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Case Study

Twenty years of applied experimental research on wood-plastic composites. An Italian case study

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Abstract

The article describes the development of a WPC product, and it was possible to explore the topics in depth thanks to the multi-year cooperation between some Universities and an Italian manufacturing company. It summarises, in a critical manner, the activity that led to the optimisation of the product according to a series of criteria such as durability, physical–mechanical characteristics, production costs, processability and reduction of environmental impact. The data collected along the way are numerous, concerning flexural strength, imbibition, durability and real behaviour in relation to the exposure to atmospheric agents, solar radiation and the marine environment, of applications carried out with continuity from the early 2000s to the present day. The analysis of the evolution of the product, both in terms of its material composition and its applications, is conducted through the main steps that led to the variations in the formula of the compound, to the changes in the production process, such as the transition from 'one-step' to 'two-step' production lines, and to important implementations for building and marine industries. The final section of the article deals with possible future research topics to lead to product improvement in response to real technical and market needs. The novelty of this contribution lies in providing a concise view of the product development process in relation to experimental tests and the needs of manufacturers and users.

Keywords Wood plastic composites · Thermoplastic composites · Waste and recycled plastics · Durability

1 Introduction

Wood Plastic Composite (WPC) is a material that combines wood fibres or wood flour with a plastic matrix. The wood material used in WPCs is usually a by-product of the mechanical wood processing industry from conifer, hardwood species or other cellulose-based fibre fillers. Plastic or polymer material used in WPC is generally recycled or waste plastic: either thermoplastic (like polypropylene or polyethylene), or thermoset (like phenol plastic or urea formaldehyde). The evolution of WPCs in the building sector can essentially be summarised in five main phases: Early Development (1970s–1980s); Introduction of Coupling Agents (1990s); Commercialization and Market Growth (2000s); Enhanced Aesthetics and Performance (2010s); Smart and Advanced WPCs (2020s and beyond).

The first experiments which combined wood fibres with plastics date back to the 1960s and 1970s, when attempts were made to create materials that merged the best properties of organic and synthetic components. However, at this early stage, the processes and technologies were not yet sufficiently developed for large-scale production. A serious obstacle was given by the fact that fillers, particularly cellulose fibres, did not disperse easily throughout the plastic

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formulations during compounding and moulding. As a consequence, the finished products did not have the desirable physical characteristics ordinarily associated with fibre reinforced plastic composites. This problem was addressed with a series of patents, as described in Klyosov's seminal book [1]. In the 1980s, advanced extrusion technology enabled better integration of wood fibres with plastic matrices. The US began to invest significantly in this technology early on, as companies sought alternatives to traditional building materials.

During the 1990s, US businesses were among the first to launch WPC products for use in outdoor applications such as decking and fencing. The combination of durability, low maintenance and wood-like appearance made WPC very popular [2]. This decade saw a rapid growth of the WPC market, with an expansion of applications and available products. In addition to decking, WPC began to be used for the production of garden furniture, exterior cladding, interior flooring and more. Furthermore, research and development led to improvements in the quality of the material, making it more durable and aesthetically pleasant. The first positive results were achieved by mixing fibres and polymers together, but the development path of this new material was not easy. In various parts of the world, there was a race to understand which materials to use and what characteristics they should have. The process began by trying to blend wood sawdust with recycled products such as polypropylene (PP), polyvinyl chloride (PVC), or polyethylene (PE). Each solution might have seemed promising, but only time and the variety of usage environments provided answers, and the product's initial phase caused no small number of issues for manufacturers. In the early years, manufacturers had their own 'secret recipe' and believed they had found the solution, but time, unfortunately, disproved the optimistic expectations of the brilliant idea behind the possibility of creating this product, namely: to liquefy the polymer component, mix the ingredients, and 'encapsulate' each fibre perfectly through hot mixing. The idea is theoretically sound, but practically challenging to execute. The earliest products were very raw, the fibres were made of wood, cloth, or other materials, but they were not well covered and, often, protruding from the surface of the extruded profiles, they were visible; fibres easily absorbed moisture with consequent deterioration of the fibres and, therefore, reduction or loss of mechanical properties.

In the 2000–2010 decade, in various parts of the world, mixers were designed and manufactured to remove residual moisture from the components [3]; in fact, heating the mixture above 100 °C—especially wood, the most hygroscopic element—led to the creation of steam and as a result, the extruded parts had conspicuous surface defects and internal cavities. In that period single-screw or twin-screw co-rotating or counter-rotating extruders were realised that decisively improved mixing; obviously each solution brought positive aspects, but also negative effects that had to be solved. At the same time, the chemical industry 'fine-tuned' new and more effective coupling agents to better amalgamate polymers with the fibres, which, with the passage of time, decreased in size until they became flour. New lubricants that replaced waxes, new anti-ageing additives to minimise damage during heating and extrusion were studied and tested. New anti-ageing additives proved their worth by considerably increasing the service life of WPC products even when exposed to sunlight, temperature changes and weathering in general. New dyes and additives were developed to limit colour changes when exposed to sunlight and the external environment.

Significant progress was made during that period, but improving mechanical performance remained a priority, leading to the development of new and effective coupling agents. The market began to open up to this new material and the number of companies that began producing WPC grew rapidly, especially in the USA and China, less so in Europe [4, 5]. However, competition between manufacturers in the first decade of the 2000s led to a real product crisis. Since the polymer, by its nature, always covers the extrusion like a skin on the outer perimeter, it is very difficult for anyone to recognize a good product solely by its aesthetic appearance. When, in the absence of other parameters that could put the consumer in a position to choose, the selling price became, substantially, the only element of selection, so began the race of manufacturers to reduce prices, consequently modifying formulations by reducing the quantities of the most expensive components and pushing the extrusion speeds of the machines to the limit. Many manufacturers, at that time, faced significant issues with product complaints, and even large companies were forced to shut down due to substantial losses incurred from disputes. Many researchers gave their important contribution to prevent a new, innovative and promising product from sinking on the market due to a price battle. The world of research asked manufacturers to use quality products, without reducing excessively the polymeric part, but using additives in the right percentages suggested and maintaining correct extrusion speeds to avoid serious problems with material shrinkage.

The paper traces the development of the Italian company's composite product, which in fact mirrors the development of WPC worldwide, and concludes with a reflection on future trends. It shows how the development of WPC represents a continuous process of improvement through applied experimentation. The materials used depend on the availability in individual geographic areas and the possibility to reuse them.

