NATURAL FIBER-REINFORCED PLASTICS COMPOSITES: LONG-TERM PHYSICO-STRUCTURAL PERFORMANCE IN FAÇADES

D. Friedrich[1]*

[1] Cooperative State University of Mosbach, Faculty of Civil Engineering,
Neckarburkener Straße 8, 74821 Mosbach, Germany

*Corresponding author; e-mail: d.friedrich@lehre.mosbach.dhbw.de

Abstract

Mixing fossil-based plastics with wood fibers is an effective measurement for a more responsible use of scarce crude oil resources. However, products made from such wood-polymer composites (WPC) not necessarily show similar properties as if made from neat plastics specifically if intended for structural outdoor use such as façades. This papers reports from a multi sampling of three WPC compounds showing different surface finishings. After one year natural weathering in Central Europe, physico-mechanical properties were determined by density and water uptake as well as impact and bending strength in dry and saturated state. It was found that brushing a WPC`s surface potentially accelerates ageing by unhindered humidity- and UV-penetration but this effect is compensable by increasing the compound`s density. Alternatively, negative consequences from a high fiber content usually resulting in low density can be offset by a weather protecting co-extruded surface layer. Such a compound revealed lowest decline in impact and bending strength and consistent surface appearance over the weathering period. This particular finishing obviously best supports durability and eco-friendliness of fiber-reinforced plastics composites.

Keywords:

Wood-plastic composites; durability; natural weathering; mechanical strength; physical properties

1 INTRODUCTION

Wood-polymer composites (WPC) are a new generation of bio-based materials. They contain up to 80% plant fibers which are encapsulated in a thermoplastics matrix. This helps preserving scarce crude oil reserves [Friedrich 2018]. Hence, from an environmental point of view, the production of products made from WPC can be thought of as an abatement technology turning the economy into a bio-based one. Nevertheless, mixing hydrophilic plant fibers with hydrophobic plastics is complex and therefore production and compound technology still challenges scientists and producers. Further, there is insufficient application-oriented WPC research which gives proof of WPC being technically equivalent to conventional plastics.

The production volume of WPC and natural fiber-reinforced plastics (NFRP) in 2017 was 410,000 tons and growth rate is 3%. Extruded decking and cladding count to the main applications of WPC making 200,000 tons [Carus 2018]. In terms of decking, polyvinylchloride (PVC) and polyethylene (PE) is mostly in use whereas for fencing polypropylene (PP) has the highest share [Carus 2015]. To date, the main WPC products are used outdoor and increasingly in building applications. Particularly for fencing, the Construction Products Regulation (CPR) No.305/2011 demands from manufacturers and planners that produced and selected building products must contain bio-based ingredients to a maximum amount. On the other hand, since material contents from natural feedstock react sensitive to weathering, there is reasonable doubt if WPC building products indeed are durable enough to perform as initially supposed during the engineering design process. In this context, Mohamadzadeh et al. [2012] demand that design values for WPC products must incorporate adjusting factors which consider ageing throughout the constructional lifetime. Such ageing-related factors were elaborated by Friedrich [2016] who found that initial bending strength of WPC should become reduced by some 50% if used as design value. To better understand the load-bearing nature of fiber-reinforced plastics, Kumari et al. [2007] focused on the interface between fiber and matrix and they found that adhesion between both is the key property-forming aspect of such composite materials. The interaction between fiber and matrix throughout weathering was researched by Thirmizir et al. [2011], Badji et al. [2017] and Kenichi and Noboru [2015] who measured photodegradation effects by global radiation translating into WPC color change, loss of gloss and surface roughening. Berdahl et al. [2008] explain this by polymer chain scission and crosslinking under UV energy and Hung et al. [2012] consider this as secondary crystallization of WPC`s polymer matrix.

So far it does appear that photooxidation of polymers potentially also damages the interface of the hydrophilic fibers which initially were effectively protected against humility by the plastics around. In this regard, Messiry [2013] suspects that chain scissions have a dual effect on WPC. Firstly, water uptake increases the compounds density and secondly, fibers start swelling.

