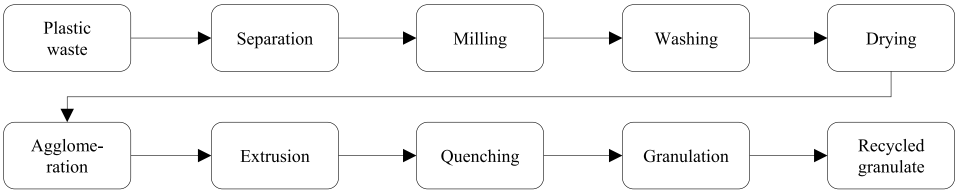

Fig. 8. Mechanical recycling of plastic (adapted from Aznar et al., 2006).

mingled and separation is required. In practice, considerable separation purity is achieved by employing the combination of near-infrared spectroscopy sorting with other plastic sorting technologies [70]. Systems designed for extracting specific plastics from known plastic mixtures have been reported to achieve yields of over 95% [71]. Sorted fractions with 90–95% purity are further upgraded with pure polymer before reprocessing. The plastics polyethylene, PS, PP, and polyethylene terephthalate are difficult to separate mechanically because of their similar densities. Consequently, the mingling of plastics with different qualities can be expected when handling a large variety of plastic materials [70,72]. In the agglomeration phase, pigments and additives are incorporated, after which the plastic is sheared into strands and pelletized by extrusion [73].

Polymers are mostly immiscible, and therefore incompatible for blends [61]. Such immiscibility can significantly affect the mechanical properties of polymer pairs [74,75]. Recycled plastics are obtained from various sources and exposed to different storage and reprocessing conditions. Accordingly, they may perform differently depending on their levels of degradation and mixing [61]. The environmental conditions in use need to be considered as UV radiation and hygrothermal ageing effect the mechanical and surface properties of thermoplastic composite [76]. In mingled thermoplastic systems with filler contents, components have dissimilar elastic properties, and stress concentrations develop around the heterogeneities upon loading [77]. The bonding of reinforcement fibers to the matrix should be improved to the extent that fiber fracture becomes the dominant deformation mechanism. Poor interfacial bonding between the fiber and matrix leads to microcracks when the material is mechanically stressed. These cracks easily propagate into the composite material [78]. Often, in materials with higher fiber contents, the adhesion between the plastic and filler fiber is compromised. Subsequently, testing with different filling rates is necessary when new composites are designed. The use of coupling agents improve the interfacial adhesion between the filler and thermoplastic matrix [47,77]. Coupling agents and compatibilizers can also compensate for the negative effects of polymer blending. Compatibilizing is affected by the ratios in which different polymers are mixed. Therefore, the recycled plastic feed stream itself has to be fairly consistent for compatibilization to be effective [74,79–83].

An important phenomenon that occurs in polymer matrices is their degradation because of high temperatures and moisture absorption. This causes swelling in the polymer and reduction in its glass transition temperature. The material used as filler or fiber needs to be dried before processing because hygrothermal effects can lead to severe internal stresses in the thermoplastic composite. The thermal mismatch of the matrix and fiber is a universal problem with composites, but more so with polymers because of their high thermal expansivity [36,84]. The lifetime of the material and environmental conditions cause physicochemical changes in the polymer structure. These changes can cause structural heterogeneity in polymers, affecting the mechanical properties and stability of the plastic. During processing, the polymers are exposed to thermomechanical degradation, leading to a decreased molecular weight of polymeric chains. This chain scission increases the degree of crystallinity in semi-crystalline polymers resulting in the progressive embrittlement of the reprocessed material [58].

4.4. Recycled wood fibers for composites

The amount of CDW wood produced in the EU area is approximately 10–20 million tons annually [2]. In Europe, CDW wood is handled according to the EU framework policies, which regulate how it should be recycled and when new products can be made from the waste. The use of recycled wood differs from one country to another, but recycled wood is generally burnt for energy. The equipment for processing wood waste includes shredders, grinders, magnetic separators, and various screen systems [12]. The reuse of industrial byproduct wood has been adapted in the industrial scale in particle board manufacturing and production of wood-based composites [85]. A recent study by Azambuja et al. [86] concluded that also the CDW wood could be used in the production of particle boards. Large-scale reuse of CDW wood is uncommon because of the varying quality and supply of CDW wood. Contaminants in CDW wood can include lead from paint or heavy metals, such as arsenic, chromium, and copper. The current practice is, contaminated recycled wood is incinerated for energy in specialized facilities, where burning gases are cleaned, and thereafter, ashes are safely landfilled. For wood plastic composite applications (WPC) the wood waste should be dried and grinded to a suitable size. Consequently, this increases the cost of processing [87]. Only clean untreated wood fibers can be used under the end-of-waste status for composites production.

The extrusion of WPCs is common in the decking industry. Injection-molded components, such as electrical casings, packaging, living supplies, and materials for civil engineering applications are also often made of WPCs. Cellulosic fibers are used for improving the stiffness in the plastic and are used as fillers for their low cost. The hydrophilic nature of cellulosic fibers has an adverse effect on the fiber adhesion into the hydrophobic plastic matrix, often resulting in poor strength properties and fiber pull-out under heavy loading. Although using recycled waste wood in composites is not a common industrial practice, attempts have been made to utilize this material to create new products, such as decking (see Fig. 9), wall panels, acoustic barriers, flooring, and outside furniture. The degradation temperature of wood and other lignocellulosic fillers is approximately 200 °C, which sets their limit for processing methods and combination with other materials [88].

Wolfe and Gjinolli [41] conducted a pilot study on the use of CDW wood treated with copper chromium arsenate (CCA) in the production of cement-bonded composites for use in highway sound barriers. According to their study, the aforementioned composite could have special applications in structures where impact and dynamic loads are design considerations. However, the reuse of CCA-treated wood fibers is not allowed in Europe. Moreover, Kamdem et al. [43] presented WPC as a possible alternative to reuse CCA-treated wood. They tested compression-molded WPCs for their mechanical properties, as well as their endurance to accelerated weathering, and fungal and water exposure. It was found that CCA decreased the hydrophilic nature of the wood fiber, subsequently improving the compatibility of materials and impact strength of the composite. The leaching rates from CCA wood exceeded the limits for a product exposed to water and used by humans. The use of CCA-treated wood fibers also increased the ultraviolet and decay resistance of WPC. Adhikary et al. [47] studied the dimensional

Fig. 9. Extruded wood-plastic composites from recycled raw materials (LUT University).

stability and mechanical behavior of WPC based on virgin HDPE and recycled HDPE (rHDPE), by varying the polymer-fiber volume ratio. The flexural strength and modulus of elasticity were higher in fiber-composite samples compatibilized with maleated polypropyle (MAPP) compared to fully plastic control samples. Compared with composites without a coupling agent, the addition of MAPP decreased the porosity in the composite, thus improving the dispersion of fibers in the matrix and increasing the interfacial strength. Chaharmahali et al. [89] studied the mechanical properties of wood-plastic composite panels made with rHDPE, sawdust, and grinding waste of medium-density fiberboard (MDF) and particleboard without the use of compatibilizers. The flexural strength, screw and nail withdrawal resistance, and impact strength of the composite panel started to decline when the fiber content rose from 60 to 80%. Composite panels made with recycled MDF had a higher flexural modulus. The higher aspect ratio of the fibers was suspected to be the cause for this increase. In a study by Englund and Villechevrolle [90], WPCs with binary blends of PP, HDPE, and PVC were extruded and evaluated for their mechanical and physical performances. Ethylene bis stearamide wax and zinc stearate were added to the extrusion blends for the improved processability of composites. Repeated extrusion runs with blends, such as wood/HDPE/PVC, wood/HDPE/PP, and wood/PP/PVC were made to determine the influence of melt-blending on the flexural and water absorption properties. Polymer blending made the composites more brittle than without it. Water resistance improved with increasing extrusion runs because of enhanced wood flour dispersion and minimization of voids and capillary pathways. Poletto et al. [91] studied the use of recycled EPS and wood flour in WPCs. Polystyrene-co-maleic anhydride oligomer was used as the coupling agent to improve the bond between recycled EPS and wood flour. The use of a coupling agent improved the wetting and interfacial adhesion of fibers to the matrix and increased the mechanical properties of the composite. WoodRub project [92] studied the possibilities of using recovered wood and rubber in new composite products. Polyurethane resin glue was used to bind ground rubber and wood particles into composite products, such as acoustic panels, anti-slip floors, garden paths, outside furniture, internal wall bricks, and playmats for playgrounds. Sommerhuber et al. [87] studied the substitution potential of rHDPE and wood particles from packaging waste in WPC products. Their work differed from previous studies by their assessment of the economic feasibility and visual characteristics of WPC made of recycled materials. Pedreño-Rojas et al. [93] used recycled demolition wood waste and gypsum to make false ceiling plates. Up to 20% of recycled material could be added without additives to make products that were lighter and had good enough mechanical properties for false ceiling plates. The addition of wood particles also decreased the thermal conductivity, which is good for false ceiling plates that are used partly for insulation purposes.

4.5. Recycled paper fibers for composites

In the construction of new buildings, paper and cardboard waste is mainly obtained from packaging materials. In demolition sites, paper sources include products, such as wallpaper and gypsum board coatings. Construction and demolition waste paper contains different types of fibers, which cannot be separated in recycling [94]. Waste paper contains chemicals from a wide range of sources, such as additives, inks, pigments, and glues [95]. The typical recycling process for post-consumer paper requires sorting, pulping, cleaning, screening, and de-inking before it can be made into new paper [94,96]. The paper from CDW is usually landfilled or incinerated for energy because removing it completely from waste, such as gypsum boards, is difficult. In these cases, paper is moved with other fractions along the recycling line and mixed with recycled end products. Although post-consumer paper is one of the most frequently recycled materials in the EU region, to date, no end-of-waste criteria have been defined. Consequently, their reuse in composites can be limited according to the views of different member state officials.

Grigoriou [42] studied the use of waste paper as the raw material for fiber and particle-based composites, evaluating the change in properties with various ratios of waste paper particles and wood particles in mixtures with polymeric diphenylmethane 4, 4′-diisocyanate (MDI) resin. The boards were tested according to European norms and American standards for density, static bending, internal bond, and screw-holding strength. The processing was affected by the clustering of paper flakes during blending, which caused problems in the mat-laying processing technique used. The resin coverage to wet the paper was higher compared to that in wood particles, making it difficult to process than wood. The thickness swelling, screw-holding strength, and internal bonding strength of the material deteriorated when wood chips were substituted with mixed paper flakes. Dweib et al. [97] studied the use of natural and recycled fibers in making composite sandwich beams by the vacuum-assisted resin transfer molding technology. The recycled paper material used to make the beam was obtained from old cardboard boxes, and the foam core was a closed cell polyisocyanurate. The resin for the beams was a mixture of styrene and chemically modified soybean oil. The beam had strength and stiffness approximating those of 2×4 wooden members as reference samples. Lykidis et al. [48] used waste paper from old corrugated containers to substitute wood particles in the production of particleboards with urea-formaldehyde (UF) and MDI resins. The mechanical properties of the board decreased with the addition of waste paper. The negative effects were suspected to be caused by pulping-related chemical, physical, and structural changes of the fibers in the cell wall and possibly because of the high amount of inorganic substances obstructing the bonding when UF resin was used. A board with a 30–50% waste paper content conforms to requirements for board types for interior applications. Hyvärinen et al. [98] used a blend of mixed CDW with high cardboard content (35%) to make WPC profiles. Although the composite board with CDW content had significantly lower mechanical properties compared to the reference board made of virgin wood fibers and polypropylene it still was at an acceptable level for typical board applications.

4.6. Recycled metals for composites

Metals have the highest recycling rate of all CDWs because of its well-developed markets and relatively easy separation. Because the lifetime of metal products is long, there has been an accumulation of metals since the beginning of the construction material industry. The estimated amount of metal in CDW is 1–4% of the total volume [2,99]. The main CDW metals are steel, aluminum, and copper. When the metal scrap container is transported to the material handling facility, the metals are separated manually or magnetically, and prepared for shredding and sizing. Thereafter a combination of the density and eddy current separations can be used to sort the non-ferrous metals, which have remained after passing through the previous stages. Recycled scrap is sold for direct reuse to traders or the metal industry, where it is melted and made into new billets or sheets after alloying and post-processing [99]. In the EU, the use of iron, steel, and aluminum scraps is governed by the end-of-life council regulation No. 333/2011. The remelting and alloying of metals is currently the only route for the introduction of recycled metals into the production of composites. Composites with metal matrix are used in high-technology solutions. However, the risks posed by the impurities in recycled metals should be considered before using them. Construction and demolition waste metals in their collected state are materials difficult to use with typical composite manufacturing processes because of their hardness, which can cause wearing in equipment.

4.7. Recycled glass for composites

In 2013, the amount of CDW glass in the area of EU-28 was estimated to be 1.5 million tons, of which 83 and 17% were from renovation and demolition activities, respectively [100]. The cullet is used in glass production because of the reduced cost of energy and raw materials. By its main composition, glass can be divided into vitreous silica, alkali silicate, soda-lime, borosilicate, lead, barium, and aluminosilicate glass type [101]. Flat glass from CDW is of the soda-lime glass type. Theoretically, glass material can be recycled indefinitely without the loss of quality [102]. The recycling process of CDW cullet is performed through the following stages: washing, drying, sorting, milling, melting, and forming into new products. The washing of cullet is done by water with chemicals. The washed cullet is sorted and milled to make glass and ceramic-grade sand, and sold to respective virgin product manufacturers [103]. The challenges in glass recycling relate to the separation of cullet having different colors and removal of contaminants, such as ceramic, plastic, paper, and metal [104]. The separated cullet can be used to produce abrasives, pozzolanic additives, glass pellets, glass tiles, glass fiber (GF), glass wool, foamed glass, container glass, and new flat glass [100,102,105–109]. Glass has been used in plastic composites as a filler material in the form of chopped glass, fibers, ground glass, or hollow microspheres. Glass fiber-reinforced plastics are widely used in the construction industry, e.g., in the form of cladding, structural or non-load-bearing wall panels, window frames, tanks, bathroom units, pipes, and ducts [36]. Other uses for recycled glass have been in bricks [110], concrete composites [111,112], polymer matrix-based composites [113], glass foam [109], and glass composites [114]. Recycled glass has been utilized in glass-concrete composite countertop designs for their unique look. The earliest trials to add glass aggregates for cement concrete started from the 1960s. The biggest problem encountered has been the cracking of concrete systems containing glass aggregates [101,104]. The compressive, flexural, and tensile strengths decrease in proportion to the increase of waste glass content in concrete mixtures [115]. The functionality of glass-concrete composites has been based on controlling damages caused by the alkali-silica reaction through the selection of glass type, particle size, content volume, and additives [104,115,116]. Recycled glass powder has also been used as fly ash replacement in cementitious composite due to its pozzolanic properties [117].

4.8. Recycled gypsum for composites

Gypsum board (GB) is one of the most widely utilized building materials today for interior wall construction. Consequently, relative portion of it in waste will evidently increase in the future. In the area of EU-27, the amount of GB construction waste was estimated to be approximately 1.77 million tons, of which over 93% was landfilled [118]. Gypsum board waste from construction is usually cleaned and separated. However, demolition waste has greater physical contamination and more difficult to reprocess into high-quality products. When the material-handling facility accepts the GB waste, it is shredded to separate it into gypsum, paper, and impurities [118,119]. Mixing gypsum with other materials is a problem, as it does not otherwise deteriorate in the reprocessing. The paper content in the gypsum agglomerate after recycling is estimated to be below 0.5%. Trials with recycled gypsum have been made to produce GBs, but currently the cost of the product would be similar to one produced with virgin materials [118,120]. Waste-sourced gypsum may be used in prefabricated products and plaster production [56]. Several studies have been made to find new uses for recycled gypsum in combination with other materials: thermoplastic [121], paper fibers [46], rubber [122,123], and mineral wool [44]. Recycled gypsum is introduced to the mix in powder form and liquid is often used to help in mixing it with other materials. The composite production method includes casting, extrusion foaming, pressing, and vacuum dewatering.

Carvalho et al. [46] studied the mechanical properties of gypsum composites reinforced with recycled cellulose pulp. The composite was produced by the stirring vacuum dewatering technique. The addition of cellulose fibers increased the flexibility and modulus of rupture of the composite compared to reference samples containing 90% of gypsum and 10% of limestone. Ramos et al. [121] prepared HDPE/gypsum waste composites and evaluated them for thermal, flammability, water absorption, and compression resistances. The composite with 30% of HDPE and 70% of gypsum exhibited three times lower burning rate compared to a reference sample with 100% HDPE. Water absorption was decreased as the rate of HDPE was increased, and the plastic also improved the mechanical resistance of the gypsum system. Rivero et al. [122] studied the use of ground waste rubber from pipe foam insulation in a gypsum plaster composite. The ground foam rubber was suitable for incorporation in gypsum-based composite products, e.g., embedded in the core of GB for a lightweight product with a hard surface. The use of larger particle size fillers compromised the mechanical behavior of the gypsum composite. Adamopoulos et al. [123] experimented with the production of gypsum matrix composite bricks with wood and rubber fillers and found that the reduction in compressive strength was high with both fillers. The proportion of wood or rubber should not exceed 25% in the gypsum matrix. Otherwise, the mechanical properties would be compromised. The insulation capability of gypsum-wood composite improved as the wood content was increased. Romaniega Piñeiro et al. [44] made a composite based on plaster and recycled MW fibers. The maximum amount of wool in the mixture was 1–10%, after which the workability of the mixture became unfeasible because of MW exceeding the volume of the plaster and amount of air inside it. The surface hardness and flexural strength of the gypsum matrix composite was increased with the addition of MW. Morales-Conde et al. [124] used recycled CDW wood from building renovation to manufacture gypsum composites, they found out that adding wood fibers affects negatively in the workability of the mixture. The recycled wood, however, was decreasing the density for a lighter product and improving the insulating properties. The samples with recycled wood material had lower flexural strength and hardness than the reference material without additives. Sormunen a Kärki [125] made compression molded composites with recycled HDPE and recycled gypsum from gypsum boards. The study also used wood, glass fiber, mineral wool, and soapstone as recycled particulate fillers in high filler contents of 40% and 60%. The use of gypsum particulate increased tensile modulus of the recycled plastic but decreased tensile strength considerably. The effects of filler material were quite similar with different compositions, which highlights the importance of particle geometry when reinforcement of matrix material is the intended goal. Río Merino et al. [126]

used a mixture of ceramic waste and XPS waste in a gypsum matrix to make plaster mortar, that was able to meet the requirements of current regulations for strength, however, the addition of recycled material decreased the mechanical properties compared with the reference sample without filler materials. Río Merino et al. [127] also prepared lightweight gypsums with polystyrene, XPS and EPS waste to substitute currently used perlite and vermiculite aggregates. Vidales Barriguete et al. [128] used plastic cable waste to prepare gypsum composite. The recycled plastic material improved the surface hardness and water absorption but had lower compressive and flexural strength. Geraldo et al. [129] used recycled plaster, red ceramic waste and porcelain waste to make recycled material gypsum brick by compression molding. The addition of waste material to gypsum weakened the mechanical properties but still exceeded the requirements of the standard, however, the waste material increased the setting time of the gypsum mixtures. Pedreño-Rojas et al. [130] used recycled polycarbonate filler in making composite gypsum tiles, and like in the studies by Río Merino et al. [126,127], Vidales Barriguete [128], and Geraldo et al. [129] the standard requirements for mechanical properties were achieved which seem to suggest that several types of waste based fillers could be used for making gypsum products. A possible drawback in using waste based fillers in gypsum products is that the following recyclability of the composite is more difficult than of a full gypsum product.