2 Main technological features in current WPC production

WPCs have been increasingly used, despite their higher overall costs compared to naturally durable or treated wood. Surveys suggest that these products have excellent standings for environmental friendliness, and there is an overall perception that they are maintenance free [6]. Their versatility, combined with durability [7] and low maintenance, have made it a popular choice for a wide range of applications, especially outdoors. Continuous innovation in the industry leads to the creation of new products with improved characteristics, such as UV resistance, moisture resistance and high aesthetics.

Durability is correlated to moisture resistance, UV resistance and insect attack. Polymers degrade by chemical, mechanical, photo(light)-induced, and/or thermal modes. The major polymer matrices used in WPCs include high-density polyethylene (HDPE), low-density polyethylene (LDPE), polypropylene (PP), and polyvinyl chloride (PVC). More recent work includes the use of nylon as a polymer matrix for WPCs [8]. Polymer additives used in WPC production include lubricants, colorants, light stabilizers, antioxidants and coupling agents. Specific additives or combinations of additives can potentially be part of the degradation process. For the most part, polymers and polymer additives are much less inclined to biological attack than wood; but polymers, like wood, are vulnerable to the weathering effects of UV light and oxidation [9].

Low maintenance results from the fact that the material does not need painting or other treatments during its service life: this feature is associated with the fact that the products look very similar to natural wood. Environmental sustainability is also linked to the use of recycled materials. WPC is an excellent example of how innovative materials can emerge to meet modern demands for sustainability, durability and aesthetics, becoming an integral part of the construction.

Among the main disadvantages remain the initial cost, the reduced dimensional stability in relation to temperature variations, and the weight. WPCs are generally more expensive than 'traditional' wood (European or North American soft wood), but equivalent to tropical hardwood.

The ability to bind wood flour and plastic materials in WPC is achieved through a specific mixing and treatment process. This process allows the two materials to be combined effectively, ensuring that the desired properties of the composite are achieved. The first fundamental step in the production of WPCs is the preparation of the raw materials:

- The wood flour, derived from wood processing waste, sawdust or other forms of shredded wood must be dry and of uniform grain size;
- The plastic materials, usually PE, PP or PVC;
- The additives, such as stabilisers, lubricants, compatibility agents and colour pigments.

Subsequently, wood flour and plastics are mixed together; this mixture may also include the additives. Coupling agents are crucial for improving adhesion between the polymeric phase (plastic) and the fibrous phase (wood). Examples of these agents include block or graft copolymers that have affinity for both components. Extrusion is the actual production phase during which the mixture is fed into an extruder where it is heated to the melting temperature of the plastic polymers to obtain a viscous mass. During extrusion, the mass is compressed and forced through a die to shape the final product. The extruded material is then cooled and cut into the desired shape, such as panels, boards or other profiles (Figs. 1, 2).

Chemical compatibility between wood filler and plastic material is crucial. Coupling agents improve this compatibility by promoting a stronger bond between the two components.

The size of the wood particles and their moisture content influence the quality of the bond. Particles that are too large or have a high moisture content can reduce the quality of the final product. The ratio of wood flour to plastic must be optimised. Too much wood flour can reduce the flexibility of the composite, while too much plastic can reduce the mechanical strength.

Since WPC consists of three primary components—plastic, wood filler, and additives in varying proportions—it is essential to consider several factors influencing the mechanical performance of these products [10]. Thermoplastic polymers, such as polypropylene, polyethylene, or polyvinyl chloride, generally make up 30–70% of the WPC's mass, while the wood filler, often 40-mesh sawmill residue, accounts for another 70–30%. [11]. Additionally, these composite products contain approximately 5–10% additives of various types to streamline the manufacturing process and enhance the product's appearance and durability. The quality of the raw materials, both wood and plastic, is the most critical factor in determining the overall performance of WPC products. The source and type of raw materials, whether virgin or recycled, can significantly impact the strength and durability of WPCs. Similarly, variations in the filler-to-polymer ratio,

Fig. 1 WPC extrusion line plant from pellet (two steps production), from Novowood®

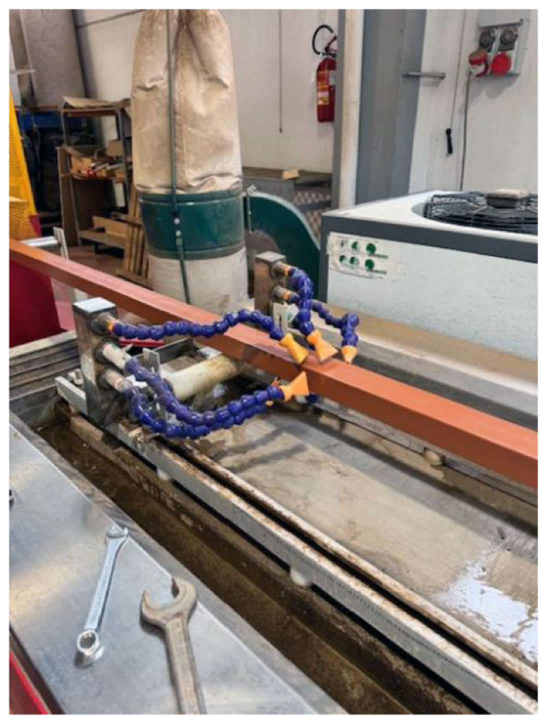


Fig. 2 WPC profile drying phase, from Novowood®

the method of mixing the primary components, as well as production techniques and process conditions, play a crucial role in determining the suitability of any WPC product for its intended use [9].

The use of additives can improve several properties of WPC, such as UV resistance, durability and adhesion between wood dust and plastics. The ability to effectively bind wood dust and plastic materials in WPC is the result of a combination of material selection, coupling agents, process conditions and additives. This bonding is crucial to ensure that WPC has the desired properties, such as durability, mechanical strength and low maintenance. Extrusion conditions, such as temperature and pressure, must be carefully controlled to ensure uniform mixing and a strong bond between the components [12].

Over the past 10 years, WPC has regained product and market stability. However, as there is no reference standard to classify and qualify products, the risk of buying a bad product at a good price still exists. Since 2010, the focus on sustainability and recycling has become increasingly important [13]. In fact, WPC being produced from recycled materials (both wood and plastic), is seen as an environmentally friendly solution [14]. Parallel to the topic of recycling related to WPC components, the recycling of composite material at the end of its use is becoming very important and represents an answer, widely shared by the scientific community, to the environmental need to avoid the production of waste and to reintroduce 'spent' materials into the production cycle.