Chavooshi et al. [2014] see in a surface-near fiber agglomeration an enabler of continuing water penetration into WPC which according to Butylina et al. [2012] accelerates oxidation and physical compound degradation. Such weathering effects are manifestly to the detriment of mechanical material properties which generally build the basis for a WPC product`s structural safety [Beg 2008].

Since WPC cladding products are fully exposed to natural weathering throughout their lifetime, a product development should thoroughly investigate water penetration into the material. The amount of water sorption was determined by Tamrakar and Lopez-Anido [2011] who revealed that modulus of elasticity (MOE) of tested WPC declines by 43% while water uptake reached some 17% after 209 days. In this context, Chavooshi et al. [2014] found the WPC`s screw withdrawal strength to decrease significantly under water impact which they explain by an impaired plastics-fiber interface. Such time-dependent WPC degradation was also researched by Kartal et al. [2013] and they tested several fiber types and geometries in WPC against each other. Differences between the compounds were less apparent and water soaking manifests itself as a matter of fiber share in general and less of their size. This as well gives credit to the findings of Chavooshi et al. [2014] who found the degree of water uptake increasing in fiber content. Further, Kumari et al. [2007] revealed that soaking is also related to the addition of processing aids, such as lubricants, which according to the authors fill the voids between fibers and plastics. Here we come to full circle because again WPC ageing manifests itself as a matter of the interface quality which so far obviously suffers from both UV-radiation and humidity. In case of freeze-thaw cycling, Pilarski and Matuana [2005] also found a trend for frost-cycling to increase water sorption since frozen vapor tend to dissolve the fibers out of the compound building further voids which make the WPC more vapor-permeable.

It can be theorized that weathering of WPC reinforces the tendency of water uptake which furtherly impairs mechanical properties. If this also counts for the material`s density, which determines a WPC cladding`s self-weight, could not be fully clarified by literature review. At least Kumari et al. [2007] suspect in this context, that long fibers support the creation of voids in the interface. This potentially translates into lower density throughout exposure lifetime and in return water uptake increases. In addition to this, Pilarski and Matuana [2005] could not reveal that freeze-thaw alone is detrimental to density. In contrast, the literature pertaining to WPC water uptake sees in the WPC profile`s surface quality a key factor to water penetration into the material. In this context, Fabiyi et al. [2008] for example found by microscopy analysis that after weathering the WPC surface is crazed and furrowed by wood-loss. The work of Catto et al. [2016] extends this because they additionally observed colonization of microorganisms and biofilms on specimens` surface after much longer outdoor exposure. Once the surface became furrowed also impact strength significantly declines which Chaharmahali et al. [2008] explain by a notch-similar effect on the profile`s outer layer coming from weathering. The same was reported by Zhou et al. [2016] who further argue that the deterioration of filler-matrix is most responsible for impact strength decline and finally, Petchwattana et al. [2012] found the less lubricants are added to the formulation the more the impact strength drops down by weathering.

The literature review revealed that ageing of WPC translates into weaker mechanical properties over time. This is attributed to damage of the WPC`s surface which supports water soak of wood fibers. In combination with UV-radiation and freeze-thaw cycling, wood particles become dissolved creating voids and furrows on the WPC`s surface layer [Adhikary 2010]. However, there is a lack of post research about the question to whether water uptake influences material density to the same extend. This topic is important for weight calculations of WPC façades. Further, if indeed interfacial strength decline is a matter of surface quality, then the application of protecting surface finishings by trend delays ageing of WPC cladding. This hypothesis is not yet confirmed by research. Finally, to date it is unsure if water saturation of aged WPC translates into lower impact strength if additionally pores are water saturated which potentially provides stability to the compound. To fill this gap in application-oriented durability research, this paper sheds light on physico-mechanical properties and it reports about a multi sampling under natural weathering for one year in Central Europe. Three representative WPC compounds with different surface qualities including co-extruded top-coating were tested for water uptake, density and impact and bending strength under dry and saturated condition to reveal how these characteristics are correlated. Findings are of paramount interest for upcoming WPC cladding developments and structural calculations of such façades. The remainder of this paper is organized as following: (1) Test specimens are characterized and testing methods are introduced, (2) recorded data about climate conditions over one year are illustrated, (3) observations from microscopy analysis and (4) data from physico-mechanical testing are compiled and discussed and finally (5) basic conclusions are drawn thereof.