4.9. Recycled mineral wool for composites

Approximately 0.2% of all CDW waste is mineral wool. It is used in the thermal insulation of buildings, and its relative presence in the waste depends on the geographic location. Mineral wool is widely considered as an unrecyclable waste outside the industrial byproduct recycling [131]. It is a low-density material and relatively expensive waste to transport. Mineral wool requires large landfill areas, where it is further contaminated [132]. An effective source separation in the demolition site could improve the reuse rate of recycled mineral wool (rMW). Useable MW should be free of materials that easily get entangled into the wool, such as dust, crumbles of concrete, fasteners, foils, tapes, and fungal and bacterial growths [131,133]. Possible uses of MW waste include its reuse in ceramics, cement or fiber-based composites, tiles, and soilless cultures. The main challenges with the use rMW are the end-of-waste classification, development of suitable separation technologies, and further development of solutions using MW waste. It is suggested that MW would be best used in applications requiring the basic isolative and heat resistant properties of wool [131,134].

Cheng et al. [135] studied the use of MW in concrete composites. Rock wool improved the compressive strength, splitting tensile strength, absorption, resistivity, abrasion resistance, and chloride-ion penetration resistance of cement-based composite. The property improvement was concluded to be related to the pozzolanic nature of rock wool waste. Mamiński [136] used MW in the production of a wood-mineral wool-hydric composite board. An increase in the MW content decreased the modulus of rupture and internal bonding of boards, but increased the fireproofing properties. Väntsi et al. [134] and Keskisaari et al. [45] tested the addition of MW into WPC with PP matrix. The replacement of wood fiber with MW decreased the flexural and tensile properties, but there was a small increase in the impact strength and moisture resistance of WPC. Kinnunen et al. [132] used the alkali-soluble nature of rock wool waste to produce a geopolymer composite with the combined mixing and dissolution method. The materials used were rock wool waste, fly ash, and an alkali solution. The resulting geopolymer paste could be molded into a rigid matrix with improved compressive strength. Ramírez et al. [137] used recovered MW fibers from CDW to produce cement with fibrous additive, they found that the use of MW caused a minor increase in porosity which could result in a decrease of mechanical properties but improve the insulating properties of the material.

4.10. Recycled inert materials for composites

Inert materials, such as concrete, ceramics, bricks, tiles, stone, and uncontaminated soil make up the highest proportion of CDW, both in volume and weight. The amount of inert materials is approximately 75–95% of all CDW [35]. The recycling process for concrete, tiles and ceramics consists of sorting contaminants and crushing them to aggregates of specified sizes according to intended use. Sometimes these mineral materials are also processed into new construction products, such as low-cost bricks, glass-concrete composites, filler material for road bases, and aggregates for new concrete [3,138–143]. Using CDW as a filler for concrete has benefits, such as the diversion of non-recycled waste from landfills to useful applications, decreased use of nonrenewable resources, saved energy in concrete production, and corresponding reductions in greenhouse gas emissions. The economic benefits of alternative materials in concrete are best realized when their cost is less than that of the cement powder while providing comparable performance [104], however, using the recycled aggregate can be more energy intensive due to possible decontamination procedures which also can lead to additional costs for material without commercial value [144]. When the requirements for mechanical performance are not as high as those with concrete with virgin materials, CDW aggregates could be used in concrete composites made by casting. Chen et al. [145] used CDW-mixed rubble of tiles, bricks, and concrete as aggregates for new concrete. The samples filled with building rubble had worse mechanical properties than the reference concrete. In the study of Medina et al. [146], the addition of recycled sanitary coarse ceramic increased the compressive strength of the cast concrete sample. Hoffmann et al. [22] recommended using recycled concrete with mixed rubble in solutions where increased shrinkage and creep are not problematic.

5. Results & discussions

Typical results with recycled material composites are summarized in Table 3. The weak bonding of used filler material to the composite matrix is a common problem. Recycled fillers and fibers often seem to increase discontinuities of the composite and weaken mechanical properties. In general, the prediction of interface characteristics is difficult because of the random orientation of post-processed recycled fibers and fillers. The visual appearance, tactile texture, and odor are rarely reported in studies using recyclates as composite raw material. The raw material quality should conform to the set product standards set by the user and the respective authorities interested in the end-of-waste legislation related activity. Therefore the recycled materials should be monitored carefully for the possible entry of contaminants or other quality errors that might enter to the material batches. The emissions of VOCs from CDW materials are difficult to predict because of numerous additives used in the construction industry. Even a good level of automatic separation does not remove the possibility of some contamination. Health risks could be controlled by utilizing source-separated materials of known origin and composition. In the future, BIM models could provide information on the composition of buildings for improved source separation [28,29].

The use of compatibilizers has generally improved mechanical properties of WPC solutions [47,77,89–91]. Composites that utilize paper and cardboard waste have had inferior mechanical properties compared to ones with wood fibers [42,48]. Currently, the usability of CDW wood for WPCs is debatable because of its relatively high processing cost. Composite solutions for CDW metals could not be found from literature. Similarly, for glass, only concrete mixture solutions were found. Glass powder could possibly be used as a filler in composites, where the hardness does not disturb the processing. Gypsum is not affected by recycling and it has been used in combination with thermoplastics [121,125,127,128,130], paper fibers [46], rubber [122,123], and mineral wool [44]. The aim of using recycled gypsum composites has usually been to create tiles, where its combination to

Table 3
Composites from CDW type of materials based on sections 4.1–4.10.

CDW material	Known types	Benefits	Disadvantages	Potential products	References
Thermo-plastics (4.3–4.4)	Used as matrix material and in some cases as lightweight filler.	Improved moisture endurance; freedom of form; lightweight.	Possibly degraded properties because of weathering, contamination, or recycling process.	Plastic lumber, frames, molded products.	[47,89,91,98,12,51,27]
Wood (4.4)	Cellulose fiber reinforced composite	Improved stiffness in WPCs; Acoustic properties.	Hydrophilic nature of fibers; Added costs because of drying and processing the wood waste.	WPC lumber, fiberboards, acoustic boards.	[41,43,92,98,125]
Paper and cardboard (4.5)	Cellulose fiber reinforced composite	Acoustic and insulative properties.	Hydrophilic nature of the fibers. Thickness swelling and low internal bonding; Fiber property loss in recycling.	Boards and interior acoustic barriers.	[42,48,98]
Metal (4.6)	–	Well-established markets for recycled metals.	The risks caused by impurities in waste; Only useable in metal products.	Recycled CDW metal can be used for new metal production.	–
Glass (4.7)	GF reinforced composite, concrete composite	In fiber form; improvement of mechanical properties.	Alkali-silica reactions in concrete composites; Cullet form would cause discontinuities in the composite; Requires energy intensive processing; Impurities in the recycled material.	Glass foams, counter tabletops, decoration, raw materials for a variety of glass products.	[89,93,102,103,117]
Gypsum (4.8)	Gypsum composite, concrete composite, use as filler	Thermal stability; fireproofing; hardness.	Delayed ettringite formation in concrete composite; High water absorption; Relatively low mechanical strength.	Boards for construction industry, tiles for interior, insulation.	[44,123–125,125–130]
Mineral wool (4.9)	Hybrid WPC, cement composite	Thermal insulation properties.	Porosity and fiber poor adhesion affect mechanical properties.	Insulation materials production.	[45,53,125,132,134–137]
Concrete and ceramics (4.10)	Concrete composites	Cost savings and possible environmental benefits.	Possibly increased shrinkage and creep; Unknown long term effects of contamination.	Concrete composite and tile production.	[145,146]

other materials for mechanical property improvement would probably not be necessary. Mineral wool is a waste that substantially consumes landfill space and is currently without considerable reuse possibilities [131,132]. The challenges of utilizing MW waste are related to its high porosity and bonding to the composite matrix [45,134]. The problems caused by porosity of MW might be resolved by grinding MW waste into powder. However, this would increase processing costs. Inert CDW, such as concrete, tiles, stone, and ceramics have been used as fillers for concrete or road bases. However, benefits from the use of inert CDW aggregate in concrete composites is not clear.

The research in the field of recycled material composites is primarily focused on technical properties without the estimation of economics and environmental effects of production. That the applicability of studies could benefit from the inclusion of economic and environmental estimations as presented by Keskisaari et al. [14], Rajendran et al. [52] and Sommerhuber et al. [87].

Regardless of the recycled material type, similar contributing factors for successful material circulation were found (see Fig. 10). Several of the current building materials used have not been originally designed for recycling, which is a consequence of the desired property enhancement against mechanical strain, fire, or environmental conditions. The choices made in the design stage of building materials have defined their further usability as raw materials after their lifetime. The lifetime and age of a demolished building have a great significance on the composition of materials that can be extracted, as well as the contamination expected to be present. The use of source separation can improve the homogeneity of recycled materials. The recycling process of a material handling facility defines the final separation quality level of materials entering the recycled material market. Industrial symbiosis with recyclers and users could be possible if there were more demand for recycled raw materials. In this manner, previously vague or missing quality criteria for material handling facilities could naturally emerge.

6. Conclusions

This study has taken a broad perspective at the possibilities of typical CDW materials, such as thermoplastics, wood, paper and cardboard, metals, glass, gypsum, mineral wool, concrete, ceramics, and stone as raw materials for composites. It provides a summary of previously conducted studies that are applicable to CDW materials and highlights the challenges to consider in further studies. Common factors for the successful recirculation of CDW materials back to use were identified.

Advances in recycling technologies have made it possible to separate cleaner fractions for reuse. The mixing and possible contamination of CDW materials are challenges limiting the open-loop recycling of materials into composites. Post-consumer CDW wood, paper, and plastic have been recycled for energy in most countries, but recycling them into raw materials for open-loop applications, such as composites, is still uncommon. Metals, glass, paper, cardboard, and gypsum recycling require specialized technologies found in industries that produced the waste in the first place. The required closed-loop recycling technology could complicate the use of a material for purposes other than those intended for the original product.

Generally, potential CDW materials for composite manufacturing are thermoplastics, gypsum, mineral wool, and wood. Of these, thermoplastics and gypsum have been used as matrix material. The properties of recycled material composites are often affected by the degradation and contamination of materials. The repurposed materials often cause discontinuities in the composite if they are not properly processed. The applicability and benefits of recyclates employing conceived solutions should be weighed by case. The methods used to produce composite samples in studies have often been made with laboratory equipment, making it difficult for the manufacturer to assess the feasibility of such processes utilizing production equipment.

The economic benefit that can be derived from manufacturing is

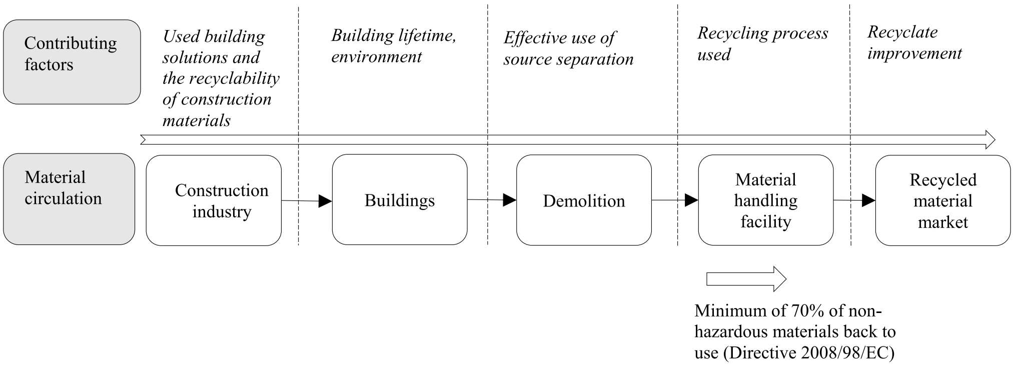

Fig. 10. Contributing factors for successful recirculation of CDW material back to use.

often the motivation to use recycled materials to make new products. However, currently, this is supported by limited research. In the case of WPC, economic benefits might result because of the use of recycled thermoplastic, as the processing cost of recycled wood diminishes the gap between it and virgin material prices. On the other hand, possible environmental benefits that may be obtained depend on the composition of the composite material.

The limitations of the research stem from the considerably few number of studies conducted on composites with recycled raw materials. Estimating the true potential for the composite manufacturer remains difficult as studies on the processing quality, economics, carbon footprint, and health and safety are few and composition specific. Future studies on recycled material composites could benefit the estimation of the economic and environmental impacts of their application. Studies on the consistency and quality of production could be conducted in order to better evaluate the feasibility of recycled materials in composite manufacturing. Application-based research might open new potential uses for composites made of CDW materials.

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Publication II

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Case Report

Compression Molded Thermoplastic Composites Entirely Made of Recycled Materials

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Abstract: Recycled post-consumer high-density polyethylene pipe plastic was agglomerated into composite samples with wood, glass fiber, mineral wool, gypsum, and soapstone as recycled particulate fillers. The tensile strength, tensile modulus, impact strength, and hardness were the mechanical properties evaluated. Scanning electron microscopy was performed on the broken surfaces of tensile strength samples to study the interfacial interactions between the composite matrix and the filler materials. Heat build-up, water absorption, and thickness swelling were the physical properties measured from the composites. The addition of particulate fillers demonstrated the weakening of the tensile and impact strength but significantly improved the rigidity of the post-consumer plastic. The composites filled with minerals had mechanical properties comparable to compression molded wood plastic composites but higher resistance to moisture. A lack of hot-melt mixing affected the mechanical properties adversely.

Keywords: composites; recycling; mechanical properties; physical properties

1. Introduction

The addition of organic and inorganic fillers to polymers has been an important industrial method in creating new materials with tailored properties for specific applications. The legislative pressure pertaining to waste materials in Europe reinforces the need for identifying new uses for previously discarded wastes as recycled materials. The use of selected recycled particulates from post-consumer and industrial by-product waste currents as property changing fillers for polymers could be a way to reuse such materials in the manufacturing of new products. Properties of polymers such as corrosion resistance, light weight, and ease of processing into a variety of shapes can be combined with the unique properties of fillers to form composites with modified appearance, cost, mechanical strength, thermal and electrical conductivity, thermal stability, magnetic characteristics, flame retardant, electromagnetic shielding, dielectric, and barrier properties [1,2]. Productivity can also be increased with particulate fillers due to decreased specific heat and increased heat conductivity [3,4]. The filler addition affects the composite system also by introducing new interfaces, imperfections, impurities, and flaws, which in turn affect the thermal properties and can interfere the processability [5]. Particulate fillers have traditionally benefitted polymers by decreasing the amount of costs of production, which can best be achieved by using the largest amount of filler possible, while retaining the integrity of the polymer matrix holding the product together. The most common fillers for thermoplastics are calcium carbonate, talc, silica flour, clay and wood fiber. To change the properties of polymers, the use of high filler rates is often required, which will lower most of the mechanical properties of the material, reducing the possible field applications. If the filler content of the recycled particulates was high, the environmental, cost, and property-changing effects would potentially be greater in the composite. The high filling rate has often a negative effect on the impact strength, elongation to break, tensile strength, and flexural strength [2]. Improvements by particulate fillers are most likely to take place in the elastic modulus of the composite. The use of low-cost filler content decreases the costs in thermoplastic composites when the relatively virgin plastic is replaced [6]. It could also be an economical way to change the properties of the recycled thermoplastics.

The main aim of this paper is to study mechanical, moisture resistance, and heat build-up properties of compression molded high-density polyethylene (HDPE) composites filled with recycled wood fiber, glass fiber, mineral wool, gypsum, and soapstone particles by empirical testing in order to evaluate the effect of recycled low-cost fillers on the recycled plastic. The analytical methods presented by Halpin-Tsai [7] or Mori-Tanaka [8], which are often used to evaluate the effects of filler geometry, stiffness and orientation were not used in this study due to diverse types of materials used, expected variance in the recycled material and the strong particle–particle interactions caused by the high filler content. For more information about the issues related to analytical method the reader is referred to the work of Fornes & Paul [9]. The comparison of composite properties achieved with different recycled materials could help potential users to rate materials for a variety of open loop recycling thermoplastic based applications such as plastic lumber [10], packaging material, pallets [11], green space and outdoor construction, agriculture and livestock, public construction and traffic barriers [12]. Previously, the compression molding of recycled material composites with a high filler content has been done using kinetic mixing to heat the material [13], a heated mold [14,15], and pressing extruded re-heated composite sheets [16]. In this study, the material is heated in an oven without pressure or mixing.

2. Materials and Methods

2.1. Materials

Recycled high-density polyethylene (rHDPE) from a construction waste sewer pipe was supplied by the Destaclean company and used as matrix material with all the samples. The plastic was identified by manual sorting and recycled mechanically, after which it was crushed to smaller fractions using Untha LR 630. Spruce (*Picea abies*) was prepared into two particle sizes, fine wood flour of 20 mesh (0.85 mm) and rough hammer milled wood flour of over 20 mesh (max 4.00 mm). The specific gravity of wood flour is 1.3–1.4 g/cm^3 [17]. The size of the wood was reduced with a chipper combined with a hammer mill after which it was sieved to the designated size. Glass fiber was the by-product reject from the glass fiber mat production of the Ahlstrom Corporation. The glass fiber reject was chopped to a size of 25 mm with the density 2.5 g/cm^3, which became even smaller in the agglomeration phase. Recycled rock wool from construction waste was crushed and milled to powder. The Paroc Group provided by-product grinding dust from rock wool manufacturing, which was collected with a vacuum used in the process. Rock wool consists mainly of silicon dioxide (40–52%, SiO_2, 2.65 g/cm^3), calcium oxide (10–12%, CaO, 3.35 g/cm^3), magnesium oxide (8–15%, MgO, 3.58 g/cm^3), and aluminum oxide (8–13%, Al_2O_3, 3.95 g/cm^3) [18]. Recycled construction and demolition waste gypsum was provided by the material handling facility Etelä-Karjalan Jätehuolto. The gypsum waste was ground to powder, and the powdered gypsum wall board specific gravity is 1.76 g/cm^3 [19]. Tulikivi provided the by-product soapstone powder from its stone sawing process. Soapstone consists primarily of talc (40–50%, 2.98 g/cm^3) $Mg_3Si_4O_{10}(OH)_2$ and magnesium carbonate (40–50%, 2.96 g/cm^3) $MgCO_3$ in almost equal quantities. In addition, there are small proportions of chlorite (2–10%, 2.42 g/cm^3) $H_4(Mg,Fe)_2Al_2SiO_{11}$ and magnetite (0–15%, 5.15 g/cm^3) (Fe_3O_4) [20]. As a coupling agent, 3% of DuPont™ Fusabond® E226 anhydride modified polyethylene was used with the density of 0.93 g/cm^3, the melt flow rate (190 °C/2.16kg) 1.75 g/10min, and the declared melting point 120 °C. Maleic anhydride modified polyethylene has been used to improve the interfacial adhesion between the organic fillers and polymer matrix [21–24]. Processing additive Struktol® TPW 113—a blend of complex modified fatty acid ester—was used with all of the samples, with a density of 1.005 g/cm^3 and a dropping point of 70–88 °C.

2.2. Agglomeration of Composites

The filler material, recycled HDPE, coupling agent and processing additive were compounded using a TRL 100/FV/W turbomixer combined with an RFV-200 cooler. The wood materials for NFF and NFR recipes were not pre-dried. The composites were prepared into 14 different formulations. Tables 1 and 2 present the composition of the prepared composite agglomerates. The density by rule of mixture (RoM) was calculated according to the materials used. After the composites were produced, the density was estimated using the weight and the molded volume of the samples.

Table 1. Composite formulations, part I (the proportion of material by weight).

	REF	NFR40	NFR60	NFF40	NFF60	GF40	GF60
HDPE, recycled	94%	54%	34%	54%	34%	54%	34%
Wood flour, rough recycled	0%	40%	60%	0%	0%	0%	0%
Wood flour, fine recycled	0%	0%	0%	40%	60%	0%	0%
Glass fiber, by-product	0%	0%	0%	0%	0%	40%	60%
Coupling agent	3%	3%	3%	3%	3%	3%	3%
Processing additive	3%	3%	3%	3%	3%	3%	3%
Density by Rule-of-mixture g/cm^3	0.95	1.09	1.16	1.13	1.22	1.57	1.88
Measured density g/cm^3	0.95 ± 0.00	1.02 ± 0.01	1.03 ± 0.02	1.02 ± 0.02	1.05 ± 0.01	1.21 ± 0.03	1.24 ± 0.10
Porosity	0.1%	6.5%	11.3%	9.8%	14.0%	23.0%	34.1%

Table 2. Composite formulations, part II (the proportion of material by weight).