Ongoing applied research is addressing issues such as product regulation and recycling at the end of life and facades as a key component of the building envelope [15]. In the regulatory sphere, there have been limitations related to the fact that composites hardly fall under many regulations that make specific material categories explicit; given the variability of compositions, interpretations or adaptations have to be made from time to time. Currently, in Europe, there are several regulations and standards. These regulations cover various aspects, including safety, durability, mechanical properties and fire resistance. EN 15534 [16] is a series of standards that specify requirements and test methods for wood-based and plastic composites. It covers several aspects, including mechanical properties, durability, weathering and fire resistance. These regulations provide a basis for ensuring the quality and safety of such materials, but have some shortcomings in terms of coverage, long-term durability, environmental sustainability and the ability to adapt to technological innovation. Continuous updating and the inclusion of more specific guidelines could improve the relevance and effectiveness of regulations for a rapidly evolving market. Furthermore, WPCs can be produced with a wide range of combinations of polymers and lignocellulosic fibres, which can lead to significant variability in material properties [17]. However, current regulations may not adequately cover all possible combinations or new formulations and applications. This is an important limitation for product development.

The issue of product recycling also emerges [18]. With current standards the product can be shredded and re-extruded numerous times without losing its physical–mechanical characteristics [19]. This means being able to use and reuse a material, without having to draw on new sources of supply, for a very high lifespan. The downstream pathways of post-consumer WPC products were analysed from the recycler's perspective through an LCA approach. Systems with equivalent functions were created to ensure a valid comparison of end-of-life (EoL) treatment methods: the results indicated that WPC produced from secondary materials is the ecologically and technically superior option [20].

In addition to the topics mentioned above, coextruded WPCs deserve to be mentioned among the latest innovations in the industry and new future trends for research. Co-extruded WPCs (Co-WPCs) are multi-layer composites created by adding a protective outer shell to standard WPCs through co-extrusion. This core–shell structure addresses some of the inherent limitations of traditional WPCs by enhancing surface properties through targeted modifications [21]. As co-extrusion technology advances, Co-WPCs are positioned to become a significant trend in the WPC industry [22]. Coated WPC technology is evolving rapidly, with innovations focusing on improving the aesthetic appeal, environmental footprint, and overall durability of these materials, which are subject to biological degradation [23]. From UV stabilization to hydrophobic, anti-microbial, and flame-retardant coatings, the future of WPCs lies in integrating advanced coating technologies that make them even more versatile, long-lasting, and eco-friendly for a wide range of applications. There are still few studies reporting an increase in fire resistance time through the use of nanostructured hybrids coating WPC surfaces. Efficient multilayer hybrid coating methods can be developed to improve fire resistance and smoke suppression for WPCs and other materials [24].

3 Experimentation and applications: an Italian case study

The case study concerns WPCs developed in Italy since the early 2000s for application, mainly, in the maritime field, specifically for the construction of floating structures for marinas [25]. The manufacturer had been using tropical wood planks (imported from Indonesia, Brazil, Mozambique and other tropical countries) for over 30 years to build the decking of its structures located in maritime or lake and river environments.

With the beginning of the twenty-first century, the availability of many exotic wood species, among those most widely used and suitable for that specific use, declined—costs rose considerably and, at the same time, quality declined drastically—as well as sensitivity to the issue of environmental sustainability increased. These were mainly the reasons that led the company to start researching in the field of composite materials, first by studying and applying those already existing on the market and used mainly in North America and China, and later, by starting its own research and development.

The aim was then to fine-tune and develop its own formulas through study, applied research and field experimentation. Therefore, an attempt was made to select the most suitable components to achieve the physical–mechanical and durability characteristics required to obtain extruded profiles for decking to be used in an exposed and aggressive environment such as the marine environment. The research involved the company's technicians, component suppliers, production plant suppliers and the University of Ferrara [26]. The product characteristics are the result of decades of research using laboratory tests.

3.1 Initial tests on product durability

In order to understand the role of recycled PE in relation to durability, the manufacturer performed many Oxidation Induction Tests (OIT) on WPC samples. The OIT test makes it possible to predict the lifespan of the extrusion batch from which the samples are taken. The OIT parameter is always incorporated into the characterization of WPC products and the assessment of their real-world lifespan, particularly on actual decks. Essentially, the OIT value provides a quantitative measure of the lifespan of a composite (or any organic-based) material during accelerated oxidation in pure oxygen at elevated temperatures, such as 190 °C. For instance, in unstabilised WPC materials (without added antioxidants), the OIT can be as low as 0.3–0.5 min.

OIT represents the material's lifespan in a chamber filled with pure oxygen and heated to a specific temperature, typically between 180 and 200 °C. At this temperature, the oxidation process occurs 1–10 million times faster than under ambient conditions. In other words, if a material takes 1 min to oxidize completely at 200 °C, the same process might take 2–20 years in a natural environment. The reference standard for this test is the ASTM D3895-19S [27]. The OIT test could also be carried out following ISO 11357–6 2013 [28], withdrawn in 2018. There is no accepted sampling procedure, nor have any definitive relationships been established for comparing OIT values on field samples to those on unused products, hence the use of such values for determining life expectancy is uncertain and subjective. Exact control of the specimen's weight is not required, as long as it falls within a convenient range of approximately 5–30 mg (typically 10–20 mg). While the weight may influence the peak height of the heat flow in the oxidation isotherm, it does not affect the OIT itself. Therefore, a modified ASTM D 3895 procedure (in terms of sampling) is suitable for plastic/cellulose fibre/mineral composite materials.

OIT is a relative measure of a material's resistance to oxidative decomposition. It is determined through thermo-analytical measurement of the time interval during which the material undergoes exothermic oxidation at a specified temperature in an oxygen atmosphere. The sample is initially heated at a constant rate (typically 20 °C/min) in a nitrogen atmosphere. Once the specified temperature is reached, the specimen is held at this temperature for a few minutes (usually 5 min) to achieve thermal equilibrium, and then the nitrogen atmosphere is replaced with oxygen at the same flow rate (typically 50 cc/min). The specimen is maintained at the constant temperature until the oxidation reaction appears on the thermal curve. The time interval between the start of oxygen flow and the onset of oxidation is known as the induction period. The end of this period is marked by a sharp increase in the specimen's heat evolution, which can be observed using DSC. The OIT is determined from the isothermal test data, specifically from the point when nitrogen is replaced with oxygen to the point where the steepest slope on the heat flow curve is extrapolated to the flat baseline of the thermal curve.