2 MATERIALS AND METHODS

2.1 Specimens

Three types of specimens were cut from commercially available WPC decking and cladding profiles. In order to have a large variety of formulations and surface qualities, all three types of plastics as PP, PE and PVC were contained and surfaces were brushed, non-brushed or covered with a co-extruded PVC plastics layer of 0.5 mm thickness. Formulations, dimensions and surfaces are summarized by Tab. 1. Data was gathered from the manufacturers' brochures as available.

All samples were planed on the backside in order to create equal conditions for water soaking. Only the front side was kept in its initial state since this surface was exposed to weathering during conditioning phase. Following ASTM D 1435, the specimens were mounted on a rack in shingle-style in order to simulate a real façade application (Fig. 1). In total 50 specimens per type were prepared for testing in this manner and another 50 pieces were retained as zero-samples.

Tab. 1: Nomenclature of specimens.

Manufacturer	Polymer	Polymer Content [%]	Fiber Type	Fiber share [%]	Dimension [mm]	Surface quality	Code = Polymer/wood/ surface
Konsta®	PP	50	Pine	50	150 x 150 x 5.0	non-brushed	PP/Pi/ nonbrus
Groja®	PVC	40	Bam-boo	60	150 x 150 x 3.5	brushed	PVC/ Ba/brus
Fiberon®	PE	30	Maple	70	150 x 150 x 5.0	co-extru-ded top layer	PE/Ma/ coex

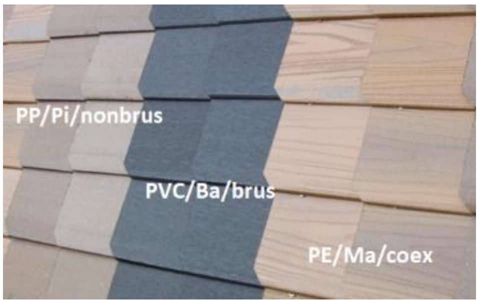

Fig. 1: Specimens on a test rack.

2.2 Climatic conditioning

The test rack was mounted on a 35°-inclined roof facing southwest. Location was Mosbach city in Germany, 8.9053°E and 49.2942°N, 240 m altitude. Starting time was 2016-07-01 and duration was one year. Fig. 2 and 3 give an overview on average global radiation, temperatures and precipitation during conditioning phase. As can be seen, natural weathering is composed by UV-radiation, freeze-thaw cycles and dry-wet conditions which all, according to the introductory section, can be seen as detrimental to the WPC surface and wood-plastic interface of the compound.

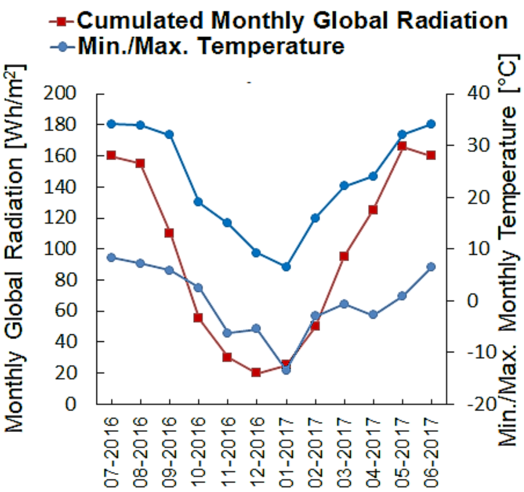

Fig. 2: Global radiation dosage and temperature profile of weathering phase.

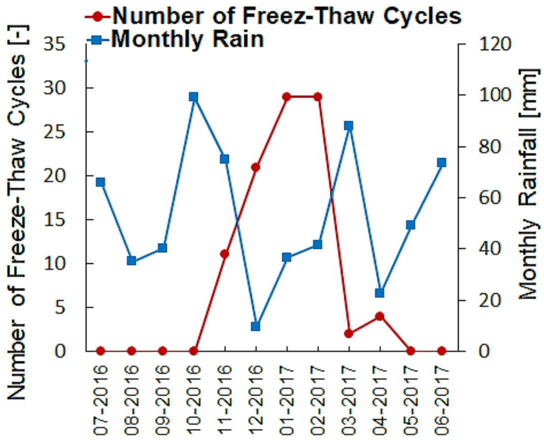

Fig. 3: Precipitation and freeze-thaw cycles within the weathering phase.

