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Case study

Comparative study on artificial and natural weathering of wood-polymer compounds: A comprehensive literature review

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ABSTRACT

Wood-polymer composites (WPC) increasingly gain in popularity in the building industry. To date there is less long-term experience from façade applications which reliably confirm that relevant material properties are sufficient throughout their expected lifetime. Therefore it is common practice to simulate WPC material ageing in climate chambers. Artificial conditions, however, not necessarily mirror practical applications. To get a clearer picture about WPC ageing this literature review draws a comparison between artificial and natural weathering of divers WPC compound formulations usually applied in cladding products. It was found that both conditioning types provoke comparable effects in the material. UV-light in combination with moisture leads to polymer crystallinity with chain scissions and delignification. As a result, interfacial bonding gets weaker and fibers become detached from the matrix. In the further course lightening penetrates deeper reducing the stress bearing cross-section of the WPC profile. In this view, material ageing of WPC manifests itself as highly dependent on promoting agents. These aim at improving interfacial bonding between fibers and matrix and stabilizing polymer chains against radiation.

1. Introduction

Natural fiber-reinforced plastics (NFRP) have gained in market acceptance over the last years. One main representative is Wood-plastic Composites (WPC). They contain up to 70% of wood fibers embedded in a thermoplastics matrix such as polypropylene (PP), polyethylene (PE) or polyvinylchloride (PVC) [1]. As composite material they combine the main advantages from plastics and wood. Polymers show low moisture susceptibility and wood fibers come from renewable feedstock. This makes WPC products more sustainable than plastic goods [2]. Reportedly, if wood fibers show an aspect ratio of 1:50 they best support a strength increase of the matrix compared to pure plastics [3,4]. However, it is also common practice to use wood flour instead [5]. The fiber content has a great influence on WPC`s strength properties. In general, if strength increase is plotted against fiber share then the relationship equals an inverse u-shaped curve. Highest strength is reached at some 70% fibers and subsequently modulus of rupture (MOR) goes down again [6]. This is explained by the low proportion of matrix material which no longer supports a proper stress transfer between fiber and plastics. Further, the wood species also play a major role in WPC`s mechanical characteristics. In a study conducted by Fibiyi and McDonald [7] several hard- and softwood fibers were tested against each other. They found that by trend softwood contributed more to strength increase than did hardwood. This is most probably because plastics and fibers show similar flexibility. In terms of weathering, the common literature sees in the fiber addition the main weakness of WPC if used outdoor. This is in contrast to pure plastics. With regard to the matrix, a review conducted by Friedrich [8] revealed from data out of 12 papers that PE has a

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tendency to much better cover weathering impacts than does PP and PVC. This again very likely comes from a comparatively more improved interaction between the polymers and promoting additives at the interface between fibers and matrix. Above all, PVC is far more brittle and more susceptible to hygrothermal impacts [9].

The main applications for WPC are decking which by majority contain PVC and PE. In terms of cladding mostly PP is used [10]. Profiles for both applications are extruded and for 2020 a total production volume of 300,000 tons per year is forecasted for Europe [11]. However, the use of bio-based materials in load-carrying applications demands excessive pre-testing of compounds and products. This is necessary to demonstrate a satisfying long-term performance. A high number of publications originate from the fact that possibilities in mixing fossil-based plastics, fibers and additives are nearly unlimited. Besides the plastics and fibers, also the production method is expected to affect the material properties. Once the compound was melted down the composite usually changes some characteristics [12,13]. Compound and product properties might differ from each other right after production and in aged conditions. In this regard, Stark et al. [14] investigated the effect of extrusion and injection molding on WPC`s ageing behavior. They found out that the loss in mechanical strength of WPC specimens during the first 3000 h of artificial weathering was not significantly different between both production methods. However, in terms of modulus of elasticity (MOE), decline was 8% less for injection molded specimens. This is due to higher density of the compound. At least MOR obviously is comparatively less affected by production method. This finding plausibly demonstrates that not only weathering is the reason why properties change over time. It is also the compound`s quality and processing method which affect ageing behavior. However, research projects mostly investigate only some selected characteristic traits for a particular compound formulation. This hardly allows for overall assessment of performance prior to manufacture of new products.