Some significant OIT tests, carried out in 2010 in collaboration with a research laboratory in Milan are selected among various tests, and reported here [29]. Five sample types were specifically compared:

- A standard blend with 100% virgin PE (sample A);
- A standard blend of 70% virgin and 30% recycled PE (sample B);
- A standard blend 30% virgin and 70% recycled PE (sample C);
- A regrind from WPC obtained with standard blend type C (sample D);
- A sample of WPC from a primary producer from the Chinese market (sample E).

The 3 standard blend samples had a minimum content of 30% PE in order to guarantee the physical–mechanical characteristics required by the product. The analysis involved fine-tuning the measurement method by carrying out 4 measurements for reproducibility on sample A and measurement on sample D. The ramp used for the measurement conditions was:

- from T = ambient to T = 190 °C, at 20 °C/minute, in N_2 with a flow of 50 ml/minute of gas;

- t = 5 min at T = 190 °C, in N_2 with a flow of 50 ml/minute of gas.
- gas switching in O_2 with a flow of 50 ml/minute of gas, for a minimum time of 30 min.

In all samples analysed, the endothermic polymer melting peak was present, corresponding to the HDPE polymer at T = 131 °C. After the 5-min conditioning and oxygen switching, the OIT (oxidation induction time) part begins. Two separate exothermic reactions were noted for sample D (Fig. 3): the first with an ONSET of 0.39 min (OIT) and the second with an ONSET of 7.25 min. The exothermic of interest was the second, the more energetic one. We then proceeded with the analysis of sample E, for comparison (Fig. 4).

Two reactions were observed: the first at 0.38 min and the second at 6.65 min. The analysis of sample A, however, showed only the weakest first transition, even continuing the test up to 2 h OIT. The curve for sample A is shown, up to 2 h after oxygen switching (Fig. 5).

The summary of OIT results (measured as ONSET of the most energetic transition) are reported below:

- Sample A: OIT > 120 min (expected figure in relation to the use of 100% virgin HDPE)
- Sample B: OIT = 57.13 min
- Sample C: OIT = 15.40 min
- Sample D: OIT = 7.25 min
- Sample E: OIT = 6.65 min

These tests provided a better understanding of the influence of PE, in qualitative and quantitative terms, in relation to durability, based also on the availability of such raw materials in Italy during those years. The sample with 100% virgin PE proved, as expected, to be the best performing and most durable. Using virgin polymer was certainly a solution to improve product performance (virgin PE already contains antioxidants), but it was not the path that the project managers decided to follow as the choice was not consistent with the principles of eco-sustainability underlying the new programme. It is also interesting to note the minimal difference in the tests between sample D and sample E.

Correlating OIT results with real-world conditions, it is important to keep in mind the following:

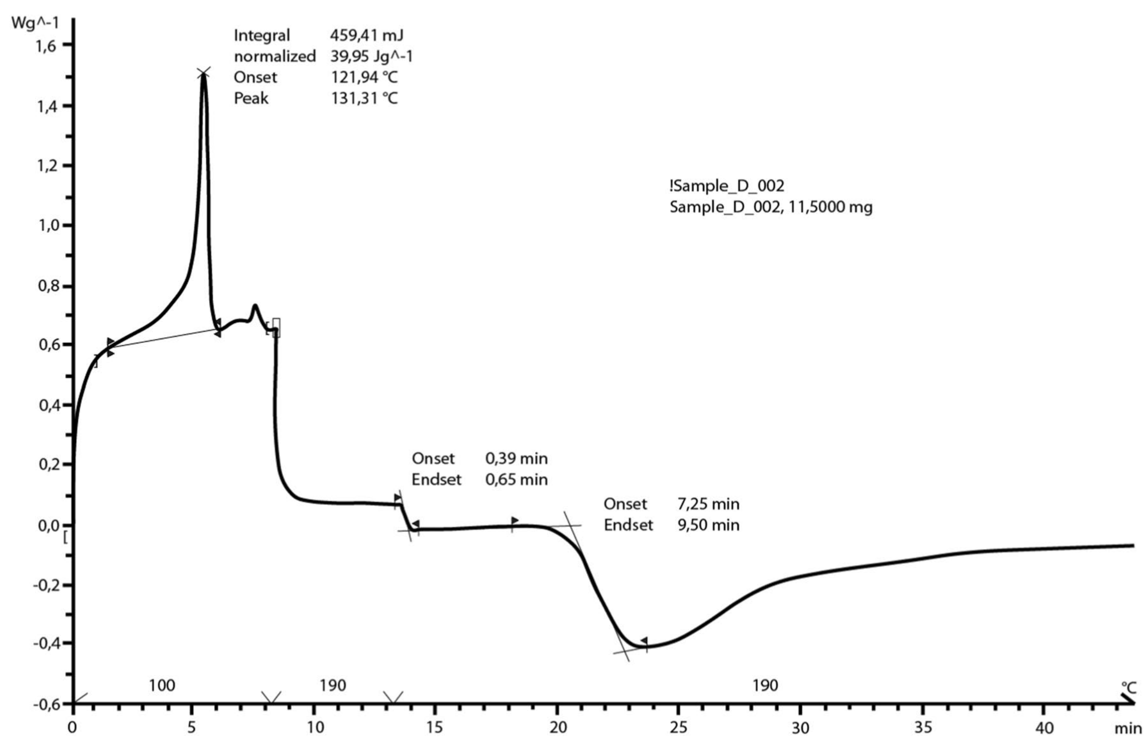


Fig. 3 DSC/OIT curve for sample D

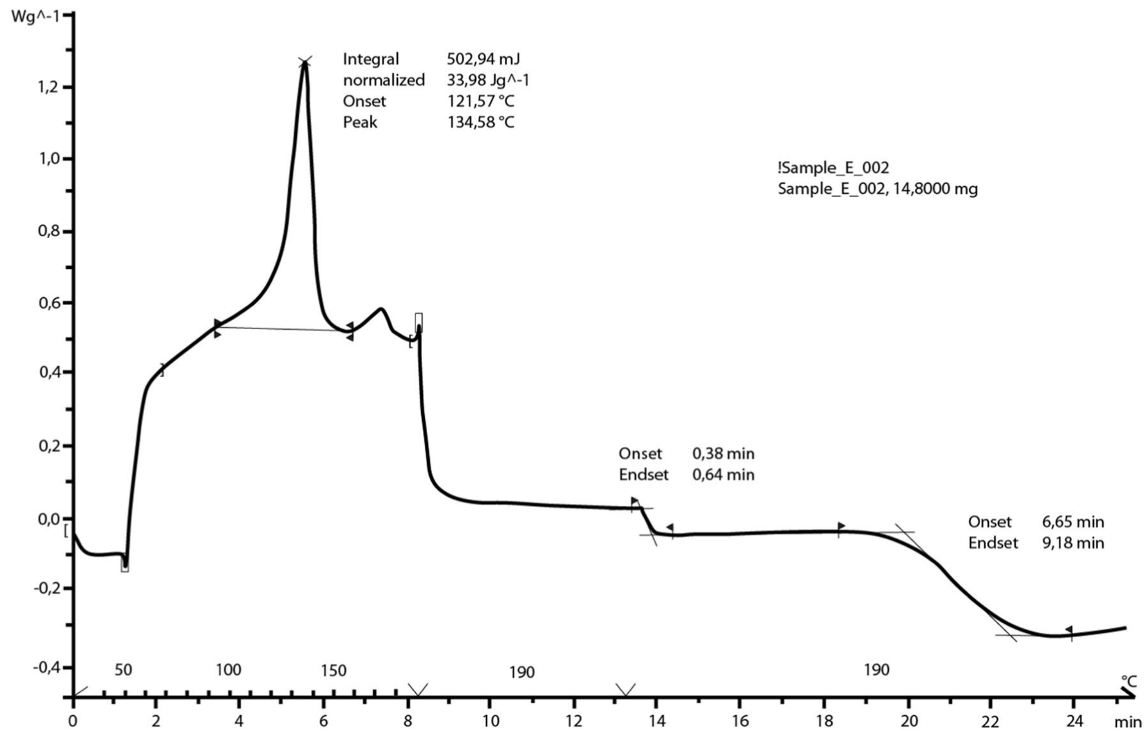


Fig. 4 DSC/OIT curve for sample E

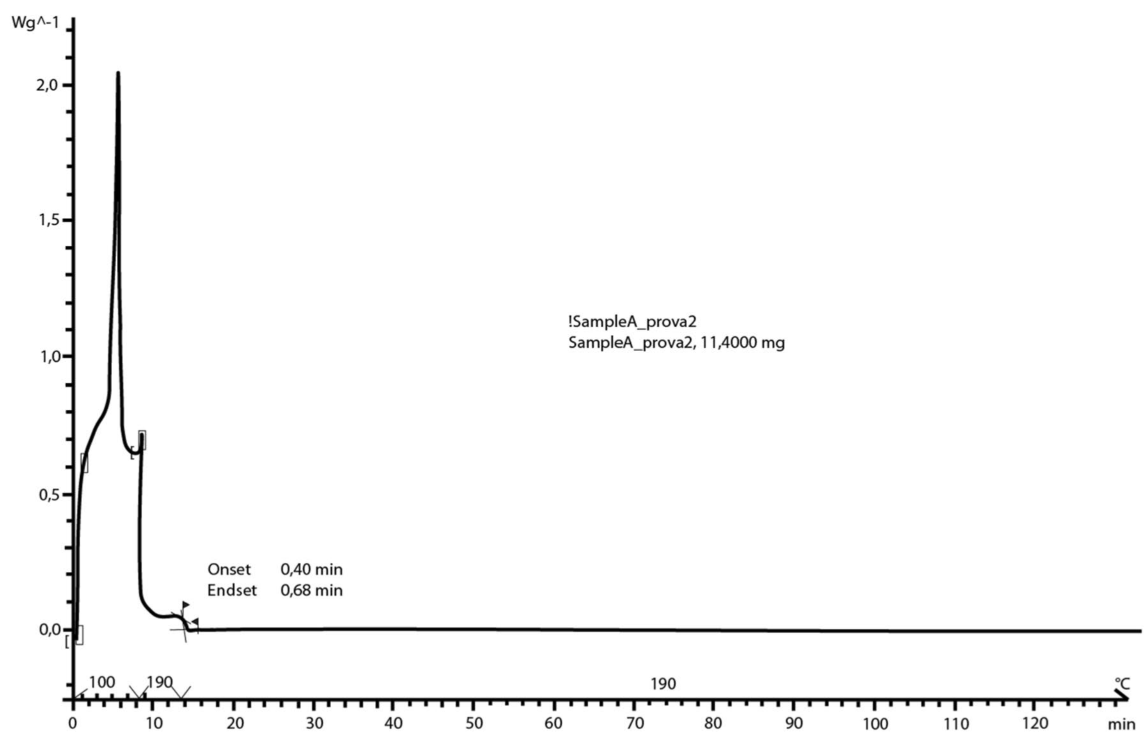


Fig. 5 DSC/OIT curve for sample A

– we used a linear correlation, but it is possible to use Arrhenius modelling to relate the elevated test temperature to real-world temperatures. The model assumes that the rate of oxidation increases exponentially with temperature, allowing you to estimate material performance at typical service conditions;

- additional factors like UV radiation, moisture, and mechanical stress combine with oxidation to affect durability;
- OIT reflects the efficiency of antioxidants or stabilizers; understanding their degradation kinetics helps predict when the material will lose its protective capacity.

From the analysis of these tests, a second important phase of product development began. When reading this data, it is important to bear in mind that the tests were carried out in 2010.