	MWR40	MWR60	MWB40	MWB60	GYP40	GYP60	SS40	SS60
Mineral wool, recycled	40%	60%	0%	0%	0%	0%	0%	0%
Mineral wool, by-product	0%	0%	40%	60%	0%	0%	0%	0%
Gypsum, recycled	0%	0%	0%	0%	40%	60%	0%	0%
Soap-stone, by-product	0%	0%	0%	0%	0%	0%	40%	60%
Coupling agent	3%	3%	3%	3%	3%	3%	3%	3%
Processing additive	3%	3%	3%	3%	3%	3%	3%	3%
Density by rule-of-mixture g/cm^3	1.62	1.95	1.62	1.95	1.28	1.44	1.76	2.17
Measured density g/cm^3	1.28 ± 0.02	1.37 ± 0.01	1.33 ± 0.01	1.57 ± 0.01	1.22 ± 0.01	1.37 ± 0.03	1.32 ± 0.01	1.62 ± 0.02
Porosity	20.8%	29.7%	17.7%	19.4%	4.3%	4.7%	25.1%	25.3%

2.3. Composite Manufacturing

A compression molding tool was used to make 110 × 110 × 10 mm square plates for the manufacturing of impact strength and water absorption samples. The composite agglomerate was heated in an oven to 165–200 °C, after which it was manually transferred to the compression molding tool see Figure 1 for the set-up. A pressure of 24.3 MPa was applied for 60 s to mold the samples. The temperature of the material inside the oven before compression and immediately before demolding was measured with Mastercool Infrared Thermometer OUTPUT <1 mW AT 630~670 nm CLASS II and documented. The tensile strength specimens were prepared with a compression molding tool see Figure 2. The tool and the press had no heating or cooling capability. The mold had channels to regulate overfilling caused by the manual transfer of heated material into the mold. The tools were mounted on a hydraulic C-frame press made by Stenhøj A/S coupled with CA-1000 connector accessory with VI Logger version 2.01 made by National Instruments. The processing of 110 × 110 × 10 mm plates was successful with all the materials, but the thinner tensile strength specimens were not possible to process with the GF60 composition as the specimens broke during demolding.

Figure 1. The setup for the compression molding of samples.

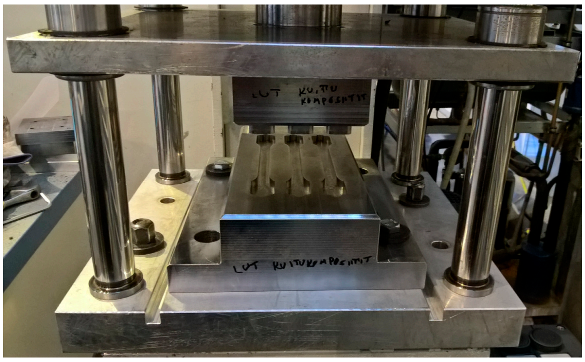

Figure 2. A tool constructed for the compression molding of tensile strength samples.

2.4. Mechanical Property Measurements

The tensile properties strength and elastic modulus were measured with a Zwick Roell Z020 testing machine. The measurement of the tensile modulus was performed according to ISO 527-1 [25] with a testing speed of 1 mm/min. The compression mold specimens were of the ISO 527-2/1A/1 type, and 12 specimens were prepared for each sample see Figure 3. The samples for the Charpy impact strength were sawn from molded 110 × 110 × 10 mm square plates (see Figure 4) into the length 80 ± 1 mm, width 10 ± 1 mm, and thickness 4 ± 1 mm; 12 samples of each material were prepared. The Charpy impact strength was measured at 21 °C with the Zwick 5102 impact tester. The impact velocity of the pendulum was 2.93 m/s, the pendulum length 225 mm, and the angle of deflection 160 degrees. Brinell hardness was tested with Zwick Roell indentation testing equipment. The diameter for the pressing ball was 10 mm and the pressing force of 1 kN was applied for 25 s. The dent was measured with a caliber after the minimum wait time of 2 min. The fracture morphology of the broken tensile strength samples was studied with a Hitachi SU3500 scanning electron microscope (SEM).

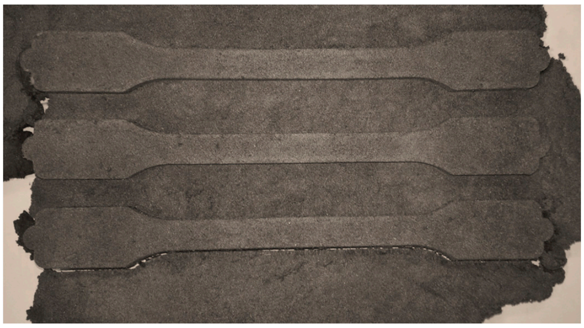

Figure 3. Tensile strength samples after molding.

Figure 4. Compression molded square plate before cutting.

2.5. Moisture Absorption and Thickness Swelling

The moisture absorption and thickness swelling of the composites were determined according to EN 317:1993 [26]. For each material, 12 samples were manufactured by compression molding see an example in Figure 5. Moisture absorption (MA) and thickness swelling (TS) were calculated with the following equations

$$MA = \frac{m_t - m_o}{m_o} \times 100\% \quad (1)$$

where m_o and m_t are the mass of the sample in grams before and after immersion.

$$TS = \frac{T_t - T_o}{T_o} \times 100\% \quad (2)$$

where T_o and T_t are the thickness of the sample in millimeters before and after immersion.

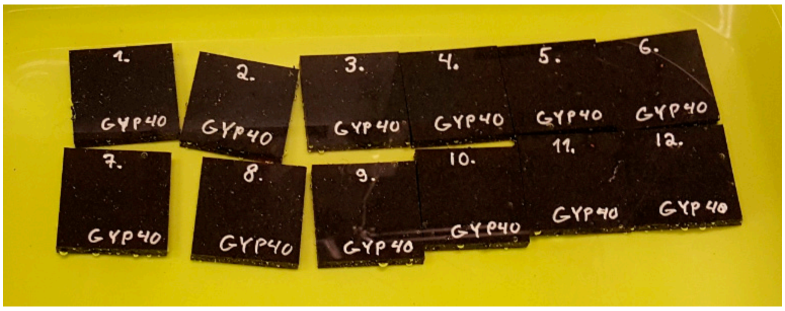

Figure 5. Moisture absorption samples immersed in water.

2.6. Heat Build-up and Color Measurements

The heat build-up of the composites was tested according to EN 15534-1 [27]. The samples with dimensions 100 × 10 × 4 mm were tested. Three specimens for each type of composite were measured with the black control specimen. An infrared heat lamp with 250 W nominal power was used to heat up the samples. The distance from the lowest part of the lamp to the bottom of the box was 375 mm. The method measured the relative value of heat build-up compared with a black control specimen under the defined conditions and does not predict the application temperature in real situations. The used black control specimen was made of the same material as the reference (REF) so that the test results would show the possible changes caused by the application of filler materials.

A Minolta CM-2600d spectrophotometer was used to determine the colors of the composite samples according to the CIE (Commission Internationale de l'Eclairage) L*a*b color system.

3. Results and Discussion

3.1. Mechanical Properties of Composites

3.1.1. Impact Strength

The impact resistance of polymers depends on geometry, the mode of loading, the load application rate, the loading environment, and polymer properties such as chain length, packing, chemical arrangement units in the polymer chain, alignment, and bonding forces. Therefore, the strength is the sum of properties that contribute to the dissipation of the forces of impact [28]. The effects of a high fill rate on the Charpy impact strength of the recycled plastic were significant (see Figure 6). The impact strength's decreasing effect with an increased particle content [29] was found across the studied materials, with an exception in SS40 (4.86 ± 1.31 kJ/m^2) and SS60 (5.27 ± 2.59 kJ/m^2), where the mean value with a 60% fill rate was higher. Compared to the REF (72.31 ± 9.94 kJ/m^2) material, the drop-in impact strength was on average 90%, as Figure 6 shows. Glass fiber GF40 had the highest impact strength of the measured composites with filler (12.71 ± 4.76 kJ/m^2). According to previous studies, the high impact test results with glass fiber thermoplastic composites have attributed to strong interaction between the silanol groups of the glass surface and the anhydride group of the coupling agent [30,31]. The standard deviation in GF40 results was the highest of all tested materials, which was likely caused by the agglomeration phase where the fibers were broken into random lengths and clustered heavily together, creating discontinuities and porosity in the thermoplastic matrix. This same reason might be the cause of the higher results in GF40, as the clustering of fibers also created zones where the tough thermoplastic was the dominant material. This seems to be supported by the SEM. This effect was not as strong in the composite GF60 (5.72 ± 2.45 kJ/m^2), which could be related to the plastic zones being smaller with a higher glass fiber content. The use of rough or fine saw flour did not seem to have a significant difference in the impact resistance properties in the wood plastic composite samples NFR40 (6.87 ± 1.07 kJ/ m^2) and NFF40 (6.77 ± 1.63 kJ/m^2) with a 40% fill rate.

Both of the particle types decreased the impact strength compared to unfilled REF, which is in line with the previous studies [14,32]. The composite NFF60 (5.61 ± 0.89 kJ/m^2) with fine wood flour performed better than the sample with rough wood flour NFR60 (4.91 ± 0.65 kJ/m^2). The variance in the impact strength was generally higher in samples with a 60% fill rate. Without the bonding effect of the matrix, the high aggregation of fillers leads to insufficient homogeneity, rigidity, and low impact strength, and the aggregated particles act as crack initiation sites in impact [1]. The mineral wool composites with recycled raw material MWR40 (11.04 ± 2.94 kJ/m^2) and MWR60 (6.32 ± 1.53 kJ/m^2) had higher impact strength than the MWB40 (7.13 ± 1.59 kJ/m^2) and MWB60 (4.86 ± 0.89 kJ/m^2) made of by-product mineral wool, which is surprising as the tensile properties in MWB cases were superior. However, MWR40 had quite a high value for elongation at break 2.81%. The composite GYP40 performed well in impact testing with a small deviation in results 8.86 ± 0.65 kJ/m^2, but as the gypsum content was increased, the results dropped as in other tested samples GYP60 6.32 ± 1.53 kJ/m^2.

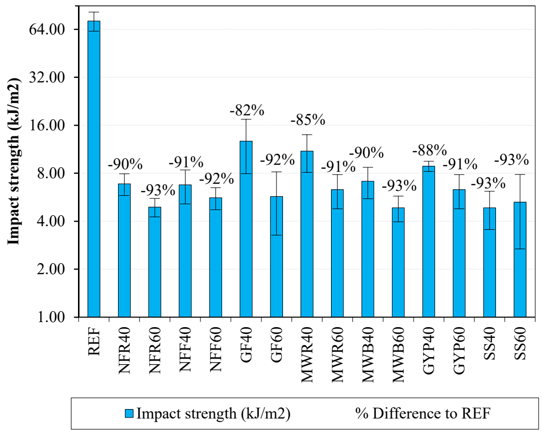

Figure 6. Charpy unnotched impact strength.

3.1.2. Tensile Strength

The tensile strength decreased with the addition of filler material compared to fully plastic REF (17.31 ± 0.48 MPa) due to weak interphase adhesion in the filler interface (see Figure 7). The calculated specific strength shows that although the tensile properties of MWB, GYP, and SS filled composites were similar, the GYP40 performs better when considering the material weight. The tensile strengths of the compression molded wood plastic composite samples were significantly below the previously reported values [14,33]. The composite NFF40 (11.29 ± 1.11 MPa) had 18% higher tensile strength than the composite NFR40 (9.13 ± 1.47 MPa), which would seem to suggest some influence by the fiber size. However, the wood plastic composite samples with a 60% fill rate demonstrated the opposite affect, and the NFF60 (6.90 ± 2.24 MPa) had 18% smaller tensile strength compared with NFR60 (8.16 ± 1.81 MPa). This seems to be in conflict with previous reports where the increased fiber size and fiber ratio has improved both the modulus of elasticity and maximum strength although in these studies the fiber size has previously been significantly smaller [33,34]. Wood plastic composite samples NFR40, NFR60, NFF40, and NFF60 all had relatively high variance in results. In the NFF60 with 20 mesh natural fiber filling of 60%, the deviation in results was over 30% of the results average. The measured densities in NFR40, NFR60, NFF40, and NFF60 were close to each other despite the different fill rate, and while NFF60 composite samples were the heaviest, NFR60 performed better both in strength and in the modulus. The agglomerate heating method and relatively low (24.3 MPa) mold pressure might also have affected the results of the tensile strength negatively in composites with a high natural fiber content. The blanket created by the wood fibers in Figure 8 acted as insulation to the thermoplastic, leading to a longer heating time and uneven temperature in the plastic matrix. The mineral filled composites performed better as group compared to the fiber filled composites; an exception to this are the samples MWR40 (7.81 ± 0.86 MPa) and MWR60 (5.85 ± 0.73 MPa). The difference between recycled and by-product mineral wool composites MWB40 (9.96 ± 0.73 MPa) and MWB60 (9.28 ± 1.79 MPa) might be in the non-hardened resin component in the by-product material. The composites with by-product mineral wool filling tensile properties are close to the previously reported 9.00 MPa with a recycled HDPE matrix and 40% rock wool filling [35]. Wood plastic composites with 40% fiber fill have previously had significantly higher tensile strengths [36]. Similarly, there was a significant variance in the results of glass fiber composite GF40 (7.81 ± 2.84 MPa) with 40% filling. While processing the GF60 tensile strength and elastic modulus samples the matrix was not able to hold the material together and they broke during demolding. In this study, the cut glass fiber also reduced significantly in size. In a study conducted in the same laboratory [37], the glass fiber was agglomerated with the same method, and the size of processed glass fibers ranged from 20 to 460 μm with the mean size of about 100 μm. Processing is known to affect the fiber length and distribution, and likewise, anisotropic particle fillers cleave and experience considerable delamination in processing [1]. In both natural and glass fiber composites, the aggregation of fibers created weak spots in the matrix leading to crack propagation. In general, the mineral fillers with a small particle size performed better in the tensile strength test, which suggests better dispersion in the matrix than with the fiber fillers. The tensile strength of mineral wool composites MWR and MWB ranged between 5.85–9.96 MPa. The lowest result was with MWR60 and the highest with MWB40. Both MWB samples performed better than the samples with post-consumer recycled mineral wool. This could be due to the reinforcing effect of the non-hardened resin in by-product mineral wool which was activated in the processing of the composite. The materials with the least variation in the mineral filled composites group where the samples with recycled gypsum GYP40 (10.07 ± 0.31 MPa) and GYP60 (10.48 ± 1.04), and a good dispersion into the matrix is visible in the SEM analysis. The tensile strength SS40 (9.74 ± 0.68 MPa) and SS60 (9.64 ± 2.62 MPa) were similar, but there was greater variation in the results of SS60 probably caused by the higher probability of local concentrations of soapstone in the mixture with a 60% fill rate.

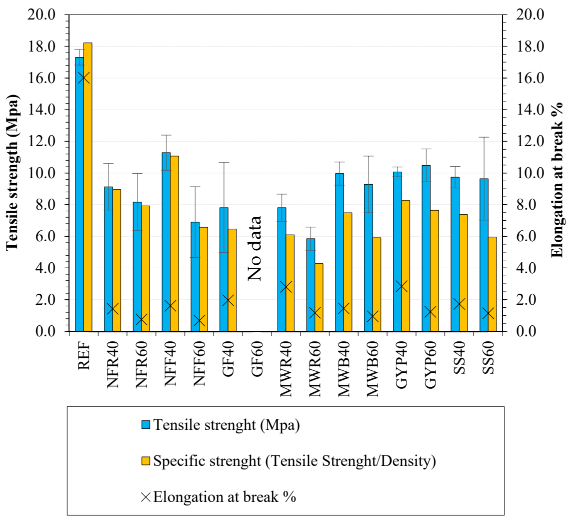

Figure 7. Tensile strength of HDPE-based composites.

Figure 8. Top and bottom view of heated wood plastic agglomerate.

3.1.3. Tensile Modulus

The addition of mineral and fiber fillers increased the tensile modulus of recycled HDPE in all samples except in GYP40 (0.89 ± 0.05 GPa) (see Figure 9). The standard deviation in samples NFR60 (1.78 ± 0.28 GPa), NFF60 (1.58 ± 0.51 GPa), GF40 (1.39 ± 0.38 GPa), and MWR60 (1.37 ± 0.73 GPa) was high due to the clustering of particulates to high concentrations in the tensile specimens. With the 60% recycled mineral wool fill MWR60 some individual tests resulted in a lower tensile modulus than in the REF material (0.94 ± 0.04 GPa). Also, the tensile modulus of MWR40 (1.16 ± 0.16 GPa) was quite close to the REF material. Mineral wool by-product MWB40 (1.38 ± 0.09 GPa) and MWB60 (1.72 ± 0.07 GPa) performed generally better than the recycled mineral wool probably due to the activated non-hardened resin in the by-product component. Wood plastic composites NFR40 (1.40 ± 0.17 GPa) and NFF40 (1.51 ± 0.10 GPa) had smaller variance in results than the other fiber composites due to the good dispersion of wood particles into the plastic matrix and the effect of the compatibilizer. Composites filled with by-product mineral wool (MWB40 and MWB60), gypsum GYP40 and GYP60 (1.65 ± 0.11 GPa) and soapstone SS40 (1.17 ± 0.12 GPa) and SS60 (1.86 ± 0.10 GPa) all had small variation in the results because of their relatively good dispersion in the matrix. The particulate and fiber filling increased the stiffness of the composites with the exception of GYP40. A great deal of variation is visible in the tensile modulus of NFR60, NFF60, GF40, and MWR60. A common factor for all of these is the large amount of porosity revealed by the SEM analysis and the calculated difference between the supposed and calculated density. Both GF40 and MWR60 exhibit heavy clustering of small fibers without proper adhesion to the matrix, which explains the variation in the tensile modulus.

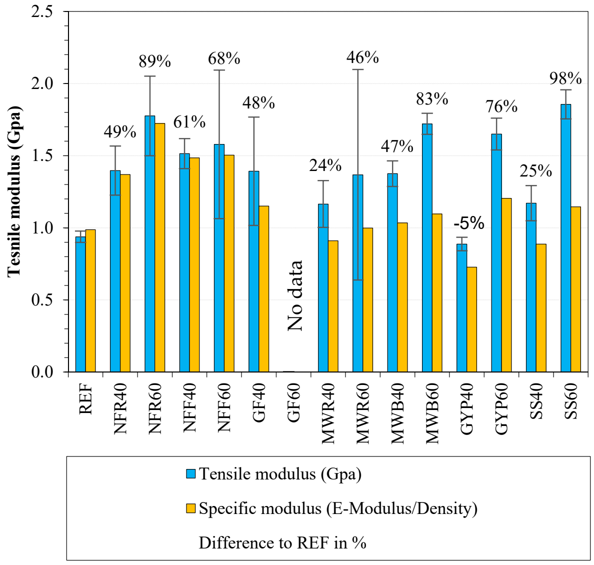

Figure 9. Tensile modulus of HDPE-based composites.