2.3 Physical testing

All testing was executed under laboratory ambient conditions at 23°C ± 2°C and 50% ± 10% relative humidity. Right after the one-year exposure a selected part of samples was transferred to water immersion. Water absorption (WA) was tested following EN ISO 62:2008-05 on original specimens 150 mm x 150 mm immersed for a first period of 36 days at laboratory ambient conditions and weights were measured periodically in 6 days. The second period thereafter took 329 days where once a month the water was replaced since it quickly became dirty. Hence, long-term water immersion took another full year after weathering. Prior to weight measurements the specimens were dried with a tissue and in total 7 measurements were conducted. The weight increase was calculated according to Equation 1 and captured in laboratory scale for weathered and control samples.

$$WA\ [\text{-}] = \frac{m_{WPC,i} - m_{WPC,0}}{m_{WPC,0}} \qquad (1)$$

, where $m_{WPC,0}$ denotes the weight [g] of the specimens before immersion in water and $m_{WPC,i}$ is the i-th weight [g] of soaked specimen where $1 \leq i \leq 7$ measurements.

Density was determined for weathered and control samples where 5 specimens 15 mm x 80 mm per type were applied according to DIN EN ISO 1183-1 and using immersion method where the material`s density is calculated as following:

$$\rho\ [\frac{g}{cm^3}] = \frac{m_{WPC} * \rho_{li}}{m_{WPC,0} - m_{WPC,li}} \qquad (2)$$

, where m_{WPC} [g] is the dry mass of the WPC specimen in air, ρ_{li} [g/cm³] is the density of the water in which the specimen is immersed and $m_{WPC,li}$ [g] is the mass of the specimen when immersed.

2.4 Impact strength

Unnotched impact strength was determined according to EN 15534-1/5 and EN ISO 179-1 on 5 replicates per run for each of the three compound types. Specimen dimension was 15 mm x 150 mm x *T* as per Tab. 1. In order to measure the difference between the weather-exposed front side and the non-exposed rear side of specimens, two runs were carried out on both weathered and zero-samples. The same procedure was then repeated for weathered and zero-samples but in water saturated state in order to make differences more discernible. A universal testing machine, HIT Pendulum

Impact Tester was used and in total 60 single measurements were carried out. The breaking energy was calculated as following:

$$E\ [\text{kJ/mm}^2] = \frac{m_{pen} * g * \Delta h}{T * B} * 10^{-3} \quad (3)$$

, where E denotes the breaking energy, m_{pen} is the pendulum`s weight [kg], the g-factor is set as 9.81m/s$^2$, T [m] is the specimen`s thickness as per Tab. 1 and breadth B is 0.015 m. Finally, Δh [m] is the measured difference in pendulum height with and without specimen applied to the apparatus.

2.5 Bending strength

Three-point static bending tests for determination of modulus of rupture (MOR) were executed according to ISO 178:2013 using a Universal Testing Machine Zwick/Roell Z010 with crosshead speed of 8 mm/min and data were processed applying the software testExpert II. All testing was again executed under laboratory ambient conditions. Five measurements were carried out on samples with dimensions 50 mm x 150 mm where the support span was 100 mm. Specimens were loaded at the exposure side in order to have to bended layer where weathering most degraded the material.

2.6 Microscopy analysis and statistics

Morphological studies were conducted using a stereo trinocular incident/transmitted halogen light micro-scope (Bresser ADL 601P) on weathered and unweathered surfaces. SPSS program version 24 was used for all statistical analysis. Results from mechanical and physical testing were expressed as the mean and standard deviation. The significance of difference was calculated by a two-tailed t-test with a significance level of 0.05.