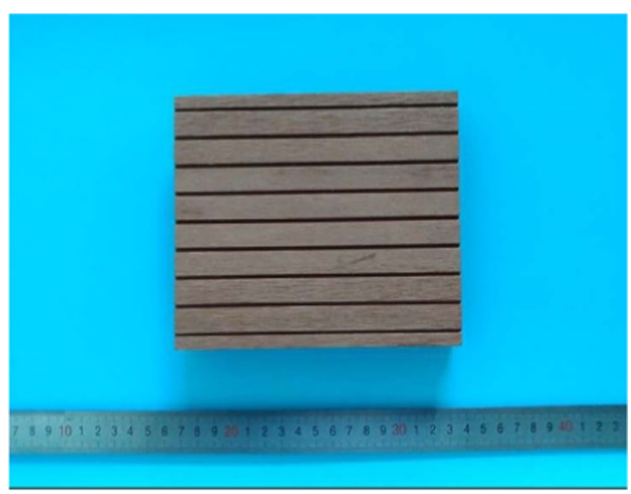
3.2 Product development

The following goal of the product development phase was to avoid, or keep as low as possible, the use of plastic components from new production, in favour of the use of materials from high quality production waste, with which it would be possible to achieve similar if not identical results to the use of virgin materials (in addition to cost reduction). The aim was then to find components on the market that were as natural (colours, fillers, etc.) and recycled as possible, as well as the best coupling agents and anti-oxidants in order to obtain a recyclable and renewable product, i.e. a product that could be shredded and re-extruded countless times at the end of its use cycle, even in different forms, but without the need to add new materials.

After about 10 years of testing and feedback on products sold, the initial idea saw its completion even though research activity is always 'in progress'. The polymers used are extruded or moulded, selected, ash-free production offcuts/scraps of new products; the wood used comes from FSC-certified Hard-Wood and Soft-Wood waste of controlled grain size; the fillers are natural products as are the colours. The product is completely renewable, i.e. at the end of its life cycle, the extruded material is shredded and reduced to granules in a special machine; the material is then re-extruded in its entirety or mixed together with other products as required. The OIT test increased from a few minutes to over 1 h, providing a clear indication of the extended life of the product, even when exposed outdoors and in harsh environments. Currently, with the level of sorting of recycled plastics, results are considerably higher than the availability of materials in 2010; in fact, mixtures containing high-quality recycled HDPE are on the market, and this is a very positive aspect for product quality and environmental sustainability. It can therefore be stated that the production of WPC has been characterised by a continuous and progressive variation in the quality and quantity of polyethylene, more or less recycled, as well as a refinement of the composition of the other components. In order to be certain of placing products on the market that meet certain physical-performance characteristics, OIT tests were carried out with each variation in the composition, i.e. of imbibition, bending strength, colour, shape stability, etc. The following is an example of OIT test performed on composite specimens (Fig. 6) at the current stage of development (Fig. 7) [30].

Starting from the assumption that each minute of OIT corresponds to approximately 2 years of life of the product in an external environment, by, as a precaution, applying a reduction coefficient that takes into account the actual operating conditions, the forecast of the life-span of the material was obtained. An important issue to address, since the beginning, was to obtain extruded products that had an oxidation time (OIT value) of minimum 40 min or, theoretically, capable of lasting, in an external environment, for a period equal to at least 10 years, considering a reduction factor of 75% hypothesized due to the outdoor use, in the climatic band of the 45th parallel of latitude (central-southern Italy), of decking

Fig. 6 WPC specimen



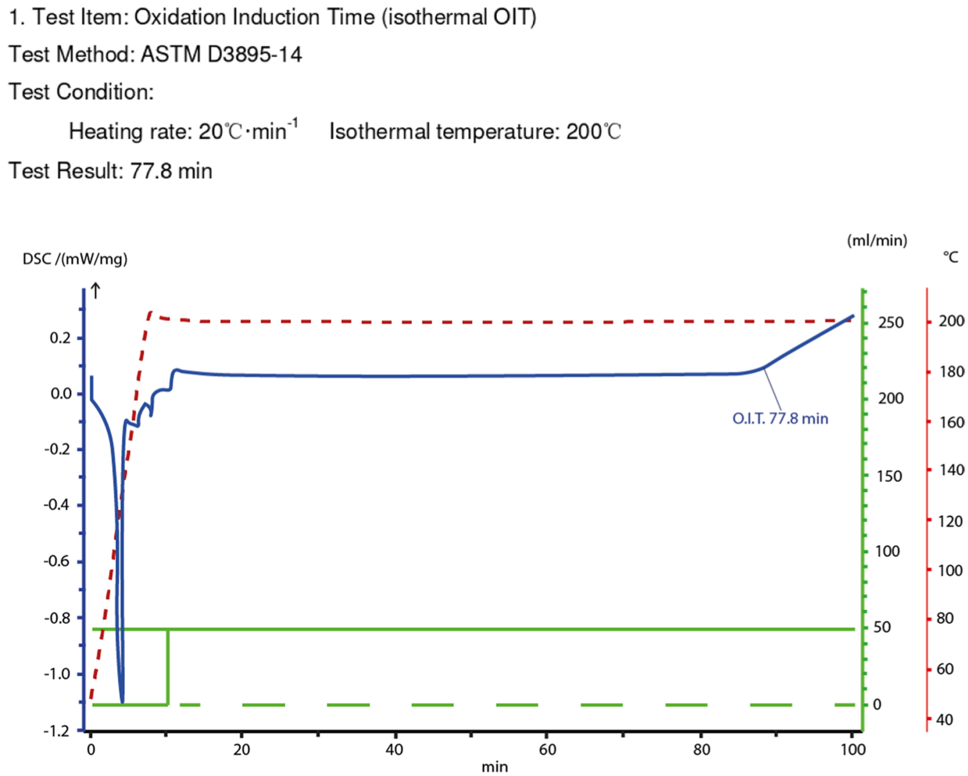


Fig. 7 OIT test Heating rate 20 °C min^{-1}, isothermal temperature 200 °C. The graph shows a value of 77.8 min, which is an excellent result compared to literature data [1]

products placed in a marine environment, exposed to sunlight and atmospheric agents. Step by step, with continuous tests and adjustments to the formula and choice of its components, over about ten years, it has been possible to significantly increase the OIT value which currently stands at around 80 min (equivalent to a minimum durability of 20 years, in 'heavy' conditions), using a portion of PE recycled. In Fig. 8 the specimen used for mechanical tests is displayed. Data from other tests, aimed at mechanically characterising the product are reported below (Table 1) [30].

The specialist literature confirmed the intuition and results obtained: the mechanical properties of composites made with highly degraded HDPEs were comparable to those of composites with virgin HDPE. In some instances, they even demonstrated superior performance, except in terms of impact strength [31].