3.1.4. Brinell Hardness

Hardness is the degree of permanent deformation of a material under an applied force. Figure 10 displays the results for the measured Brinell and the hardness in relation to density. There was a small increase in the Brinell hardness in the composites MWR60 (6.0 ± 0.5 HB), GYP60 (6.1 ± 0.3 HB), and SS60 (6.1 ± 0.2 HB) compared with the REF (5.6 ± 0.5 HB) material. However, when the increase in density is taken into consideration, soapstone is not a very efficient filler for increasing the surface hardness of the composite. In a previous study, the addition of mineral wool (40 wt %) to the recycled HDPE increased the Brinell hardness by 37% [35]. Another study reported that composites with 20, 30, and 40% of recycled mineral had 10.5, 16.5, and 20.6% lower Brinell hardness, respectively, than the reference [18]. The smaller content of the filler and better interfacial adhesion of particles to the polymer matrix was used to explain the greater hardness in the lower filler content [18]. Here, the filling effect of mineral wool lowered the Brinell hardness in MWR40 (4.7 ± 0.8 HB) by 16% and in MWB60 (5.2 ± 0.5 HB) by 7%. However, in the MWB40 (5.7 ± 0.3 HB) and MWR60 samples, the hardness increased by 1% and 7%, respectively. It would seem that the influence of mineral wool filling on hardness is not completely predictable with high fill rates. The highest hardness value was obtained in the SS60 composite; it had the least amount of variation in results. This is surprising, as soapstone mainly consists of talc, of which the Mohs hardness is lower than that of gypsum or silicon dioxide, which is one of the main components in mineral wool [38]. The composite SS40 (4.9 ± 0.4 HB) had a significantly lower hardness than SS60 and REF. This could be due to the fill rate decreasing the elastic properties of plastic but not creating highly packed zones of mineral material. GYP60 (6.1±0.3 HB) had the same hardness value as SS60 and the result for GYP40 (4.9 ± 0.4 HB) was higher than for SS40, which might be due to better packing of material, as the density comparison in Table 1 shows. Composites that had natural fiber filling demonstrated elastic behavior and spring-back, which explains the rather high values for hardness compared with the composites with mineral fillers. Both glass fiber samples GF40 (4.7 ± 0.5 HB) and GF60 (2.6 ± 0.3 HB) had the poorest results for hardness due to their soft fiber bundles on the surface of the material that gave way during the indentation test. In the GF60 samples, there was an approximately 1 mm layer of loose and soft fiber material. Previously, when glass fiber has been added as reinforcement to a wood plastic composite, a small increase in hardness has been reported [37]. However, the previous studies used only 10% of glass fiber, which dispersed more homogenously into the matrix and did not create soft fiber bundles.

The hardness for wood plastic composite samples NFF40 (5.4 ± 0.8 HB), NFF60 (5.2 ± 0.5 HB), NFR40 (5.8 ± 0.9 HB), and NFR60 (5.1 ± 0.6 HB) was lower than in the REF material, probably because of the wood fibers close to the surface that gave way under pressure. When taking into consideration the increase in density and the lowering effect of the tested fillers, it can be stated that they are not advantageous for hardening the plastic. The reference material HDPE is better protected from permanent deformation by its uncompromised elasticity.

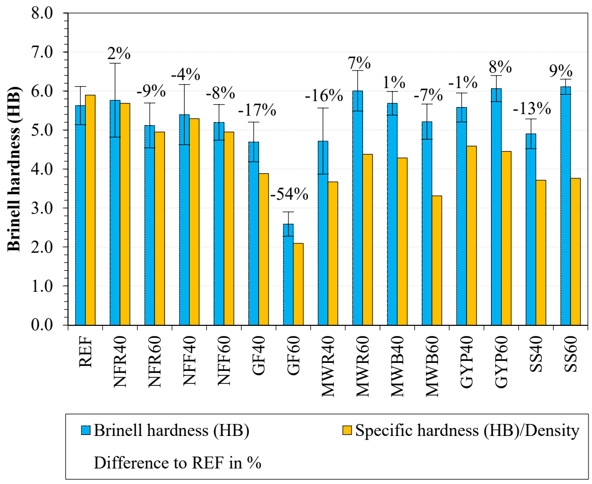

Figure 10. Brinell hardness of HDPE-based composites.

3.2. Morphology of Fractured Surfaces

The scanning electronic microscopy can be used to analyze the topography of the broken tensile strength samples to determine fracture mechanisms and the dispersion of filler materials in the matrix. Figure 11 displays the SEM images for selected specimens. The broken surface of the REF material shows small impurities. It is unlikely that these small particles would have had a major effect on the mechanical properties, as they seem to be just on the surface of the material. Small bits of unmelted plastic of different colors were visible on the surface of processed HDPE samples. Small quantities of impurities are often carried to the plastic material from the recycling process. The wood fibers seem to have been clustered in some parts of the broken surface; the concentrations of wood without the plastic matrix are weak points in the composite. Signs of fiber pullouts are visible in parts of the wood plastic composite. Debonding and fiber pullouts are dominant deformation processes when adhesion between the fiber and the matrix is poor [1]. The GF40 sample shows a small amount of plastic material on the glass fiber surface suggesting weak bonding between the matrix and the fiber. The scanning electron microscopy indicates the heavy clustering of glass fibers, which has probably impeded the flow of plastic during molding, likely causing the relatively high variation in the GF40 tensile strength results. Surprisingly, the impact strength results of GF40 were the second highest after REF. The glass fiber samples with 40% and 60% had both relatively high fill rates, and it is likely that with a smaller fill rate, the matrix would have a more heterogeneous structure and better processing quality. The fiber surface in MWR40 is clean of plastic material, suggesting weak bonding of the filler to the thermoplastic matrix. In the mineral wool based MWB40 and MWB60, the broken surfaces of the composite samples show the dislocations of the filler from the matrix. The matrix in both MWB40 and MWB60 shows signs of a tear by stretching; there are also grooves which show signs of fiber pull-outs. In the GYP60, the gypsum particulates have dispersed well into the material, which is demonstrated also by smaller deviation in the test results for mechanical properties in the samples. The gypsum filler in GYP40 and GYP60 displays clean surfaces without plastic to create proper adhesion in the points of break. The porosity and dislocation of the particulates from the matrix can be seen in the fracture scans of SS40 and SS60, but more in SS60. The large deviation in the tensile strength results of SS60 samples is related to the strong cavity formation around the soapstone particles.

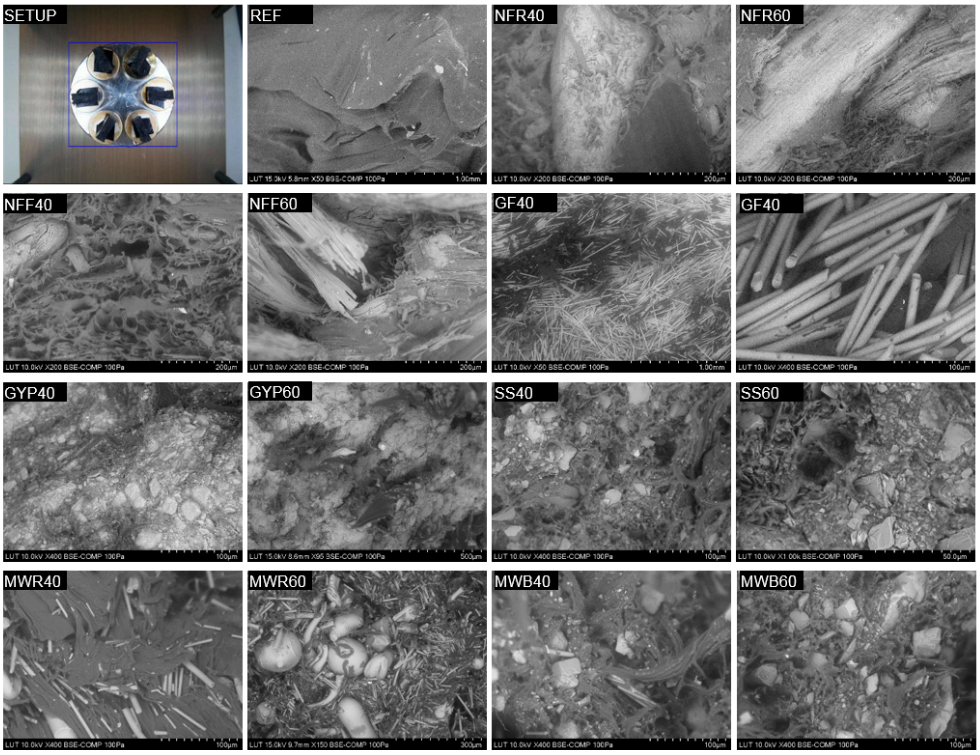

Figure 11. Scanning electron microscopy of broken tensile sample surfaces.

3.3. Effects of Porosity in Mechanical Properties

The porosity for the tested composites is presented in Tables 1 and 2. The strength of the particulate filled composite depend strongly on the stress transfer between the filler and the matrix [39]. The void content and their shape, size, and location effect on the mechanical properties and to the mechanisms leading to mechanical failure stress/strain concentration effects [40]. This phenomenon is visible in the strain curves of composite SS60 which had relatively high porosity (25.3%) see Figure 12. Similar behavior could be seen in the composites with lower volume of porosity suggesting also irregularity in the dispersion of filler material. The presence of both resin and interlaminar voids is verified in the SEM of broken tensile samples see Figure 11. The influence of high porosity is most clearly seen in the soapstone filled composites SS40 and SS60. Both SS40 and SS60 had high variance in impact and tensile strength properties, whereas GYP40 and GYP60 had little porosity and small variance. The lack of heating in the mold probably affected adversely the properties of the composite as the trapped air had not enough time to move through the channel before the solidification of material.

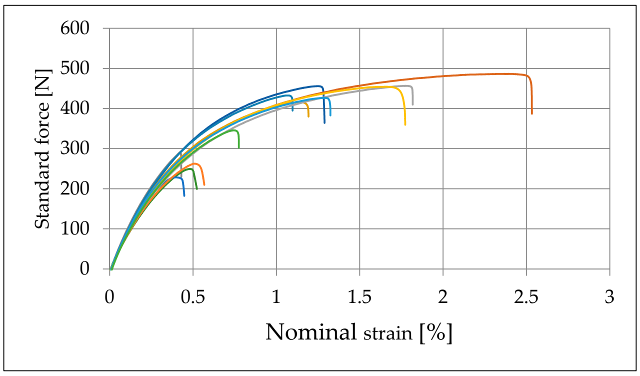

Figure 12. Strain curve of SS60 composite samples.

3.4. Moisture Absorption and Thickness Swelling

Moisture absorption and thickness swelling divided the tested materials into two distinct categories by performance: fiber and particle filled composites (see Table 3). The reference material REF did not absorb water during the immersion time of 28 days. The wood plastic composites NFR60 and NFF60 absorbed approximately 13 wt % of water during the test period. The difference in performance between the 40% and 60% mixture was considerable as the NFR40 and NFF40 absorbed 5 wt % of water. The thickness swelling in wood plastic composites NFR60 and NFF60 was 4%, while the NFR40 and NFF40 had only 1%. The fiber mesh size had only a minimal effect on the moisture absorption, as shown also in previous studies [33]. It is notable that the wood plastic composite samples with both mesh sizes had significantly smaller thickness swelling than reported previously for compression molded wood plastics [41]. This can be attributed to the used coupling agent maleic anhydride modified polyethylene, which has been shown to improve the water absorption resistance of wood plastic composites [42]. The glass fiber 60% composite GF60 absorbed approximately 10 wt % of water during the immersion, performing more weakly than the hydrophilic wood plastic composites NFR40 and NFF40. In both of the glass fiber compositions, the poor surface quality, lack of plastic film on the surface, clustering of fibers and weak bonding formed pathways for the water to enter into the composite increasing the water absorption to a relatively high level considering the hydrophobicity of the materials used. The poor quality of the glass fiber samples was evident also in the thickness swelling measurement as the material was actually separated from the samples during the immersion period.

Table 3. Moisture absorption and thickness swelling after immersion of 28 days.

	REF	NFR40	NFR60	NFF40	NFF60	GF40	GF60	MWR40	MWR60	MWB40	MWB60	GYP40	GYP60	SS40	SS60
MA wt %	0.4	5.0	13.5	5.0	12.9	2.3	9.7	0.3	0.8	0.3	0.3	0.2	1.1	0.3	0.1
TS %	0.0	1.2	4.4	1.2	4.3	−0.3	−1.1	−0.4	1.2	−0.1	−1.2	0.0	1.0	−0.2	−0.4

The water absorption and thickness swelling of the particle based composites was negligible. The highest value for thickness swelling in particle-filled composites was approximately 1% in the MWR60 and GYP60 composites. A small amount of filler material was separated during the immersion time, which would seem to suggest an incomplete covering of the particulates by the matrix on the surface of the composite samples. This could be seen from the visible mineral particles in the water container after drying the tested samples.

3.5. Evaluation of Heat Build-Up and Color Measurements

The rise of temperature in the composite material exposed to thermal radiation is related to the optical properties [43]. Figure 13 presents the measured CIE L*, a*, and b* color values, with specular component included (SCI) and specular component excluded (SCE). The lightness *L represents the darkest black at *L = 0, and bright white at *L = 100. The measured values for a* and b* represent the true neutral grey value at a* = 0 and b* = 0. The green color is represented at negative a* values and red at positive a* values. The b* negative values represent blue and the positive b* values represent yellow color. The composite CIE-LAB values were estimated using Colorizer [44]. The black reference sample REF had an *L value of 25.20, whereas the results for the mineral filled samples were in the range 25.50–28.26. The exception to this was MWR60 with *L 32.61. For the wood plastic samples, the *L value ranged between 44.01 and 51.06, resulting in decreased heat build-up. The composites with the mineral fill rate 40% increased the heat build-up by 4.5% compared with the reference material REF. The samples with a 60% mineral fill rate had no significant change in heat build-up compared with REF. The addition of wood fibers had on average a 10% decrease in heat build-up. The use of wood particles resulted in lighter colors than the black REF material. The results for wood plastic composite samples were close to previously reported ones with recycled materials [14]. Both wood and glass fiber filling had the greatest impact on the optical properties compared with the reference material. The mineral filled composites had relatively low values for reflectance compared with wood plastic and glass fiber samples. This can lead to higher heat build-up values, as Figure 14 shows. The carbon black originally used to color the recycled sewer pipe plastic had the greatest influence on the optical properties of the composite. The addition of mineral and fiber fillers, however, decreased the reflectance of the plastic, giving it more of a dull type appearance. The filler particulate size could also have affected the results of the color measurements, as the wood fibers were several times larger than any of the other filler type particles that were milled into dust in the agglomerating stage. The importance of color depends on the application and market trends; therefore, the effect of filler on the visual look of the product should be assessed case by case.

	REF	NFR40	NFR60	NFF40	NFF60	GF40	GF60	MWR40	MWR60	MWB40	MWB60	GYP40	GYP60	SS40	SS60
SCI															
L*=	25.2	44.0	51.1	43.9	48.1	36.8	38.0	27.8	32.6	27.0	25.9	25.4	25.5	28.5	28.3
a*=	0.0	2.4	2.1	1.3	1.2	0.0	0.4	−0.2	−0.3	−0.2	−0.1	−0.2	−0.2	−0.3	−0.1
b*=	−0.3	12.4	13.2	9.4	10.2	0.4	2.7	3.3	5.9	0.9	−0.4	−0.7	0.0	−0.3	−0.3

Figure 13. CIE L*, a*, and b* color coordinates of the studied composites.

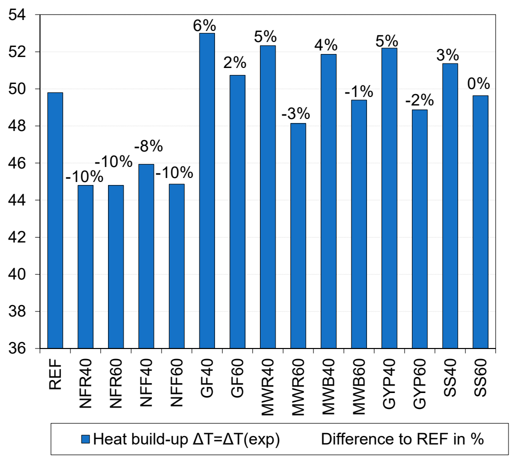

Figure 14. Heat build-up of the studied composites.

4. Conclusions

In this study, compression-molded composites were made of recycled materials, and their mechanical properties were examined. The morphology of the HDPE/recycled material composites was analyzed by observing the tensile pull-fracture surface. The recycled filler materials were able to significantly improve the tensile modulus of the recycled HDPE but had a decreasing effect on impact strength, tensile strength and elasticity. The Brinell hardness of the plastic did not improve with the addition of mineral fillers even with 60% fill rates, and most of the composites had lower values for hardness with the exception of MWR60 and GYP60. The measured densities of the composites did not follow the rule-of-mixture, which would seem to suggest uneven mixing in the processing phase and porosity in the samples. This was supported by voids and clustered particles found in the SEM analysis and in the variance in the tensile strength and tensile modulus properties especially in composites with fiber filling. Porosity and clustering of filler material were identified as major causes for variance in mechanical properties. The lack of hot-melt mixing during material processing probably had a negative effect on the final composite mechanical properties. The hot-melt mixing would have improved the dispersion of the filler materials into the matrix. The tested mineral particle filled composites could be used in a variety of compression molded products previously made of recycled plastic, especially where a large volume of material is needed. The composites with mineral fillers had better resistance to moisture compared to wood plastic composites, which would be beneficial especially in outdoor applications. The heat built-up in composites with mineral fillers was higher than in the ones with wood, which suggest that natural fibers are still a better option for producing decking products. The recycled glass fiber did not function optimally with the used recycled plastic as it did not mix properly into the matrix, therefore, the combination as such is not advisable due to the risk of fiber separation. The use of filler type specific coupling agents and improved mixing during processing could further improve the properties throughout the tested material range. Future studies on the methodology of designing products with recycled material composites are required. Furthermore, the economics and carbon footprint of such production should be verified to better understand the potential of the recycled materials in composites.

Author Contributions: P.S. designed tooling, produced the samples, tested the materials, performed the analysis and investigation part and prepared the paper; T.K. provided supervision for the project and contributed to the methodology selection.

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Publication III

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Article

Promoting and Demoting Factors of Ecodesign Methodologies for The Application of Recycled Construction Waste: A Case Study of a Composite Product

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Abstract: Thermoplastic composites manufacturing could be a potential end-of-life option for separated construction and demolition waste. This study aims to find out how well the established ecodesign methodologies support the choice of recycled composite materials in new product design, and what challenges these materials offer to the designer. A product design case study was conducted by applying the ecodesign methodologies Environmental Quality Function Deployment and Technique for Order of Preference by Similarity to Ideal Solution, to identify the main promoting and demoting factors from the designer's point of view. The rate of recycled material is the main promoting factor, but biodegradability, recyclability, and the mixing of materials are usually demoting the composite use. The use of multiple criteria analysis techniques can work in favor of the composite, as the mechanical and physical properties are taken into consideration. The paper discusses the potential challenges the designer faces when evaluating the feasibility of using recycled material composites. The design suggests that new uses for waste that previously went to landfill, such as mineral wool, can be found with composite solutions.

Keywords: eco-design; circular construction; design for environment; recycling potential

1. Introduction

Global population growth and urbanization leads to a continuous construction and reconstruction, however, this will not come without consequences. Building activities generate a large amount of waste which, in accordance with the principles of a circular economy, should be turned back to use [1]. The circular economy and sustainable construction have the potential to reduce urban carbon emissions, and create new jobs and opportunities to improve the quality of life of urban citizens [2]. The holistic process of designing future zero waste cities reconceptualizes waste as a valuable flow of material resources [3,4]. Mass flow analysis methods can be used to determine the composition of building material stock that needs to be recycled in the future [5,6], which in turn can be used to evaluate the capability needs of the urban waste management and recycling systems. The major part of the demolition waste is composed of crushed concrete, masonry, and mixed debris [1,6,7], but also include wood, plastics, gypsum, and mineral wool that have been tested as composite raw material [8]. Using the recycled materials in new product manufacturing can also help to fight resource depletion and improve material use efficiency [9,10].

The recycled material composite (RMC) is a combined material where the recycled fraction can work as reinforcement, filler, or the matrix component. The use of recycled materials in composites could be a means to improve the usability of recyclates previously sent to landfill. Some authors have criticized the use of downgrading materials, as they have the potential to increase the overall production, which partially reduces the environmental benefits [11], therefore it is important to study how these materials fare in the ecodesign design practices that are implemented in the industries of today. Products in the construction sector offer a great opportunity to implement the strategies of eco- and circular design, as the expected lifetime of a building is often planned for 50 years or more. The calculated environmental costs and benefits are distributed over the long lifetime, meaning that the design for sustainability should be inbuilt in the building product design. More efficient replacement of components with shorter lifetimes than the building is possible with the aid of digitalization and building information storing. The digital twin of a building could be used to define what materials are inside the building and how they should be recycled [12,13].