Particularly when bio-based materials are used in the building skin they are faced with multiple mechanical, physical and chemical impacts. Wind loads push and pull on a façade's cladding where loads up to 4.0 kN/m^2 can easily be reached depending on the location of the building [15]. Highest loads usually occur across the facade's corner in the upper levels of buildings if located in mountainous or coastal regions [16]. Hence, mechanical impacts are not to be underestimated. Further, moisture and temperature changes are physical effects on building skins. Freeze-thaw cycles lead to additional stresses in the cladding material which suddenly erupt in cracks or permanent deformations [17]. Specifically composites suffer from physical impacts because chemical bonds between the material's ingredients become degraded [18]. Also, thickness-swell by moisture and subsequent freezing leads to increase in volume of the water-filled pores. This goes along with microstructure damage [19]. Finally, chemical reactions between the material and atmospheric gases, pollutants and rainwater can build acids. They change the properties of particularly organic substances in the cladding materials [20]. Photo-degradation also belongs to this scope because polymer chains and their crosslinks easily break under continuous energy uptake from global radiation [21].

It seems plausible that characteristic traits of Wood-plastic Composites are negatively tied to natural weathering. This is because such bio-based compounds contain both photosensitive polymers and hydrophilic fibers [22]. Hence, UV light and moisture which are major components of natural weathering are most crucial for WPCs. They not only degrade mechanical properties but also change the surface appearance. This manifests itself in discoloration, furrows and voids where fibers become detached from the compound. As can be seen from the micrographs in Fig. 1, after one year of outdoor weathering the surface significantly changed to the worse. Irregularities increase in frequency and intensity and the WPC became brighter. This can be traced back to the fact that the thin covering plastics layer gets eroded and white lignin-free wood particles are more apparent.

The degrading effect from weathering on WPC properties eventually leads to material fatigue. Compared to conventional cladding materials from minerals or metal ores this failure might occur much earlier within a façade's lifetime. Since the life expectancy of a building`s skin is mostly assumed to last at least 30 years, there are particular doubts about WPC to be fit for use in the building envelope. It is straightforward to show by research in durability aspects how the planning risk of structural engineers can be reduced. Nowadays, for conventional building materials the effects from ageing on the structural performance of the cladding under weathering are well known. As articulated previously, mechanical impacts from wind are acknowledged as being dominant. They are mostly investigated by laboratory testing but also by experience from storm damage [23,24]. Practically, the collapse of a façade manifests itself in breaking out of single cladding parts or the crash of a complete façade section. In such a case one fastener after another either breaks off or punches through the cladding material in zipper style. If one fastener breaks because it was calculated close to its failure load without sufficient safety margin, then its individual load component is distributed to the neighbor fasteners. However, they not necessarily hold sufficient capacity in readiness. The ultimate wind resistance of WPC façades was investigated by Friedrich [25] under laboratory experiments applying simulated suction on single façade sections. Pull-out of screw heads through the cladding flanges was found to be the dominant failure mode of such cladding types. This is in contrast to standard material testing where mostly bending rupture is investigated. The author concluded that ageing of WPC material in a façade can lead to failure if visible fasteners are in use. This is because their heads are exposed to weathering. The story is different when such cladding is mounted with hidden fasteners. This is when the profiles are connected by tongue- and groove system. In such a case the material around the screw head is much less affected to UV and moisture. Then the WPC cladding can be calculated with higher design loads because degradation by UV-radiation is expected to be almost zero. A strong argument can be made that the structural performance of WPC cladding profiles not solely depends on the material formulation and its ageing behavior. On the contrary, it is also or even primary up to the interaction between material and fasteners [26]. As far as the compound is concerned, ageing most probably is an effect which is composed additively with proportions from radiation-, temperature-