Another test, the imbibing test (ASTM D1037–23) [32] was carried out on samples of different colours (Wood, Copper and Dark) to understand if and how the colour affected the material's behaviour in relation to prolonged contact with

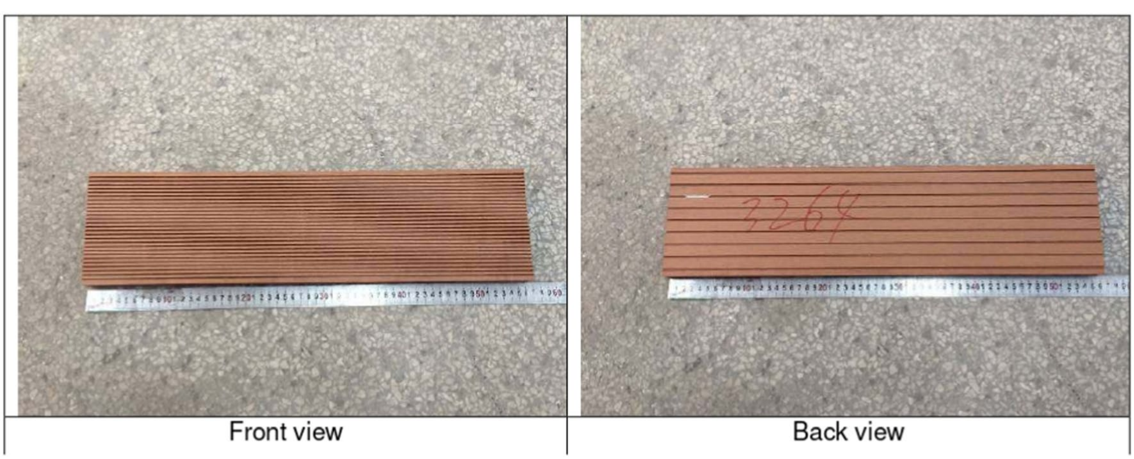


Fig. 8 WPC specimens for mechanical tests

Table 1 Characteristics of WPC product

Flexural strength and Modulus of elasticity			
Test item	Test method	Test condition	Results
Flexural strength	ASTM D6109-13 section 10.1 Method A	Specimen: 556 mm x 144 mm x 24 mm Testing speed: 11.4 mm/min Test surface: Front view	21.6 Mpa
Modulus of elasticity			2940 Mpa
Water absorption and thickness swelling			
Test item	Test method	Test condition	Results
Water absorption	ASTM D1037-12 section 23 Method B	Specimen: 161 mm x 143 mm x 24 mm	0.6%
Thickness swelling			0.3%
Specific Gravity			
Test item	Test method	Test condition	Results
Specific Gravity	ASTM D792-13 Method A	Specimen: 152 mm x 142 mm x 24 mm	1.302

Statement: Unless otherwise stated the results shown in this test report refer only to the sample(s) tested water. The WPC sample was placed in oven at 75 °C for 24 h before the test began. Subsequently the conditioning was carried out in water at 60 °C. The results are shown in the figure below (Fig. 9) [30].

Mustard ('Senape') color is a reference sample of a material of another producer. It is possible to notice that dark colors have a behavior similar to wood, and that brushed surfaces have a similar behavior of the not brushed surfaces ones; on the contrary with mustard and copper colors there is a significant reduction. This means that coloring additives have a significant influence on hygrometric increase.

The evaluation of absorption in WPC composites can also be performed according to UNI EN 317 tests [33] (for wood fibre-based panels, now under review). The tests consist of immersing a sample in a container filled with water at constant temperature for a sufficient time (typically 24 h) and then measuring the extent of absorption and the swelled thickness in the three spatial directions. Most manufacturers claim that the extent of water absorption of their products does not exceed 2% or is around those values. The results provided by the standards with which the weight content of absorbed water is estimated today are not reliable in describing the real value of water absorption in WPC composites [34]. The results of the tests can vary greatly, depending of course on the combination and quality of the plastic or wood materials used for the mixture. However, if the aim of all the above tests was to guarantee the integrity of the products for a period of at least 20 years, the condition test on some flooring laid in 2008 gave very convincing results (Fig. 10).

The composition of the current material produced by the company under the Novowood® brand name is reported in Table 2, while the technical specifications are reported in Table 3.

As can be seen from Table 2, the percentage of components is variable. Furthermore, the data sheet does not specify the presence/percentage of recycled material. In fact, the material may have variable percentages of recycled material and may also contain material from the recycling of WPC at the end of its life cycle—this depends on the final application of the product. In any case, the material complies with the limits set by the Italian CAM (Minimum Environmental Criteria), also verifying the traceability of the recycled product [35].

3.3 Research and application trends

Research on Novowood's products is mainly directed towards the composition of the material. Equally important is the research and experimentation on construction systems, assembly and fixing systems (e.g. sunshades, facade cladding, etc.) (Fig. 11) to guarantee the required performance in terms of speed of installation and low maintenance. WPC is a material used within construction systems of a certain complexity, and therefore must be integrated with other materials