RMCs have been used mainly in the wood plastic composites (WPC) sector, where the use of recycled material has been common for decades. These composites have been advertised for having green or ecological properties due to their recycled and renewable material content. Life-cycle assessment (LCA) studies have verified some of the claimed environmental benefits related to WPC products with recycled materials [14–17]. The range of WPC filler materials has been expanded by studies to encompass also construction and demolition waste [18,19]. It is shown that construction waste recycling is sustainable from economic, environmental, and energy perspectives [20–22]. Likewise, building material reuse and recycling activities in most cases provide economic and environmental benefits, but are influenced by many site specifics, such as the type of material, transport distances, and the economic and political context [23]. Despite the environmental potential, economic benefits and the technical feasibility, the use of recycled composite materials has not expanded outside the traditional WPC decking applications. The role of the designer responsible for potentially selecting the RMCs has not been studied before. This study aims to find out how well the established ecodesign methodologies support the choice of RMCs in new product design. Eco-design and design for the environment are terms that are understood as a development process that take into account the complete life cycle and environmental aspects of a product at all stages of the process, striving for products that have the lowest possible environmental impact throughout its life cycle. These two terms encompass eco-efficiency, health and safety, remanufacturing, recycling, source reduction, and waste minimization, and they are linked to life cycle assessment [24,25]. The hypothesis is that the repeating patterns in the structure of ecodesign methodologies can be used to identify promoting and demoting factors in recycled composite material use. The identification of these factors can help designers to estimate the applicability of recycled materials in their products.

2. Materials and Methods

The goal of this study is to find repeating patterns from the studied ecodesign methodologies, that affect the chances of RMCs to be chosen. A vast range of ecodesign methodologies exists, and for this study, two different methods were chosen as the framework. An extensive work called the eco-tool seeker by Rousseaux et al. (2017) [26] was used to identify ecodesign methodology through which the case study product would be put through. It was discovered that international sectoral ecodesign standards relating to the case study were not available; therefore, it was decided that a combination of two methodologies would be used. Environmental Quality Function Deployment (EQFD) [27,28] for the environmental criteria, and weightings and Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) for numerical material comparison [29]. The case study helps to understand the factors influencing the materials selection process in a functional context, where the material properties and characteristics of the product are taken into consideration. The chronological structure of the study framework is presented in Figure 1.

EQFD combined with multi-criteria decision analysis has been used to assess sustainability and materials selection with multiple constraints [29]. Multi-criteria analysis methods with weight factors are often employed when the group of possibilities is large and conflicting design objectives are ranked. House of Environment (HoE) is used to weight the different criteria and it has been employed in several ecodesign studies [27,28,30,31]. A voice of the customer (VoC) structured interview was conducted in a Finnish company that manufactures and sells heating and cooling solutions. The respondents were experts working closely with underfloor heating business-to-business customers. Respondents were asked to answer how would they evaluate different requirements given to the product from a customer's point of view (a EQFD scale of 1, 3, and 9 was used). The questionnaire featured a list of expected customer and environmental criteria, a similar approach has been applied to composites by Mastura et al. (2017) [32]. Answers to the VoC questionnaire were two-fold, as the presence of ecological factors was seen positively, but at the same time concerns were raised about how much the contractor customer values the ecological criteria over cost. Environmental criteria was seen as important, as long as it does not affect the functionality negatively or increase the price of the product. A House of Quality (HoQ) table was developed from the VoC questionnaire results, and the customer requirements were translated into metrics, of which the dependencies of requirements were cross-checked and the technical importance ratings (T_R) and relative weights (R_w) were calculated. The EQFD metrics and component matrix relative weights (R_{WM}) were used as an input for the functions and components matrix, where the concepts were also compared against the main functions that the product should fulfil. Functions and components relative weight (R_{WF}) indicates which functions the designs mostly focus on. The main phases of the TOPSIS material selections procedure following the EQFD are shown in Figure 2.

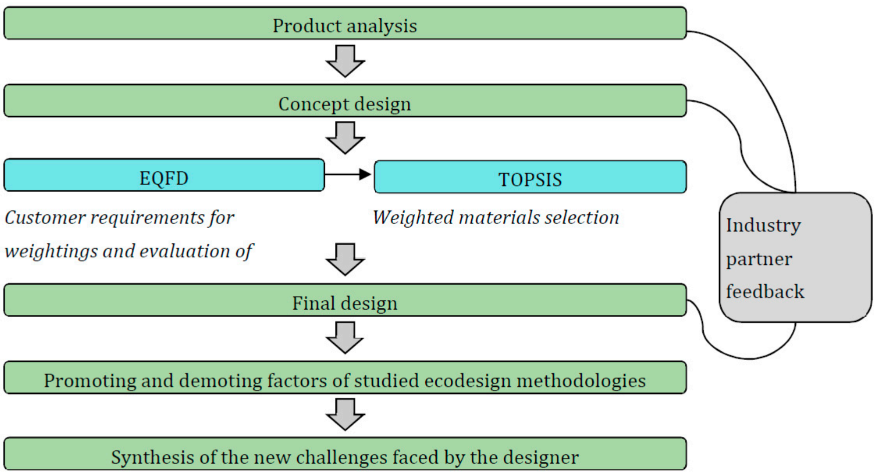

Figure 1. Structure of the study.

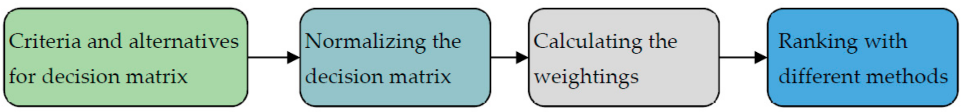

Figure 2. TOPSIS (Technique for Order of Preference by Similarity to Ideal Solution) method main phases.

In order to benchmark the RMCs to virgin materials, a group of materials with properties is needed. The used composite recipes from recycled materials are described in Table 1 [18,19,33–35]. The abbreviations for fillers are PP (polypropylene), PE (polyethylene), WF (wood fiber), CDW (mixed construction and demolition waste), MW (mineral wool), GYP (gypsum), and SS (soapstone processing waste). The recycled material studies did not contain all the required physical properties; therefore, we estimated the missing properties such as coefficient of thermal expansion (CTE), density, and thermal conductivity. The CTE was estimated from the respective plastic matrix to be inversely proportionate to the filler amount [36]. Thermal conductivity of recipes 1–3 and recipe 6 was estimated as 0.35–0.36 W/(mK) and for recipes 4–5 0.40 W/(mK) [37–39]. Density for recipes 1, 2, 3, and 6 was estimated from their composition; the extruded WPC density is commonly 1.05–1.20 g/cm^3.

Table 1. Composition of materials.

Composite	PP	PE	WF	CDW	MW	GYP	SS	Coupling Agent	Processing Aid	Ref.
Recipe 1	12%	28%	54%	-	-	-	-	3%	3%	[33]
Recipe 2	30%	-	44%	20%	-	-	-	3%	3%	[34]
Recipe 3	30%	-	24%	-	40%	-	-	3%	3%	[18]
Recipe 4	-	54%	-	-	-	40%	-	3%	3%	[19]
Recipe 5	-	54%	-	-	-	-	40%	3%	3%	[19]
Recipe 6	-	30%	44%	20%	-	-	-	3%	3%	[35]

The case study product is an underfloor heating and cooling installation platform for house renovation projects, which are typically used when the application of cheaper flooring screed is not possible. The benefits of a radiant heating system are quiet operation, no air movement, reduced vertical temperature gradient, possibility to use renewable energy due to low temperature heating, lower pumping energy due to high thermal capacity of water, and reduced heating load due to precise heating areas. The use of WPC boards for flooring has previously been studied by Yi et. al. (2017) [37]. The underfloor heating insulation boards have two main functions: They act as a platform to quickly install underfloor heating piping and as a surface on which to install parquet flooring. The material used for the platform should be cheap, have sufficiently good properties to remove the need for additional floor layers, and it should be able to transfer heat efficiently enough towards the outermost layers of the floor, but limit the transfer of heat toward the ground. The underfloor installation plates need to withstand the stresses caused during the installation of the pipe. The stresses are caused mainly by the weight of the operator. The principal load situation in the product is bending. The design requirements are presented in the Table 2.

Table 2. Design requirements for underfloor heating installation platform.

Caption	Caption
Temperature range	The used temperature range is limited upwards by a maximum of 27 °C due to comport and subsequent floor layers.
Product dimensions	400 × 1200 mm, maximum board thickness 22 mm.
Installation method	Snap-fit or push-fit connection.
Mechanical properties	Elastic moduli of the used material and toughness against impacts as the plates are subjected to stepping during installation.
Thermophysical properties	Weight, thermal conductivity of the body and surface and linear thermal expansion of the used material.

An oval-shaped installation groove for the composite pipe was designed so that the pipe would hold in the groove during installation; see Table 3 for studied concepts. It should be possible to cut the installation platform material with typical hand tools that are available on site because of the need to customize boards to fit the size of the room.

Table 3. List of studied concepts.

Concept	Description
c1	Virgin plastic extruded profile.
c2	Co-extrusion composite
c3	Extruded composite with separable heat transfer sheet
c4	Machined particle board with separable heat transfer sheet.

3. Results

3.1. Environmental Quality Function Deployment

The results of VoC questionnaire can be seen in the Table 4. The respondents valued r1, r7, r8, r12, r14, and r16 to be most important customer requirements for the case study product. Metrics and their goals were concluded from the list of customer requirement; see Table 5. The metrics in relation to the customer requirements were compared and given evaluation of significance on a scale of 1, 3, and 9, which formed the HoQ charts.

Table 4. Results of voice of the customer questionnaire.

	Customer Requirement	Relative Weight	Customer Importance
r1	Low cost	8.22%	9.00
r2	Easy to reuse	1.83%	2.00
r3	Easy to recycle	2.28%	2.50
r4	Easy transportation	3.65%	4.00
r5	Easy to manufacture	5.71%	6.25
r6	Durability	6.39%	7.00
r7	Lightweight	8.22%	9.00
r8	Maintenance free	8.22%	9.00
r9	Reliability	6.85%	7.50
r10	Long lifetime	4.79%	5.25
r11	Free from hazardous substances	6.85%	7.50
r12	Less materials	8.22%	9.00
r13	Harmless to the living environment	6.85%	7.50
r14	Low height	8.22%	9.00
r15	Uniform heat distribution	5.48%	6.00
r16	Easy to install	8.22%	9.00

Table 5. House of quality metrics.

		Criteria	Goal
Technical requirements	m1	Density (g/cm^3)	Min
	m2	Lifetime (years)	Max
	m3	Modulus *E* (GPa)	Max
	m4	Coefficient of thermal expansion (10^{-6} m/(m K))	Min
	m5	Thermal conductivity (W/mK)	Min
	m6	Thermal resistance (K/W),	Max
Environmental criteria	m7	Toxicity of materials (n/a)	Min
	m8	Noise, vibration, smell, volatile organic compounds, electromagnetic waves	Min
	m9	Maintenance (n/a)	Min
	m10	Rate or reusable material (%)	Max
	m11	Rate of recyclable material (%)	Max
	m12	Rate of recycled material (%)	Max
	m13	Volume	Min
	m14	Number of parts	Min
	m15	Number of types of materials	Min
	m16	Change in appearance	Min
	m17	Hardness	Max
	m18	Biodegradability	Max
	m19	Amount of energy consumption	Min
	m20	Mass of air pollutant	Min
	m21	Mass of water pollutant	Min
	m22	Mass of soil pollutant	Min
Costs	m23	Material price €/kg	Min
	m24	Processing cost index	Min

The five most important metrics according to the HoQ analysis were density of the material, the Young's modulus, material price, volume of the product, and processing cost; see Tables 6 and 7.

Table 6. House of quality analysis for metrics m1–m11.

	m1	m2	m3	m4	m5	m6	m7	m8	m9	m10	m11
r1	9										
r2		3					9		1	9	
r3							9				9
r4											
r5											
r6	1	9	9	3							
r7	9										
r8		3		3					9		
r9		9	1	1							
r10		3		3							
r11							9	9			9
r12	9		9								
r13							9	9		3	9
r14			9								
r15					9	9					
r16	1			9							
T_R (%)	21.2	11.7	17.9	11.5	3.0	3.0	10.1	9.2	6.7	1.9	9.8
R_w (%)	10.67	5.92	9.0	5.79	1.49	1.49	5.09	4.66	3.38	0.94	4.92

Table 7. House of quality analysis for metrics m12–24.

	m12	m13	m14	m15	m16	m17	m18	m19	m20	m21	m22	m23	m24
r1	9	3										9	3
r2			9									3	
r3			9	9								3	3
r4		9											
r5		3											9
r6						1							
r7		3											
r8													
r9													
r10						1	3						
r11									1	1	1		
r12		9	3						9	9	9	9	9
r13	3						3		9	9	9		
r14													
r15								9					
r16													
T_R (%)	8.2	13.5	3.1	0.5	0.0	0.7	2.3	3.0	11.8	11.8	11.8	13.6	12.3
R_W (%)	4.14	6.80	1.54	0.26	0.00	0.35	1.16	1.49	5.95	5.95	5.95	6.86	6.18

The importance of volume and density increase when the number of environmental criteria increases, as more mass greatly affects the LCA of the product. The product concepts were evaluated on how well they fit the metrics see Table 8.

Without specifying which composite recipe to use, the concepts c2 and c3 achieved a higher score than virgin plastic c1. The low price and low thermal expansion favored the particle board (PB) solution c4 over composites. The composite had points due to being a remeltable material, unlike the PB. The properties of the board should be on a level, which makes possible the installation without additional support layers on top for the parquet flooring. Resistance to deflection should be best with the concept c3, as the heat spreader provides stiffness to a composite with already good stiffness. Concepts c3 and c4 employing the aluminum heat spreader got points for the quick response to temperature changes due to the thermal conductivity of the aluminum. Concept c4 is probably the easiest to install, as it is a known material and can be mechanically fixed to common wooden structures by screws and nails. Concepts c2 and c3 would probably require extra fixing even with the mechanical interlocking of plates. The PB was estimated to be cheaper than the composite with smaller production quantities, but c4 has two components, so we gave the same number of points to c2 and c4. All the concepts are maintenance-free in normal conditions, but the polymer solutions gain more points for their resistance to insects that might cause problems in some parts of the world. Thermal resistance towards the floor was given equal points for c2, c3, and c4, but this property depends on the composition of the composite recipe. Concepts c3 and c4 received equal points, see Table 9, so a closer comparison of the materials was needed—this was done in the TOPSIS analysis.

Table 8. EQFD (Environmental Quality Function Deployment) metrics and components matrix.

	R_W	c1	c2	c3	c4
m1	10.7	3	3	3	9
m2	5.9	9	9	9	3
m3	9.0		3	3	3
m4	5.8		3	3	9
m5	1.5		1	9	9
m6	1.5	3	3	3	3
m7	5.1	9	9	9	9
m8	4.7	3	3	3	3
m9	3.4	9	9	9	3
m10	0.9				
m11	4.9	9	3	3	1
m12	4.1		3	3	3
m13	6.8	1	1	1	1
m14	1.5	9	9	3	3
m15	0.3	9	1	1	1
m16	0.0				
m17	0.4				
m18	1.2		1	1	
m19	1.5				
m20	5.9				
m21	5.9				
m22	5.9				
m23	6.9	1	3	3	9
	Row score	2.54	2.96	2.98	3.72
	R_{WM} (%)	20.8	24.2	24.5	30.5

Table 9. EQFD functions and components matrix.

	R_{WM} (%)	Surface Heat Conductivity	Easy Installation	Light, Low-Cost Structure	Stiffness, Low Height	Maintenance Free	Thermal Resistance of Body	Total Score
c1	20.8		3	1		9	1	13.2
c2	24.2		3	3	1	9	3	22.4
c3	24.5	9	3	1	3	9	3	39.6
c4	30.5	9	9	3	1	3	3	39.6
Row score		4.94	4.83	2.09	1.28	7.17	2.58	
R_{WF} (%)		21.6%	21.1%	9.1%	5.6%	31.3%	11.3%	

3.2. TOPSIS

The EQFD phase demonstrated that the composite concept could achieve a higher rating only when it can resist deflection better than the PB solution. The composite should have either a surface layer of heat conductive material or the product should employ aluminum heat spreader like in particle board solutions. The main body of the composite product should be able to act as insulation. Concept c2 uses the idea of a heat conductive surface, but the related study [38,39] report relatively small increases in heat conductivity. Heat conductivity improving filler should be used in large quantities, which would affect the mechanical properties and the cost of the composite. The EQFD criteria m2, m6, m7–m9, m13–m14, and m16–m22 were not used in the multi-criteria analysis, as there were no numerical values used for the case studied. Target numbers were set according to the goal to minimize or maximize the given metric. The m3 was set to 3.50 Gpa according to the accepted deflection under uniformly distributed load with the designed profile. The materials that have Young's modulus lower than the target should be specified for different span length and dimensions. The target values should be set closer to the approximated product criteria values if the set of compared materials was to be enlarged to encompass material groups with high range in properties, otherwise the normalization leads to unrealistic rankings. Recipes 2 and 6 included mixed CDW fractions, which were composed of at least four different materials [35]. The material properties in Table 10 were normalized to values ranging from 0 to 1. See Table 11.

Table 10. Material properties.

Objective	**Min**	**Max**	**Min**	**Min**	**Max**	**Max**	**Max**	**Min**	**Max**	**Min**	**Min**
Criteria	**m1**	**m3**	**m4**	**m5**	**m10**	**m11**	**m12**	**m15**	**m18**	**m23**	**m24**
HDPE *	0.96	0.97	108.00	0.42	0	95	0	1	0	2.10	0.80
LDPE *	0.92	0.21	120.00	0.11	0	95	0	1	0	1.90	0.80
PP *	0.94	1.90	72.00	0.30	0	95	0	1	0	2.40	0.80
PB, low *	0.64	1.40	5.00	0.99	0	0	50	2	0	0.25	0.50
Pine wood *	2.10	7.00	5.00	0.13	100	100	0	1	100	0.73	0.80
Recipe 1	1.05	3.44	33.12	0.35	0	0	94	3	0	0.40	1.00
Recipe 2	1.10	4.04	25.92	0.35	0	0	64	6	0	0.62	1.00
Recipe 3	1.15	5.42	24.48	0.36	0	0	64	3	0	0.58	1.00
Recipe 4	1.22	0.89	64.80	0.40	0	0	94	2	0	0.38	1.00
Recipe 5	1.32	1.17	64.80	0.40	0	0	94	2	0	0.46	1.00
Recipe 6	1.10	4.38	60.48	0.35	0	0	94	6	0	0.32	1.00
Target	0.00	3.50	0.00	0.00	100	100	100	1	100	0.00	0.00

* Mechanical and thermal conductivity of plastics properties [40], material price for virgin polymers [41], material prices for composites [42], particle board properties [43], coefficients of linear thermal expansion [44].

Table 11. Normalization of material properties.

	m1	**m3**	**m4**	**m5**	**m10**	**m11**	**m12**	**m15**	**m18**	**m23**	**m24**
HDPE *	0.54	0.63	0.10	0.57	0.00	0.95	0.00	1.00	0.00	0.04	0.20
LDPE *	0.56	0.52	0.00	0.89	0.00	0.95	0.00	1.00	0.00	0.04	0.20
PP *	0.55	0.76	0.40	0.70	0.00	0.95	0.00	1.00	0.00	0.00	0.20
PB, low	0.70	0.69	0.96	0.00	0.00	0.00	0.50	0.80	0.00	0.90	0.50
Pine wood	0.70	0.48	0.96	0.87	1.00	1.00	0.00	1.00	1.00	0.70	0.20
Recipe 1	0.50	0.99	0.72	0.64	0.00	0.00	0.94	0.60	0.00	0.83	0.00
Recipe 2	0.48	0.79	0.78	0.64	0.00	0.00	0.64	0.00	0.00	0.74	0.00
Recipe 3	0.45	0.72	0.80	0.63	0.00	0.00	0.64	0.60	0.00	0.76	0.00
Recipe 4	0.42	0.62	0.46	0.59	0.00	0.00	0.94	0.80	0.00	0.84	0.00
Recipe 5	0.37	0.66	0.46	0.59	0.00	0.00	0.94	0.80	0.00	0.81	0.00
Recipe 6	0.48	0.87	0.50	0.64	0.00	0.00	0.94	0.00	0.00	0.87	0.00

The materials were ranked using the normalized values and the weightings gained from EQFD; see Table 12. The highest (V+) and lowest (V–) values were returned and used in the following calculation. The matrix product of two arrays returns the sum of squares of differences corresponding values in studied array compared for highest value (D+) and lowest value (D–). The half-squared distance (C) is used to rank (R) the materials. The top five materials for the product concept according to the study were recipe 3, virgin polypropylene (PP), recipe 4, recipe 5, and virgin high-density polyethylene (HDPE).