3 RESULTS AND DISCUSSIONS

3.1 Morphological analysis

Fig. 4 a to c illustrate the composite`s surface before and after natural weathering. Firstly it is evident that specimens of type PP/Pi/nonbrus (Fig. 4.a) and PVC/Ba/brus (Fig. 4.b) faded slightly. This was due to the wood fibers which became bleached. This at first gives credit to the findings of Thirmizir et al. [2011], Badji et al. [2017] and Kenichi/Noboru [2015] who all report about significant change of surface appearance attributed to the degradation of cellulose, hemicellulose, lignin and extractives. However, the co-extruded top-coat of specimens type PE/Ma/coex (Fig. 4.c) revealed no variation and surface apparently stayed unchanged. In terms of surface roughness, zero-samples from type PP/Pi/nonbrus (Fig. 4.a) previously had a smooth surface and after ageing it shows many irregularities. As can be seen from Fig. 4.a and Fig. 4.b right hand side, wood particle protrusion at the surface leads to visible imperfections which are more pronounced for the former type containing larger fibers. The reason lies in progressive crystallinity of the thermoplastics and connected chain scissions. Wood fibers which then become exposed to weather absorb moisture and start swelling which repeals interlocking with the plastics matrix. Rain and wind easily erode the brittle surface. In this context, Butylina et al. [2012] measured a depth of the degraded layer of 0.5 mm which is consistent with the findings on hand. Akin to type PP/Pi/nonbrus (Fig. 4.a), the brushed surface of the PVC-containing specimens also gained in roughness but comparatively less obvious owing to the brushing effect. Nevertheless, fading is notable which supports the work of Berdahl et al. [2008] who state that darker wood becomes lighter. Chaochanchaikul et al. [2013] confirm photobleaching effect also for PVC-based WPC and Butylina et al. [2012] found that dark color pigments significantly mask such color changes. Hence, similar to type PP/Pi/nonbrus (Fig. 4.a) but less intensive, surface roughness of type PVC/Ba/brus (Fig. 4.b) also increased and furrows from surface brushing slightly became deeper. From a broader perspective it appears that the co-extruded top coat of type PE/Ma/coex (Fig. 4.c) containing no wood particles is much less susceptible to photodegradation. On the one hand this is because the previously described effects on the cellulose and lignin don`t occur. On the other hand findings from Fabiyi et al. [2008] revealed that total color change and lightening of HDPE-based WPC is significantly less compared to PP-based WPC. Both effects obviously suppressed visible signs of ageing for type PE/Ma/coex. If this type indeed shows comparatively less water susceptibility is subject of proof in the following sections.

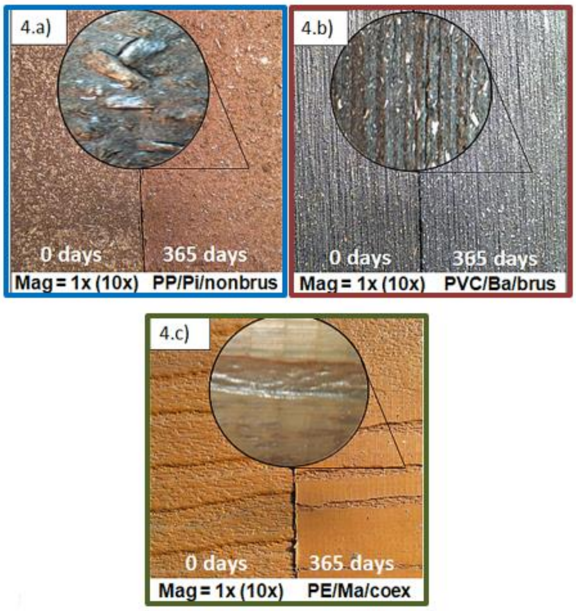

Fig. 4.a to c: Microphotographs of zero-samples (0 days) and weathered (365 days) WPC surface after natural weathering.

3.2 Water absorption

In Fig. 5 water absorption is plotted versus time from 0 to 365 days. The results point out that weight increase of type PP/Pi/nonbrus is 1.20% for most immersion intervals of 6 days within the first period of 36 days and of type PVC/Ba/brus 0.68% and type PE/Ma/coex 0.44% respectively. As can be seen, WA-curves increase linearly until reaching an equilibrium level. In this context, Fabiyi et al. [2008] revealed an average increase in weight of 2% each 5 days for a 40PP/60 wood-based WPC similar to type PP/Pi/nonbrus. Likewise results were achieved by Chavooshi et al. [2014] for 50PP/50MDF-dust WPC which initially soaked at a rapid rate and subsequently the uptake slowed down till saturation.