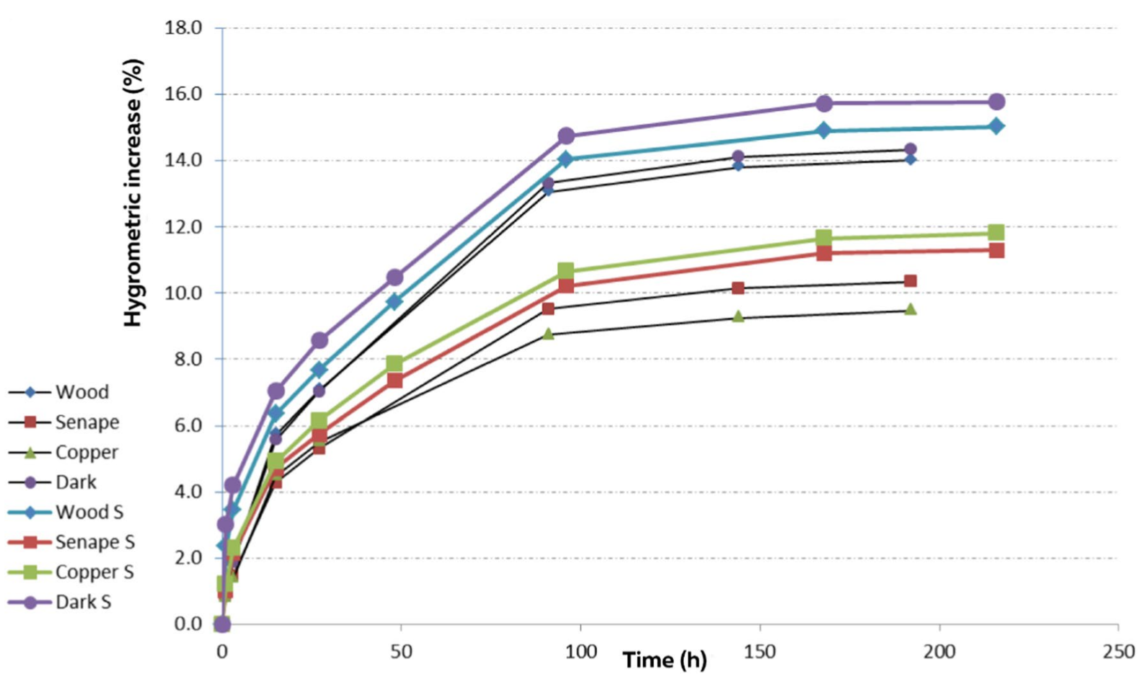


Fig. 9 ASTM D1037–23 Samples with different colours. "S" means Brushed surface—Other ones are not brushed samples

Fig. 10 An emblematic WPC project: a kindergarten outdoor decking in 2008, as built, and in 2024

Table 2 Product components, from Novowood®

Components	Percentage presence in the compound
Wood flour	50–70%
High density polyethylene (HDPE)	25–35%
Additives	10–15%

Table 3 Technical specifications, from Novowood®

Properties	
Density (EN ISO 1183–1)	1300 kg/m^3
Flexural strength, average value (EN ISO 178:2003)	25 MPa
Modulus of elasticity, average value (EN ISO 178:2003)	2500 MPa
Tensile strength, average value (EN ISO 527:1996)	5 MPa
Tensile modulus of elasticity (EN ISO 527:1996)	3000 MPa
Brinell hardness	68 N/mm^2
Coefficient of expansion (DIN 53752)	0,04 mm/m/°C
Anti-slip classification with stockinged feet (DIN 51130)	R11
Barefoot anti-slip classification (DIN 51097)	C
Imbibition index (24 h) ASTM DI037 Non-brushed surface	1,2%
Imbibition index (24 h) ASTM DI037 Brushed surface	3,5%
Fire reaction class (Italy) (UNI EN 13501 1:2009) For decking Classified by the Ministry of the Interior	C_{FL} s1
OIT test (ISO 11357–6:2008) Average value	52,7 min
Allowable live load (NTC 2008) (Joist spacing 350 mm)	500 kg/m^2
Solar reflection index SRI with convective heat transfer coefficient h_c = 12 W/m^{2}K ASTM E1980-11 (2019)	30,2 wood 15,4 copper brown 35,5 pearl grey 64,3 white 43,1 sand
Thermal conductivity λ (UNI EN 12664:2002)	0,385 W/mK

Fig. 11 Examples of sunshades, privacy screens, sliding panels, stairwell and facade cladding with WPCs from Novowood®

with different characteristics. From this perspective, the initial costs of all materials must be balanced, installation optimized and the maintenance burden reduced.

The successful development of durable WPC cladding remains a challenge for the industry. High values of modulus of rupture (MOR) and Young's modulus (MOE) are considered crucial for the engineering design of WPC façades, as both parameters serve as effective indicators for assessing the ageing of WPC cladding. Weathering tends to reduce MOE more significantly than MOR, with UV radiation posing a greater threat than freeze–thaw cycles. To minimize the loss in MOR and MOE, it is recommended to use PE in extruded panels with a low content of large-sized hardwood fibres [36]. The company has not yet introduced coatings into extruded products to improve durability, unlike other markets.

An optimization strategy, related to the life cycle of the products, is being studied by the company. This consists on the free recovery process of composite wood waste from the construction site. These wastes, by virtue of their particular formulation, can be reused by the manufacturing company, after shredding and re-extrusion, to create new products, thus contributing to the reduction of CO_2 in all the production stages, but mostly in the transportation stages, up to 50%. It is essential to raise awareness and educate both participants in the production chain and end consumers on the importance of recycling these materials [37]. Moreover, the company is starting a new optimization strategy, where old construction systems installed in previous years are dismantled from the buildings and reused (Fig. 12).

The introduction of this product recycling action during the production and installation phase, as well as during the component replacement phase after an initial life cycle, should lead to reducing the impacts by 20%, considering the total life cycle of the product. The decisive element is given by the fact that the recycling of the material concerns both the plastic component and the wooden component. From this point of view, the manufacturer is developing an EPD that takes into consideration this reduction during production phase.

4 Conclusions

The article addressed the topic of the use of wide-ranging WPC characteristics, specifying data from a manufacturing company in Italy. The role of the Universities was to collect these data and support tests. It was highlighted how the product has been constantly evolving over the last twenty years and continues to do so. While at the beginning the objective of research and development was to stabilize the material and solve some problems related to imbibition, in

Fig. 12 WPC façade cladding panels: an example of the re-use cycle, from Novowood®

recent years the issue of reusing recycled material has become important, not only to achieve environmental sustainability objectives, but also to reduce costs without lowering performance levels.

The evolution of WPCs over the past 20 years demonstrates the material's transformation into a sustainable, durable and versatile solution for the construction industry. The WPC market is global and therefore its regulation is important for manufacturers. From the point of view of designers and users, especially in Europe, it is important to ensure that quality remains high in compliance with the standards on green products suggested by the directives. Continued innovation and alignment with environmental trends, particularly regarding material recycling and reuse, should ensure that WPCs will remain a key component of modern construction and architectural design.

Today, WPCs that are approaching the end of their life cycle after twenty years are starting to be reused to reproduce them with the same or even better characteristics. One aspect to take into consideration seems to be maintaining good product quality; in fact, the reduction of costs also leads to a reduction in the durability of the material. In any case, WPCs confirm themselves to be very promising materials for the future and completely competitive compared to the production of wooden components, precisely in view of their circular economy.

Next steps in research could include OIT studies on co-extrusions to determine their durability. In addition, the likely increase in environmental impact due to co-extrusion could be assessed. Our area of interest also concerns the development of new building systems using WPCs, considering that the material has reached a maturity of its own and can therefore be designed for more complex components concerning, for example, the building envelope.

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Declarations

Competing interests The authors declare no competing interests.

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