Table 12. Ranking based on normalized values with weightings from EQFD.

	m1	m3	m4	m5	m10	m11	m12	m15	m18	m23	m24	D+	D-	C	R
HDPE *	0.06	0.06	0.01	0.01	0.00	0.05	0.04	0.00	0.00	0.00	0.01	0.017	−0.006	−0.51	5
LDPE *	0.06	0.05	0.00	0.01	0.00	0.05	0.04	0,00	0,00	0.00	0.01	0.017	−0.005	−0.41	6
PP *	0.06	0.07	0.02	0.01	0.00	0.05	0.04	0.00	0.00	0.00	0.01	0.014	−0.008	−1.16	2
PB, low	0.07	0.06	0.06	0.00	0.00	0.00	0.02	0.00	0.00	0.06	0.04	0.008	−0.014	2.30	7
Pine wood	0.07	0.04	0.06	0.01	0.01	0.05	0.00	0.00	0.01	0.05	0.03	0.010	−0.012	5.14	9
Recipe 1	0.05	0.09	0.04	0.01	0.00	0.00	0.04	0.00	0.00	0.06	0.00	0.008	−0.014	2.41	8
Recipe 2	0.05	0.07	0.05	0.01	0.00	0.00	0.03	0.00	0.00	0.05	0.00	0.011	−0.011	16.45	10
Recipe 3	0.05	0.06	0.05	0.01	0.00	0.00	0.03	0.00	0.00	0.05	0.00	0.013	−0.009	−1.78	1
Recipe 4	0.04	0.06	0.03	0.01	0.00	0.00	0.04	0.00	0.00	0.06	0.00	0.015	−0.007	−0.94	3
Recipe 5	0.04	0.06	0.03	0.01	0.00	0.00	0.04	0.00	0.00	0.06	0.00	0.015	−0.007	−0.85	4
Recipe 6	0.05	0.08	0.03	0.01	0.00	0.00	0.04	0.00	0.00	0.06	0.00	0.011	−0.011	40.61	11
V+	0.07	0.09	0.06	0.01	0.01	0.05	0.04	0.00	0.01	0.06	0.03				
V-	0.04	0.04	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00				

3.3. Synthesis of the Used Criteria in Relation to Recycled Material Composites

The density (m1) of the composites is generally higher than that of HDPE and PP, but the higher modulus (m3) of the composite materials something that can increase their ranking compared to HDPE and PP. The ability to make hollow sandwich structures makes it possible to decrease the weight of the structure and further benefit from the higher modulus. A physical lifetime (m2) at the product level is a system level issue, but at the component level it can be considered a material issue. The behavior of recycled material composites over a long time is relatively unknown, and this could potentially scare the designer responsible for the material selection. One underlying problem for finding new applications for recycled materials composites is that some properties needed in the design of new products have not been measured in the studies. The compared composite recipes did not have thermal properties (m4–m6) ready, so they had to be estimated, which is a likely situation for any designer interested in these materials.

Toxicity of materials (m7) is a metric that does not promote composites over virgin materials. The manufacturer is responsible for the safe use of the product and should enforce appropriate quality and health safety controls for the materials used. Noise vibration electromagnetic waves (m8) or maintenance requirement (m9) were not significant metrics in this study, but in some other cases, the improved moisture resistance could favor WPC type solutions over wood materials. The rate of reusable material (m10) relates to the probability of product material circulating back to existing or new applications. Because the property is dependent on the product type, it is difficult to estimate the reusability property for different materials. The reusability was not seen as a possible end-of-life solution for polymer-based materials in the construction sector context.

The rate of recyclable material (m11) has the effect of composites from recycled materials being less tempting, as they are multi-materials with often no other realistic end-of-life potential than energy use. Studies have been made in the recycling of both thermoplastic [45,46] and thermoset composites [47], but to the author's knowledge, the waste management practices in this field are still lacking. A collection scheme by manufacturers would affect this, but in the case study, the construction material needs to stay in the building for at least 50 years, therefore, this type of business model is not a credible alternative, as the collecting company would probably not exist at the end-of-life stage. The rate of recycled material (m12) should be maximized in the composite recipe in order to gain an advantage over virgin materials; but this needs to be done with functional properties in mind, otherwise the environmental benefit is detrimental to the overall design.

The volume (m13) or dimensions of the product can in some previously thermoplastic applications be designed smaller due to improved properties of the composite compared to virgin plastic. The use of volume as analysis metric requires additional calculations for the optional materials. After which, the required product dimensions for each material can be used in the EFQD and multi-criteria comparison matrices. The number of parts (m14) has a two-fold influence in multi-material product systems as the potential of single material in relation to environmental or cost benefits becomes smaller, therefore, reducing the likelihood of changing the material from virgin to recycled. The number of types of materials (m15) tends to shift designs to more simplified bill-of-materials and fewer different suppliers, which can be good from the supply chain point of view. The number of different materials in the case of singular parts is something to be minimized, as it makes recycling a more realistic end-of-life option.

The change in appearance (m16) is a metric that is related to the tendency of discarding products that look worn or dirty. Composites and recycled plastics have relatively good protection against absorption and smooth surfaces, but the same can be said about many other materials. The hardness metric (m17) is the product's ability to resist dents, but there is no clear push towards recycled material composites.

Biodegradability (m18) usually demotes the use of recycled material composites and favors the use of natural materials and biodegradable plastics such as polylactic acid. The amount of energy consumption (m19) during life cycle can promote composite materials if their use reduces energy consumption, e.g., lightweight parts for vehicles. The embodied energy can be reduced due to recycled material content or in some cases longer lifetime of a product. Good examples of this are wood-plastic composites with their low maintenance demand and good resistance to moisture. The end user does not need to replace the terrace material as often as if modified wood was used instead. The mass of air (m20), water (m21), and soil pollutants (m22) are metrics that can be used in the analysis after the LCA has been performed to the group of compared materials. A problem that the ecodesign methodology user faces is that the LCA requires knowhow that is often not available inside the company. The LCA is also very time consuming and difficult to use procedure in the early stages of design. The most difficult thing to input was the material price (m23) and the processing cost index (m24) for the materials, as there is a lack of data concerning the economics of the composites. The use of recycled thermoplastics is known to lead to a lower melt-flow index number, which usually means that they are harder to process. The thermoplastic composites made of recycled content are often improved with processing aid and compatibilizer, which increases the total cost of otherwise cheap material. There is a great deal of variance in the processability of plastics from postindustrial and post-consumer sources [48]. The recycled material can increase the scrap rate and decrease the total output, therefore, we estimated the processing cost index (m24) to be higher than of virgin materials.

Table 13 shows the ranking with the methodologies used. The TOPSIS method was used only for materials comparison, and therefore concepts c2 and c3 have the same ranking. By comparing EQFD and TOPSIS, we can see some ranking reversal. The change in ranking is caused by the inclusion of material property values in TOPSIS that are not used in the EQFD method. The high weighting of modulus can help to explain this. The contemporary PB solution fares better in EQFD analysis where it is a slightly stronger contender compared to concepts made of composite. The inclusion of LCA could have also changed the ranking of materials in the TOPSIS ranking.

Table 13. Concept rankings with different methodologies.

	EQFD	**TOPSIS**
c1	4	2
c2	3	1
c3	1	1
c4	1	3

The promoting and demoting factors in used methodologies in relation to recycled composite material are presented in Table 14.

Table 14. Positive and negative factors of studied ecodesign methodologies.

	Specifics	Promote	Demote
EQFD	Numerical qualitative method, which cross checks customer requirements to functional requirements in order to evaluate the design. The method is often used to gain weightings for more detailed design.	Rate of recycled material works in favor of the composite if compared to virgin plastic product concepts when the functional properties are otherwise at a similar level.	The criteria biodegradability, recyclability, and the number of materials generally demote the use of composite materials.
TOPSIS	Quantitative method where the material properties are normalized to the design target number. Weightings are used to steer the importance of certain properties over others according to design criteria.	Functional properties if higher than base matrix material of the composite. Depend on the selected environmental criteria.	Demoting factors depend largely on the sustainability properties that are selected for the numerical evaluation.

3.4. Product Design Based on Ecodesign Methodologies

The final design employs an extruded composite frame on top of which aluminum heat spreaders are installed on site. The composite frame is installed on top of a wooden floor frame or a flat surface. As the initial idea of the concept was to be mostly used in renovation cases, the goal was to make it possible to use a longer support span without the need for additional cross joists that are needed with other underfloor heating installation systems. Table 15 summarizes the estimated benefits and disadvantages of composite product compared to products on the market. Compared to some solutions in the market, the composite concept would likely compete only with the particle board underfloor heating boards in renovation or wood building cases. The most common solutions based on the extruded polystyrene boards or screed are really cheap and fast ways to install underfloor heating in new buildings, whereas the composite boards require special fixing systems and taking into consideration the potential heat expansion.

Table 15. Benchmarking of composite concept to available solutions.

Solution	Benefits	Disadvantages
Extruded polystyrene	The composite system does not require as many support structures underneath.	Underfloor heating offer with composite solution is likely to have more expensive materials.
Particle board	Longer floor frame span can be used in the composite design. The matrix material in the composite is remeltable, unlike the resin-based PB system.	Composite solution might be difficult to sell with ecological values, as the particle board has a more wooden look and feel to it. People are used to PB and might resist new materials.
Screed	The composite solution can be installed on top of the floor frame, making it a less complex installation in the renovation of older wooden houses.	Composite solution is much more expensive than screed solutions, which is the most common solution when the installation type is possible.

The final concept prepared for the case study design is presented in Figure 3. The design takes advantage of the higher strength of composite plates for a longer assembly span and low installation height. The product could be especially useful in retrofitting suspended underfloor heating in renovation cases. The extruded profiles should be clearly marked so that the components of the composite would be recognizable for future recycling.

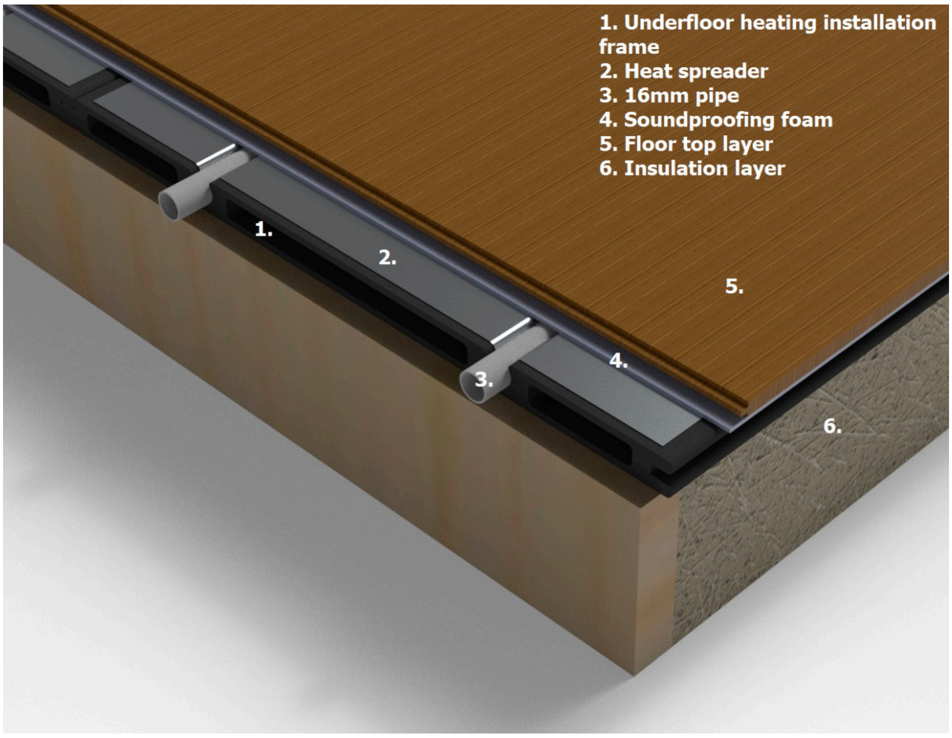

Figure 3. Final concept.

4. Discussion

When estimating the suitability for design, the recycled materials present a practical difficulty, which is the lack of design values. The properties are in turn relatively easy to acquire with commercial virgin materials from the supplier data sheets. The data sheet in turn is the supplier's declaration of its product (material), which the designers are inclined to trust; this is a connection that is hard to obtain with academic papers. A variety of studies have been carried out about recycled and other sustainable materials in composites. The focus has been on material properties testing, and they often suffer from not going to the application level, which in turn could provide more credibility for their potential. In the case of insufficient information, the data extracted from handbooks and online databases can be used to estimate the results, but it does not provide a feeling of security, as the material providers are not supplying this "hypothetical" material. The results of the material tests depend on several factors such as material quality, pretreatment, processing equipment used, processing parameters, the interface compatibility of the matrix and the filler, the mechanical effect between reinforcement and the matrix, know-how of the tester, and so on. In studies, it is common to process the material with laboratory equipment, which might cause differences compared to industry-level volume producing equipment. It is difficult to get a clear picture of the potential challenges caused by the novelty materials when they are transferred to the production environment.

One obvious difference is that the recycled hybrid or composite materials are not available in the materials data banks, so just looking through the data banks or handbooks will not ever give you these materials as options. Therefore, it is quite natural to assume that the recycled composite materials solutions will be adapted only in the fields that are able to use composite mixtures close to the ones used in the industry, such as wood-plastic composites. Besides the properties, there are other more pressing issues when considering the adaptation of recycled material. The company needs to consider the sourcing of the material in a deep manner at a very early stage of the product design, which affects the attractiveness of these potentially sustainability improving materials.

Transportation distance has often been mentioned as a significant factor in whether recycled material is ecological or not. It also has a great effect on how cost efficient it is to use them for the processing factory. The gap where the price advantage in composites can be reached depends on the relative price of the virgin matrix and filler material. Product design can be used to influence manufacturing costs, which in turn can decrease or increase the price advantage gap. The factors affecting the additional costs have been addressed by Sommerhuber, Welling, and Krause [15], in the WRAP project [49], and by Hestin, Faninger, and Milios [50]. A company willing to get involved itself in processing recycled material composites should be situated close to the recycled material suppliers. This "equation" makes the situation difficult for a designer, whose primary role is to design a product with materials filling the functional requirements and which are suitable for the available supply chain. If the new design of a product were to apply the principle of "circular material," then the designer requires extensive information about the future uses of the applied material. The designer should also be aware of the gap where the cost and ecological advantages of the total system can be achieved.

In recent years, the safety of building materials has been a big topic. The safety issues are also a cause for concern in some people because of the lack of studies about the potential emissions from the recycled material. There is still a lot of work in the field of health and safety, and the variety of different materials makes conducting comprehensive studies difficult. This is probably not an issue in practice, as the material supplier should be able to convince the buyer about safety issues and quality with product specific testing procedures. The circular economy is increasing the knowledge requirements and widening the recycling business perspective to field of material science. This transformation can prove to be difficult in what were previously rather simple industries, such as material handling plants and waste management, which now want to be a reprocessor of plastics. The producer applying the recycled material can only work with suppliers who are committed to the quality and supply reliability of the material. The suppliers play a key role in the search for new applications for these materials.

5. Conclusions

The study presents the first comparison of ecodesign methodologies applied to a product design focusing on composite materials made of recycled materials. Sustainable product design is a hot topic today, and the use of ecodesign methodologies has been suggested to help designers in selecting greener materials. The application of composites with recycled content is further complicated by the lack of data, which the designer faces. As these rather novel materials are not yet applied commonly outside WPC solutions, the designer is put in an uncomfortable place in terms of responsibility. The main benefit of using a holistic ecodesign approach such as EQFD combined with multiple criteria analysis is that it helps the designer to examine the environmental benefits in relation to functional design for better designs. The methods that take the voice of the customer into consideration all through the development process, such as EQFD, are a good way to incorporate sustainability in the design process while keeping the market demands at the center of attention.

The relatively good ranking of composites in the case study with previously non-recyclable material content such as mineral wool shows the potential of combined materials in increasing the utilization of previously unrecycled fractions. The promoting factor in favor of RMCs in EQFD is the rate of recycled material, but biodegradability, recyclability, and the mixing of material favor the homogenous virgin materials. TOPSIS and other multiple criteria analysis methods can further promote the RMCs if the technical criteria properties are higher than in the base plastic material of the composite matrix. Topics of future research include cost and lifecycle analysis of the case study materials in order to study the economic and environmental benefits often attributed to recycled materials.

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Publication IV

Sormunen, P., Deviatkin, I., Horttanainen, M., and Kärki, T.
An evaluation of thermoplastic composite fillers derived from construction and demolition waste based on their economic and environmental characteristics

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An evaluation of thermoplastic composite fillers derived from construction and demolition waste based on their economic and environmental characteristics

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A B S T R A C T

The use of waste is often justified by the economic and environmental benefits of their use. This study compares the use of waste materials derived from construction and demolition waste—namely wood waste, mineral wool waste, gypsum board waste, and stone cutting dust—as alternative fillers in the production of thermoplastic composites using recycled high-density polyethylene as a matrix material. In total, nine alternative composites were studied in terms of their production costs, as well as their climate change impacts in three distinct product applications. Compared with the plastic matrix, the wood fiber achieved a cheaper price of €0.8–1.2/kg and the best properties in relation to weight. The price of mineral-based fillers varied between €0.5–1.1/kg, but the effect of the higher density on the weight increased the total price of the products. The unfilled recycled plastic was the cheapest solution in the application where the covered volume was important. The impact of using recycled high-density polyethylene in composites production totals at −1.24 kg CO2-eq./kg, out of where 1.75 kg CO2-eq. is the avoided impact from avoided waste disposal and 0.51 kg CO2-eq. is induced impact from producing the composites. When also accounting for the avoided impact from the substitution of virgin high-density polyethylene with the recycled high-density polyethylene composites, the avoided impact further increases to −3.17 kg CO2-eq./kg. The mineral fillers with were preferable in the application where mass was important, however, had lower avoided impacts than unfilled polyethylene ranging between −2.06 kg CO2-eq. and −2.47 kg CO2-eq. Wood fiber filler was the preferred filler option in the application where the material properties were taken into account in the amount of required material, but resulted in the lowest cumulative avoided impacts ranging between −1.79 and −2.25 kg CO2-eq., with most of the avoided impact originating from the replacement of virgin high-density polyethylene.

1. Introduction

Recycling materials back into the economy embodies the strong potential for the reduction of manufacturing costs. It is also often seen as a means of mitigating climate change through the avoidance of using virgin raw materials. To prove that recycled materials are beneficial for the environment and for the producer, their carbon footprint and their costs should be lower than that of virgin materials.

The construction sector is one of the largest plastic consumers in Europe with a share of 19.8% of total converter demand (PlasticsEurope, 2019). The major plastic types in the sector are polyethylene, polypropylene, and polyvinyl chloride, all of which can be used in the production of thermoplastic composites. Furthermore, the construction sector is responsible for the largest waste-generating activity in the European Union, accounting for 36.4% of total waste generated in 2016 (Eurostat, 2016). Globally, the amount of construction and demolition waste constitutes

Abbreviations: LCA, life cycle assessment; LCI, life cycle inventory; LCIA, life cycle impact assessment; GWP, global warming potential; HDPE, high-density polyethylene; CDW, construction and demolition waste; r-PE, recycled high-density polyethylene; MW40, mineral wool waste composite 40% fill rate; MW60, mineral wool waste composite 60% fill rate; PB40, plasterboard waste composite 40% fill rate; PB60, plasterboard waste composite 60% fill rate; SC40, stone-cut waste composite 40% fill rate; SC60, stone-cut waste composite 60% fill rate; WF40, wood fiber waste composite 40% fill rate; WF60, wood fiber waste composite 60%.

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astonishing 3 billion tons annually (Akhtar and Sarmah, 2018). Plastic waste generated during construction and demolition activities could be combined with other construction waste—such as size-reduced wood (Sommerhuber et al., 2017), mineral wool (Väntsi and Kärki, 2014), and gypsum board (Sormunen and Kärki, 2019a) —acting as filler.

The cost of products manufactured from recycled materials is influenced by several factors, such as transportation costs, landfilling fees, recycling process, volumes, the quality of the material, gate fees, plant operating costs, and the taxation of waste (Coelho and de Brito, 2013; Duran et al., 2006). The identified measures for policymakers to influence the cost factors include green taxes, green public procurement and standardization of recycled materials (EEA, 2019). Typical applications for thermoplastic composites made with recycled material include wood-plastic composites, outdoor building, billets, profiles, and different types of cladding. The potential applications for recycled material composites are slowly expanding to include even more technically demanding applications, such as compression-molded door panels, molded with stiffening ribs, thickness variations, and molded-in holes (Gardiner, 2019).

In general, recent studies involving product or material cost calculations for alternative composite fillers are not widely available. According to Hueber et al. (2016) good cost prediction of is possible when the estimated component is part of an established family of products and sufficient historic manufacturing and cost knowledge is available. In the case of calculating the processing and material costs of waste derived fillers the historic data is not available. Bottom-up approach where the processing steps are calculated separately is usually the best option when limited information about new processing technology is available (Hueber et al., 2019). Åkermo and Åström (2000) modelled the component costs in the compression molding of thermoplastic-composite and sandwich components. Their study found that raw material cost dominated the component costs in the compression molding of composite components. They also found that compression-molded thermoplastic composites are cost-competitive for small and medium-sized components and for a small production series of large components. Bader (2002) highlighted the need for cost-performance evaluation in a comprehensive study of thermoset composites produced with a variety of manufacturing methods, but the study did not consider the use of recycled materials or thermoplastics. A study by Verrey et al. (2006) highlighted the high effect of mold-in times in thermoplastic-composite production, which can raise the total cost over thermoset molding due to longer cycle times. A modulus−cost ratio was used by Zampaloni et al. (2007), who compared compression-molded kenaf-polypropylene to kenaf-, sisal-, and coir-reinforced thermoplastics; their study did not calculate the price of the processing of materials. Zhou et al. (2019) compared the environmental and economic efficiency of compression-molded sludge cellulose plastic composite compared to traditional wood plastic composite; their study suggested that using cellulose sludge based filler was more eco-efficient than using recycled wood flour.

The environmental impacts of composite manufacturing using waste have been studied to some extent, with studies mainly focusing on a narrow range of materials with limited recipes. Liikanen et al. (2019) studied the impacts of manufacturing two composites: one recipe utilized 54% of wood waste and 40% of plastic waste while another recipe utilized 24% wood waste, 40% plastic waste, 15% mineral wool waste, and 15% plasterboard waste. Both scenarios of manufacturing composites resulted in avoided impacts on climate change and abiotic resource depletion compared with the baseline scenario of their incineration and landfilling. Other studies focusing on the environmentally-sound choice of the waste materials to be used in composite production include those of Sommerhuber et al. (2017) and Väntsi and Kärki (2015). Sommerhuber et al. (2017) compared the use of virgin and recycled wood and plastic whereas Väntsi and Kärki (2015) studied wood waste, glass fiber, mineral wool waste, recycled plastic, and virgin plastic. These studies did not analyze the economics of the raw material selection process.

Building on previously conducted research and the identified research gap, this study aims at comparing the use of several construction and demolition waste (CDW) materials as fillers in thermoplastic composites in terms of their economic and environmental performance. The specific objectives of this study were: to identify the production costs for the manufacturer, to assess the impacts on climate change from raw material provision till the production of composites, and to identify the trade-offs between the economic and environmental parameters for different groups of materials and applications.

2. Methods

This paper features a life cycle engineering study of thermoplastic composites made of waste-derived materials. Life cycle engineering represents a product development concept considering the technical, economic, and environmental characteristics of the specific product being assessed (Jeswiet, 2014). The study, however, omits the social impacts. The economic parameters were calculated using the accounting principle, considering the material provision cost and the cost of processing. The environmental impacts were calculated using the principles of life cycle assessment (LCA). Three different types of products were used to demonstrate the effect of design criteria on the best fitness of different filler materials. The volume related solution represents a typical commodity plastic application where it is used as a cover or a packaging material, the results of this example are presented in Fig. 7 for a product with 564 cm^3 of material. The mass related solution represents an application where the part is used as a counterweight, the results of this example are presented in Fig. 8 for a product with a required mass of 20 kg. The property related solution is a plate like application where the surface area is set to 0.4 m^2, but thickness can be optimized based on the material properties the results of this application are presented in Fig. 9.

2.1. The studied recipes

The composites comprised of a matrix of a filler, a coupling agent, a processing aid, and recycled high-density polyethylene (r-PE). Table 1 lists the nine recipes selected for this study, following the composition in a previous study by Sormunen and Kärki (2019). The variation in the rate of a specific filler highlights the effects of the particular filler on the results. The following assumptions regarding the recipes were made:

- High-density polyethylene is recycled post-consumer plastic, and it is used as a thermoplastic material in all composite recipes.
- Wood fiber is a size-reduced construction and demolition waste of A-grade (chemically untreated construction wood) or B-grade (chemically treated wood boards, plywood, etc. without hazardous contaminants), classified according to the study by Alakangas et al. (2015).
- Mineral wool size-reduced powder includes portions of both stone wool and glass fiber.
- Plasterboard waste is a size-reduced powder, consisting of gypsum and 3−6% of paper.

Table 1
The studied recipes of composites by mass.

Composite	Polyethylene	Wood fiber	Mineral wool	Plasterboard	Stone-cut waste	Coupling agent	Processing aid
r-PE	94%	–	–	–	–	3%	3%
WF40	54%	40%	–	–	–	3%	3%
WF60	34%	60%	–	–	–	3%	3%
MW40	54%	–	40%	–	–	3%	3%
MW60	34%	–	60%	–	–	3%	3%
PB40	54%	–	–	40%	–	3%	3%
PB60	34%	–	–	60%	–	3%	3%
SC40	54%	–	–	–	40%	3%	3%
SC60	34%	–	–	–	60%	3%	3%

- Stone-cut waste is assumed to be size-reduced particles of soft stone mining tail, such as soapstone.
- Coupling and processing aids were estimated to be consumed in equal amounts in all the compositions at the rate of 3% each.

The application of these fillers for potential applications has been studied in a review by Sormunen and Kärki (2019b).

2.2. Life cycle assessment of analyzed system

The environmental impact of the studied composites was assessed using the LCA methodology, only focusing on the climate change impacts. LCA is the most commonly used systems analysis tool in the field of waste management (Laurent et al., 2014; Pires et al., 2011) and is widely used for the assessment of the environmental impacts of products and services. The climate change impacts were assessed following (but not strictly complying with) the ISO 14040/44 standards (SFS-EN ISO 14040, 2006; SFS-EN ISO 14044, 2006), as well as the ISO 14067 standard (SFS-EN ISO 14067, 2018). The study was conducted using GaBi software (version 9.0.0.42, DP service pack 38) (thinkstep AG, 2019).

Each LCA study is typically initiated with definition of the goal and scope, a phase that determines the development of the study and defines the key research questions. Then, the studies are taken further through the collection of a life cycle inventory (LCI), the most laborious phase, required in order to collect the data for the studied product system in the form of either elementary flows or intermediate flows, supplemented with unit processes from secondary data. Once the data on the inputs and outputs of the product system are collected, the life cycle impact assessment (LCIA) phase takes place, the phase in which all the inventory data is classified into specific impact categories and characterized to be represented via a single pre-defined unit. LCIA could be expanded with normalization and weighting, which however were not included in this study. Finally, in life cycle interpretation, the results and their applicability to fulfilling the goal of the study are assessed. Each phase is described in detail in this section.

2.2.1. Goal and scope definition

The goal of this LCA study was to support a decision-making process for the selection of specific fillers and their amounts in the production of thermoplastic composites. The study is conducted for the recipes previously identified in Table 1. The function of the studied product system is to utilize waste-derived materials in the production of intermediate composite products without any intended specific application. Thus, the functional unit was set to 1000 kg of the manufactured composite.

The system boundaries are shown in Fig. 1. The impacts in this study are assessed, starting from the provision of waste running through to the composite production process (i.e., it adopts the so-called zero burden approach) (Ekvall et al., 2007). The waste separation facility receives different fractions of the construction and demolition waste from various operators. The impact from the collection of waste and its possible separation are not included since it is expected to occur in both scenarios that are compared. Furthermore, the possible impact from additional separation being required to produce composites is expected to have a negligible impact on the results overall.

Once the waste has been received and possibly separated, it is sent either for landfilling or incineration in the baseline scenario, which represents the business-as-usual case in Finland. Because the landfilling of waste containing more than 10% organic carbon is banned in Finland, only mineral wool, stone-cut, and plasterboard waste were modelled as being landfilled. For when plasterboard is landfilled, a 4% share of paper (Jiménez Rivero et al., 2016) was modelled using the process for the landfilling of paper that generates small amounts of landfill gas, thus giving it a credit through electricity substitution. The remaining waste fractions, namely polyethylene and wood, were modelled as being incinerated with energy recovery. The electricity and thermal energy generated were modelled to replace the average electricity and heat profiles of Finland through system expansion.

In the alternative product system, the waste was utilized in the production of composites. In this study, the composite production plant was located in the same place as the waste separation facility. Thus, there was no need for the transportation of waste to the place of production of the composite. The same machinery as that which loads the waste onto the trucks in the baseline scenario was used to load the waste into a crusher, so the impact from the loading operations was excluded. After crushing, the waste is milled and sent to agglomeration, where it is mixed with a coupling agent and a processing aid. Finally, the composite products are formed using the injection molding process. The intermediate composite products were modelled to replace the average molded products made of HDPE.

2.2.2. Life cycle inventory

The LCI in this study largely follows a previously conducted study by Liikanen et al. (2019). In the baseline scenario, the landfilling of inorganic waste was modelled using the process "EU-28: Inert matter (unspecific construction waste) on landfill ts." The landfilling of paper from plasterboard was modelled via the process "EU-28: Paper waste on landfill ts <p-agg>." The "p-agg" part of the name of the unit process indicates a partly terminated system. The incineration of wood waste and plastics were modelled using the processes "EU-28: Waste incineration of untreated wood (10.7% H_2O content) ELCD/CEWEP <p-agg>" and "EU-28: Waste incineration of plastics (PE, PP, PS, PB) ELCD/CEWEP <p-agg>" respectively. The mass of waste landfilled or incinerated equaled 940 kg in each scenario, which is the mass of waste otherwise required to produce 1000 kg of composite products. The masses of waste disposed and energy generated in the baseline scenario are shown in Table 2.

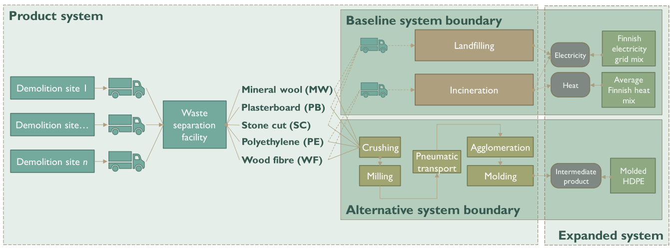

Fig. 1. The product system, expanded system, and the system boundaries of the baseline and alternative scenarios.

Substituted electricity was electricity supplied from the Finnish grid mix, modelled using the process "FI: Electricity grid mix ts." The Finnish average heat supply was modelled using the statistics on the Finnish district heat generation described in the work of Liikanen et al. (2019).

The alternative scenario of composites production was modelled using the inventory of Liikanen et al. (2019) with the following several variations to the data used. First, the electricity consumption for crushing and milling soap stone was modelled in the same way as for plastic waste. Second, the composite production process was changed from extrusion to injection molding using the unit process "GLO: Plastic injection molding (parameterized) ts <u-so>." The default energy consumption of injection molding is 4.5 MJ/kg injected product, which is higher than that of the extrusion process of 1.8 MJ/kg product used by Liikanen et al. (2019). Elduque et al. (2018) reported the electricity demand for the injection molding of plastic from Ecoinvent as 5.2 MJ/kg molded part and the value of 3.0 MJ/kg molded part, which were derived from laboratory tests. Third, the share of the coupling agent and the processing aid were increased from 0.5% to 3% each. Lastly, the work of Liikanen et al. (2019) was expanded by including the injection molding of HDPE using the same process as for molding of composites: "GLO: Plastic injection molding (parameterized) ts <u-so>."

2.2.3. Life cycle impact assessment

Owing to the complementary nature of this LCA study, only the impacts on climate change were studied. The limitation of using only one impact category is addressed in the Discussion section. The climate change impacts were characterized using the characterization factors developed by the Intergovernmental Panel on Climate Change (IPCC, 2014) and implemented in GaBi software as "IPCC AR5 GWP 100, excl. biogenic carbon." The results are calculated using carbon dioxide (CO_2) as an impact category indicator, thus giving the results in kilograms of carbon dioxide equivalent (kg CO_2-eq). The carbon uptake during the growth of the wood used in the process has not been accounted for as carbon sequestration, neither was its release during incineration considered to have a climate change impact.

Table 3
The density and estimated price range for material components.

Material	Density ρ (kg/m^3)	Unit cost (€/ton)
Mineral wool	2500–2700	−250 to −50
Gypsum waste	2400–2570	−100 to −50
Wood waste	900–1150	50–100
Soapstone, fine cutting waste	2800–3130	100–150
Polyethylene, recycled	900–970	500–700
Coupling agent	900–1000	4000–5000
Processing aid	900–1000	4000–5000

2.2.4. Sensitivity analysis

The sensitivity analysis was conducted by changing the parameters affecting both the composites production process and the substitution of the products. The impact of electricity on the impacts of the composites production is expected to be high, so the electricity source was changed from the Finnish electricity grid to electricity from natural gas, which is still a commonly used fuel in Finland for electricity generation (Suomen virallinen tilasto (SVT), 2019), and to solar electricity production to reflect a possible situation of green electricity procurement by a manufacturer. As per the impacts from the substitution, a substitution ratio was varied by 20% as to reflect for possible difference in properties of the produced composites versus products made of virgin plastic.

2.3. Economic analysis

The costs are calculated for the production phase including preproduction activities: labor wages, and energy and material consumption. The expenditures related to capital costs—such as machinery and tooling costs, as well as the maintenance of equipment—were not calculated as they were estimated to be similar regardless of the filler used. The range of the costs was calculated for each composite based on the lower and upper boundaries of the expected material cost and density seen in Table 3. The negative cost values represent gate fees to the waste producer. The range of material unit cost includes the cost of transportation from the demolition site. The unit cost values for material and processing are based on the market prices in Finland. The following equations do not include the unit transformations between volume and mass.

Table 2
The mass of the waste disposed and energy generated in the baseline scenario, depending on the studied composite recipe.

	Unit	r-PE	WF40	WF60	MW40	MW60	PB40	PB60	SC40	SC60
Waste landfilled	kg	0	0	0	400	600	400	600	400	600
Waste incinerated	kg	940	940	940	540	340	540	340	540	340
Electricity generated and substituted	kWh	1380	997	806	791	498	793	501	791	498
Heat generated and substituted	MJ	16 300	11 700	9430	9370	5900	9370	5900	9370	5900

The estimations assume that the tooling is fully utilized, and the production is continuous.

The total cost (C_T) of processing was calculated as a sum of the material cost (C_M) and the processing costs (C_P). The material cost of a composite is estimated by using equation (1):

$$C_M = C_{Ma} + C_F + C_{CA} + C_{PA}, \tag{1}$$

where.

- C_{Ma} is the cost of the thermoplastic,
- C_F is the cost of the filler,
- C_{CA} is the cost of the coupling agent,
- C_{PA} is the cost of the processing aid.

The processing cost of a composite is estimated by using equation (2):

$$C_P = C_A + C_D + C_C + C_{CM}, \tag{2}$$

where.

- C_A is the cost of agglomeration,
- C_D is the cost of drying,
- C_C is the cost of size reduction and sieving,
- C_{CM} is the cost of compression molding.

The drying cost (C_D) was calculated for wood, gypsum, and mineral wool. The cost of size reduction and sieving (C_C) were calculated for all the waste fractions. The processing cost (C_P) for the coupling agent and processing aid were only calculated in the agglomeration phase. The calculation for phases C_A, C_D, and C_C were done according to equation (3). All the cost calculations employ the rule-of-mixture to calculate the minimum, average, and maximum density of a composite from Table 3. The processing cost values are presented in Table 4.

$$C_P = (w_i \cdot \rho_i \cdot C_i) / \rho_c, \tag{3}$$

where.

- w_i is the share of a material in a composite,
- ρ_i is the density of a material in a composite,
- ρ_c is the density of the composite,
- C_i is the unit cost of processing (see Table 4)

The calculation of the composite compression molding cost (C_{CM}) was done according to equation (4):

$$C_{CM} = \rho_c \cdot C_i, \tag{4}$$

where the density of the composite ρ_c was calculated according to equation (5):

Table 4
The processing unit costs used in the calculation.

Production	Cost (€/ton)
Crushing and milling	40–50
Drying	20–30
Agglomeration	100–150
Compression molding	450–550

$$\rho_c = 1 \Big/ \left(p_\% \big/ \rho_p + f_\% \big/ \rho_f + ca_\% \big/ \rho_{ca} + pa_\% \big/ \rho_{pa} \right), \tag{5}$$

where.

- ρ_p is the density of a polymer (see Table 3),
- $p_\%$ is the share of a polymer in a composite (see Table 1),
- ρ_f is the density of a filler (see Table 3),
- $f_\%$ is the share of a filler in a composite (see Table 1),
- ρ_{ca} is the density of a coupling agent (see Table 3),
- $ca_\%$ is the share of a coupling agent in a composite (see Table 1),
- ρ_a is the density of a processing aid (see Table 3),
- $pa_\%$ is the share of a processing aid in a composite (see Table 1).

The property index corrected total cost C_{TM} was calculated for the minimum and maximum value of C_M and C_P with equation (6):

$$C_{TM} = PU \cdot \rho_c \cdot (C_M + C_P) \cdot i_E, \tag{6}$$

where.

- PU is the volumetric production unit in m^3,
- is the index value based on the corresponding amount of material compared to the base value of r-PE calculated with equation (7).

The sensitivity analysis was conducted by calculating a range based on the variation of material weight and estimated price fluctuation. Life cycle costing usually also accounts for research and development, use, maintenance, and end-of-life costs, but these were left out of the scope for being dependent on the product application.

The technical analysis of filler composites is based on the results of a study by Sormunen and Kärki (2019) about the properties and densities of these materials when processed by compression molding. To evaluate to the reinforcement efficiency of fillers an index value i_E was calculated based on the corresponding amount of material compared to the base value of r-PE with the equation. The reinforcement efficiency i_E is calculated referring to r-PE due to its use as a material to be reinforced in the technical analysis by Sormunen and Kärki (2019). The application examples in this study are dimensioned according to Young's modulus (E) of the material. The calculated values for i_E are presented in Table 5. The smaller the value for i_E the greater the reinforcement property of the filler.

$$i_E = E_{HDPE} / E_{composite}. \tag{7}$$

3. Results

The results of this study are presented in their respective parts: environmental impacts and economic assessment.

3.1. Environmental impacts

The environmental impacts in this study are shown in a comparative way reflecting, first, the impacts of avoided disposal on the waste and provision of electricity and heat in the same amounts as derived from waste; second, the impacts of the production of composites from waste; and third, the impacts of the substitution of products on the market with composites.

3.1.1. Avoided impact from conventional disposal

Fig. 2 shows the results of the avoided disposal of 940 kg of

Table 5
The calculated indices for materials.

Index	r-PE	WF40	WF60	MW40	MW60	PB40	PB60	SC40	SC60
i_E	1.00000	0.62252	0.52809	0.81034	0.68613	1.05618	0.56970	0.80342	0.50538

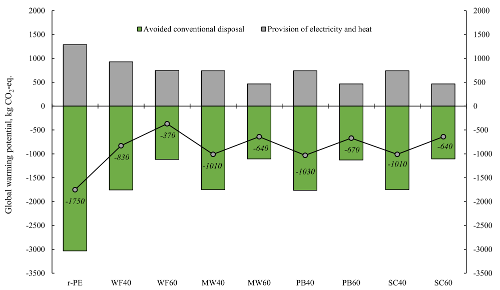

Fig. 2. The global warming potential of the avoided conventional disposal of 940 kg of waste and the provision of electricity and heat generated during conventional disposal.

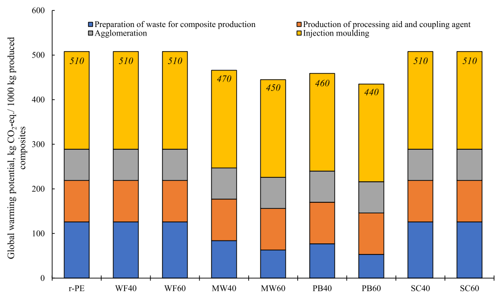

Fig. 3. The global warming potential of manufacturing 1000 kg of intermediate composite products.

waste and the impact originating from the provision of electricity and heat (see Table 2 for the amounts). The avoided incineration of polyethylene (unfilled recycled plastic [r-PE]) waste results in the largest avoided impacts (−1750 kg CO_2-eq) compared with the other scenarios. This is explained by the high emission factor of the incineration of plastics and the relatively low carbon intensity of the Finnish electricity grid and heat mixes that were used to model electricity provision if the plastic is not incinerated in order to maintain the same functionality in the study. When the mass of plastic incinerated decreases to 540 kg (i.e., scenarios WF40, MW40, PB40, and SC40), the avoided impact shrinks to −830 to −1030 kg CO_2-eq and further to −370 to −670 kg CO_2-eq when the mass of plastic incinerated decreases to 340 kg (i.e., scenarios WF60, MW60, PB60, and SC60).

Comparing the impact from different waste streams, avoiding the incineration of wood (WF60 and WF40) is seen as the option with the lowest avoided impact. This is because the impacts from wood combustion on climate change are lower than those of the average Finnish electricity grid and heat mix. There was no significant difference between the avoided impacts of soap stone, mineral wool, and plasterboard as all those waste streams are inorganic and are landfilled in the same way. The slight difference for the plasterboard is due to the low share of paper in it.

3.1.2. The impact from composite production

Fig. 3 breaks down the impacts associated with the production of composite materials (i.e., attributional cradle-to-gate impacts). The impact of the production of composites ranged from 440 to 510 kg CO_2-eq across all scenarios. No difference was expected between the impacts of producing composites from plastic, wood, and soap stone waste (scenarios r-PE, WF40, WF60, SC40, SC60). The impacts were the same because the expected energy consumption for their pre-treatment is the same. A slightly lower amount of electricity was required for the preparation of mineral wool and plasterboard, accounting for their lower strength compared to the other waste materials.

Considering the impacts of the separate phases of the production process, it can be seen that injection molding has the largest contribution to the results (43–50%). This is related to the high energy demand of the process required to melt the materials. However, there is a large variation in the energy consumption of injection molding based on the desired product. Therefore, the specific energy demand should be clarified for the specific product being manufactured. The production of the coupling agent and the processing aid, with the shares of 3% each from the total mass of composites produced, accounts for nearly a fifth of the impacts on climate change. However, the share of the additives can be as low as 0.5% (Liikanen et al., 2019).

3.1.3. Cradle-to-gate impacts

Fig. 4 aggregates the results of the impacts on climate change from the studied product systems, accounting for the changes in the waste management system, as well as the potential substitution of products on the market with waste-derived composites. Accounting for a constant avoided impact from plastic products made of HDPE of 1920 kg CO_2-eq, the largest avoided impact out of all the recipes studied is achieved when utilizing the largest amounts of plastic waste, which was −3170 kg CO_2-eq per 1000 kg of composite produced. Herein, more than half of the avoided impact originates from the replacement of plastic products made of virgin

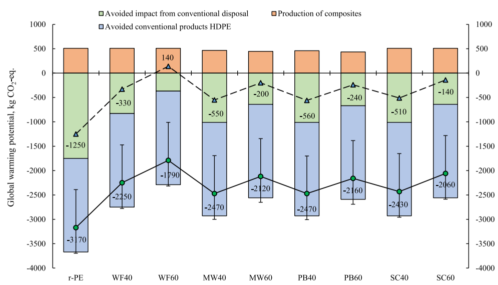

Fig. 4. The global warming potential of the product system utilizing waste for the production of 1000 kg of composite, substituting molded products made of virgin HDPE on a 1:1 mass basis. The dashed line sums up the impacts from avoided conventional disposal and only includes composites production whereas the solid line also accounts for the avoided impact from the substitution of HDPE products.

HDPE. The lowe

st avoided impact of −1790 kg CO_2-eq originates from the scenario utilizing wood the most (i.e., WF60). If no plastic were replaced, then the cumulative impact in scenario WF60 would be 140 kg CO_2-eq, the only scenario with induced impact if the substitution of plastic products is not considered.

The sensitivity analysis showed that the electricity and substitution of virgin plastic have a high impact on the results. However, the cumulative impact across all scenarios studied did not exceed the impact from the baseline scenario: the maximum reduction of the climate change impacts achieved in the scenarios is reduced by 25–44% in the worst case when the electricity is supplied from natural gas and only 0.8:1 substitution rate is achieved. When supplying the electricity from solar energy and substituting plastic on a 1.2:1 substitution rate, the increase in the environmental impact is in the range 17–29%.

If the electricity supply to the composites production was from natural gas and there were no substitution of plastic at all, then the scenarios WF40, WF60, MW60, PB60, and SC60 would have a higher impact from the composite production compared to the avoided impact from conventional disposal. The minimal break-even substitution rate of plastic in those scenarios is 4% (WF40), 34% (WF60), 12% (MW60), 10% (PB60), and 17% (SC60).

3.2. Economics

The total cost (C_T) and impact on climate change for composite manufacturing is presented in Fig. 5. More than half of the avoided impact originates from the replacement of plastic products made of virgin HDPE. The use of recycled filler material in a plastic matrix decreases the kilo price of the composite. On average, the use of wood filler decreases the cost of the r-PE plastic, by 13% in WF40 and by 19% in WF60. The results indicate that the recipe with the highest costs, namely r-PE, has the highest avoided impacts of −3.17 kg CO_2-eq per kilogram of composite. The decrease in cost compared to r-PE is 21% in MW40, 20% in PB40, and 16% in SC40. The drop in cost compared to r-PE further increases with higher filler rates to 31% for MW60, 29% for PB60, and to 25% for SC60. The mineral-based composites of equal filler rate have similar total cost despite the differences in material cost. The avoided climate change impacts do not vary significantly between mineral composites of equal filler rate.

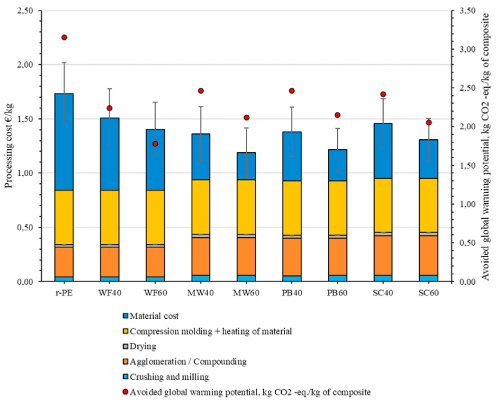

Fig. 5. The total cost (€/kg) of compression-molded composite material and the division of processing costs. The tolerance bar shows the variance in total cost.

Fig. 6 shows the price per volumetric product unit (in m^3) for different composites. When i_E is taken into consideration, the total cost of a product unit decreases in relation to property improvement. The result suggests that when possible the property improvement should always be taken into consideration in the product dimensioning to gain a cost advantage of waste filler materials. If the replacement of material is done on a one-to-one basis, there is no expected cost advantage in mineral composites due to expensive pre-processing activities.

The volume-based application has a set of space that the application needs to fill. In this case, the lower total cost (C_T) per kilogram of mineral waste–based composites offer no benefit as the material properties cannot be taken into consideration. In the volume-based application, the total avoided impacts on climate change per product are higher in the mineral waste–filled composites; this is due to a higher mass of the product with mineral waste–based composites. The comparison of composites in the volume-based product example is shown in Fig. 7. The calculation was made for 564 cm^3 of material. The cheapest solution is achieved with filler combination WF60, which decrease the total cost of the composite while having a low avoided impact see Figs. 4 and 5.

The mass-related solution presents an application where the product needs to have a certain weight. The example was calculated for 20 kg of material, which could represent a product application such as counterweight. Lower C_T favors the mineral fillers over the r-PE, due to their high density and low cost per kilogram. From the climate change point of view, the product design favors the unfilled plastic because of the high avoided impact per kilogram of r-PE as larger volume of HDPE is replaced with recycled material. The comparison of composites in the mass-based product example is shown in Fig. 8.

In the last example, a property-optimized profile has been calculated. Here the property index i_E is used to take the properties of the composite into consideration in material usage. The height of the profile can be optimized while keeping the needed surface area 0.4 m^2. The wood fiber–filled composite WF60 is the cheapest solution for the studied materials for this product. The superiority of wood fiber filler compared to other alternative fillers in reinforcement can be seen in quite clearly from the results in Fig. 9. The wood fiber filler does not significantly increase the mass of the composite but affects the modulus more effectively than the mineral-based fillers such as minerals or gypsum. Less raw material can be used produce the profile with the lighter WF40 and WF60,

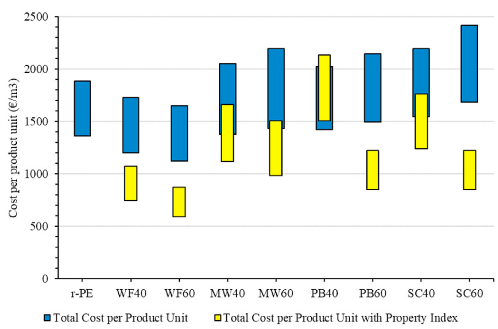

Fig. 6. The cost per product unit of compression-molded material with property index (i_E) values.

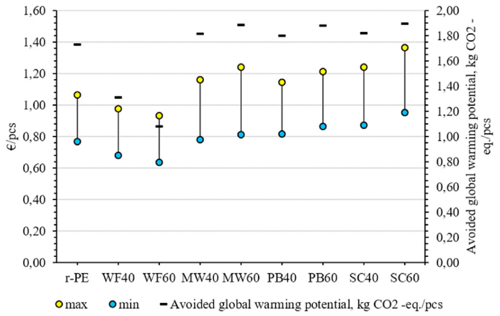

Fig. 7. Example of a volumetric application's (564 cm^3) unit costs.

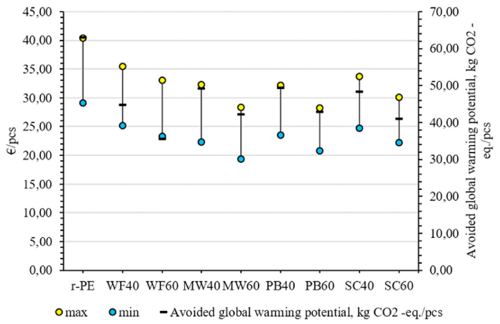

Fig. 8. An example of a mass-based (20 kg) product unit costs.

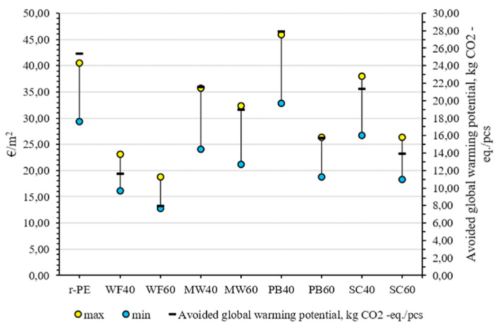

Fig. 9. An example of the property-optimized profile 0.4 m^2 costs per m^2.

therefore the avoided impact from HDPE substitution is also smaller.

4. Discussion

The climate change impacts of producing 1 kg of composites in this study ranged 0.44–0.51 kg CO_2-eq which is line with the results of Liikanen et al. (2019) indicating the impact of 0.4–0.5 kg CO_2-eq. Somewhat higher impact of 0.76–0.78 kg CO_2-eq was reported by Sommerhuber et al. (2017) where waste plastic and waste wood were utilized. In the study by Väntsi and Kärki (2015), however, the impact from the production phase cannot be distinguished from the cumulative impacts presented in the study, thus eliminating cross-comparison. When virgin plastic was used in the production of composites, the impact from the raw materials provision stage was roughly 1.5 kg CO_2-eq per 0.68 kg of plastic used (Sommerhuber et al., 2017) or 2.2 kg CO_2-eq per kg of plastic used. However, in this paper, the impact from virgin plastic production was modelled in this paper as avoided impact at the level of 1.9 kg CO_2-eq per kg of replaced HDPE. If no plastic were substituted, the cumulative impact from composites production was higher than the avoided impact from conventional disposal in the scenario WF60. According to the study by Liikanen et al. (2019), the minimum substitution rate of 6% was required to achieve lower impact from composite production than the production of the substituted material.

The potential environmental benefits were evaluated using only one impact category of climate change omitting a range of other areas of environmental concern. However, Liikanen et al. (2019) assessed a wide range of impact categories and showed that the environmental impact was reduced across the majority of impact categories when wood plastic composite replaced virgin plastic, namely for climate change; fossil depletion; freshwater and marine ecotoxicities; freshwater, marine, and terrestrial eutrophication; human toxicity; and stratospheric ozone depletion potentials. In most cases, the impact reduction was dominated by the avoided impacts of virgin plastic production. Another limitation of this study relates to the narrowed system boundary, which starts with the provision of the waste for the production process and ends at the gate of the composite production facility. The zero-burden approach that was utilized in this study implies avoidance of the debit associated with the use of waste in the process while allocating all the impacts from the previous life cycles to the products that resulted in the generation of waste. Such an approach gives substantial benefits to waste materials compared to virgin ones, yet this approach is seen as obsolete in the era of the circular economy where waste should be phased out gradually and products should be designed for recycling (Djuric Ilic et al., 2018). Also, when limiting the system boundaries to the gate of the factory, the impact from the end of life, from disposing of the composites and alternative materials, remain uncertain. Owing to the varying share of plastic in composites, the impacts from its disposal are expected to change significantly, especially if incinerated.

The cost calculation in this study present extreme cases where the processed material weight and the material price were either at their highest or lowest resulting in a range. To evaluate the cost of preprocessing the densities in Table 3 represented waste in its processed state. The low-density materials such as mineral wool (70 kg/m^3) use the same machine capacity as the high-density materials but produce lower amount of processed filler material in kilograms. Using the density in processed form takes this fact into consideration by calculating the processing cost evaluated in €/kg. Clear consensus is missing on how waste processing cost should be calculated, but most used method seems to be €/ton, which was also used in this study. A more accurate product specific cost calculation can be done by taking into consideration the geometrical complexity of a part for which production time and tooling costs for a given quantity of products can be estimated (Hagnell and Åkermo, 2015). The manufacturing cost also depend on the used material heating method isothermal (heating the tool and the surroundings) or non-isothermal (heating the material directly) (Pantelakis et al., 2009). However, this study shows a general direction of costs because the material plays a major part in thermoplastic product molding costs. The application of novel materials also requires practice and small series production is more likely to suffer from a high portion of rejects and disruptions in processing before acceptable quality is achieved. It is also probable that the processing cost variable (C_{CM}) would variate between different waste fillers in its subprocesses like heating, tool closing time, cooling time, inspection, dimensional stability control, etc. The composite agglomerate from recycled materials price ranges were calculated to be: €1.1–1.5/kg for r-PE, €0.9–1.2/kg for WF40, €0.8–1.1/kg for WF60, €0.7–1.1/kg for MW40, €0.5–0.90/kg for MW60, €0.8–1.1/kg for PB40, €0.6–0.9/kg for PB60, €0.8–1.1/kg for SC40, and €0.7–1.0/kg for SC60. The price of WF40 and WF60 suggest that reprocessing recycled CDW wood has the potential for providing cheaper fiber source as commercial wood plastic granulates cost €1.00–4.00/kg (Dammer et al., 2013). The price of composite agglomerates were not far from the virgin polyethylene prices €0.9–1.2/kg. The waste derived composites should have lower cost than the virgin HDPE for the replacement potential to turn into reality. The economic benefits of recycling are further influenced by the oil-prices that at the moment of writing have taken a drastic drop as low as 20$ per barrel due oil price war between Russia and Saudi Arabia. The cost calculation for composites made with recycled materials are quite rare, although lower costs are almost always mentioned as incentives for their use. Gu et al. (2016) used performance -material cost analysis to evaluate the use of injection molded recycled polypropylene composites and found them having a cost of 50% lower than the ones with virgin polypropylene. In a paper by Keskisaari and Kärki (2018) the composite manufacturing cost with waste fillers consisted approximately 50% from material and 50% of processing. Their paper did not evaluate the influence of material density to the processing, but the range of total cost was similar to the one in this study €0,9–1,2/kg. The processing cost was higher in this study compared to the studies of Gu et al. (2016) & Keskisaari and Kärki (2018), which is explained by more efficient processing methods extrusion and injection molding.

To benefit fully of filler materials requires the optimization of the product volume taking into consideration the reinforcement ability of the filler. This is not often possible as products usually have volumetric requirements. The example in Fig. 7 shows that heavy waste derived fillers does not lower the cost of a volumetric product due to the influence of density in volume cost. Fig. 8 shows a product type that favors waste derived mineral fillers this could be a traffic sign holder or similar where the part needs to have mass. The maximum volume of the part and cheaper material alternatives are limiting this type of application for recycled material. The structure optimization that was shown in Fig. 9 is limited by the filler particle size, and minimum and maximum wall strength by the processing method (with the studied waste fillers this would be 2–10 mm compression molding).

5. Conclusions

Recycled mineral fillers offer the opportunity to stiffen recycled polyethylene in non-structural applications. Wood filler has the best strengthening effect of the studied types when properties are compared relative to the increase in weight. Plasterboard and soapstone seem to be more cost-efficient than mineral wool in equal weight-based filling percentages. In volume-based applications, recycled wood filler is the most efficient filler material of the studied group. It also decreases the cost of the product in comparison with unfilled recycled polyethylene. In weight-based applications, the composites with 60% mineral filling (by weight) offer the most cost-efficient solution of the studied group; however, the drop in cost is relatively small in comparison to wood filling, therefore, using wood filler is more risk free for the manufacturer as the wood plastic composite solutions have a long use and production history. In property-optimized profiles, wood fiber fillers are clearly the best option from the studied group due to their reinforcement capabilities. PB60 and SC60 could prove to be better than WF40 and WF60 if other technical properties, such as moisture resistance, are taken into consideration. The impacts of producing thermoplastic composites from CDW are significantly lower than the avoided impacts from their conventional disposal (i.e., incineration and landfilling), especially for plastic waste. The production of composites has a high potential for the mitigation of climate change when accounting for the substitution of conventional products made of virgin plastic. The use of wood waste in the production of composites has lower benefits compared with that of plastic waste due to lower avoided impacts from their conventional disposal. The limitations of the research relate to its focus on the direct costs of processing in a northern European operating environment. The investment costs related starting the activities such as tooling, machinery, surrounding infrastructure, and local differences were out of the scope of this study. The results should be considered when looking for new open-cycle applications for recycled materials. The reuse of the material does not necessarily create a cost advantage or the desired reduction in CO2 emissions due to the required pre-processing or material properties. Further research could address product-specific costing for applications with CDW filler composites, in which case the tooling costs, investment costs, and the supply chain could be considered in the cost and environmental impacts modelling. Also, calculations of the climate change mitigation possibilities from the production of composites on a nation- or region-wide scale accounting for a variety of waste feedstock could be calculated to indicate a scale of the proposed solution in the climate change mitigation targets.

CRediT authorship contribution statement

Petri Sormunen: Conceptualization, Methodology, Formal analysis. **Ivan Deviatkin:** Conceptualization, Methodology, Formal analysis.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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