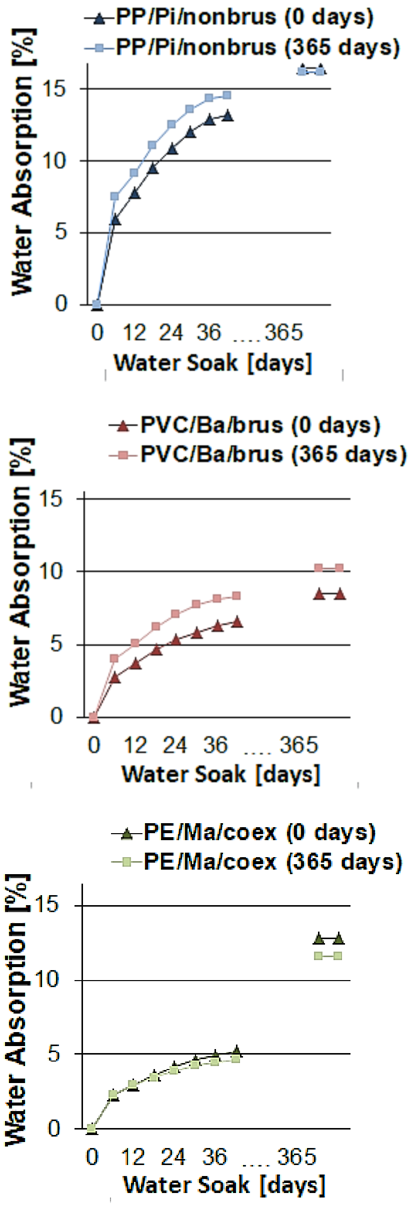

Fig. 5: Means (n=5) of water absorption before (0 days) and after weathering (365 days) of specimens.

The graphs of Fig. 5 indicate that weathered specimens initially soak more water than the control samples which is made manifest in a steeper curve within the first intervals. Conversely, type PE/Ma/coex shows nearly no difference between virgin and aged specimens over the first period. Noticeably, water uptake for weathered specimens was even slightly less compared to virgin ones. It can be theorized from this basic finding that surface deterioration which goes along with UV-radiation is an enabler for increased initial moisture suction. Also in this regard type PE/Ma/coex revealed that a UV-stable top-coat represents an effective water protection. Before comparing the long-term effect of the three types with one another it is again noteworthy to mention that all specimens were planed on the rear side in order to have the compound formulation and the original product surface as decisive factors all other things being equal. Now the results underscore that the co-extruded top-coat simply delays water sorption since WA further increased by another 7.30% reaching its final plateau at 12%. In contrast, the PVC-based type takes an intermediate position with 9.40% and the PP-compound indicates a long-term WA at 16.30%. This reinforces the findings of Tamrakar and Lopez-Anido [2011] who measured 17.00% after 209 days. The greater fiber share of type PE/Ma/coex obviously led to comparatively higher saturation than type PVC/Ba/brus containing 10% less fibers. This assumption is undermined by findings from Kartal et al. [2013] who tested 50(70)PP/50(30)bamboo-WPC for water uptake and the higher content-specimens soaked about 10% more till saturation. However, it is yet unclear why type PP/Pi/nonbrus with the least fiber share shows highest degree of long-term saturation. One reason could be that fibers were comparatively larger (Fig. 4.a). This question is also to be answered in the light of density-related investigations as discussed in the following section.

3.3 Density

Density was found to be highest for PVC-based specimens and lowest for PE-containing ones instead (Fig. 6). This can be attributed to fiber share and their density as well as to production technology. More interesting is the change in compound density over weather exposure time. As can be seen from the error bar in Fig. 6 and values in brackets, after weathering the results became strongly scattered for type PP/Pi/nonbrus and PVC/Ba/brus which also reveal a loss of 5.60% and 2.30% respectively. In this regard Fabiyi et al. [2008] report about a decrease of molecular weight with increasing weather exposure which most likely explains the huge change in density over time. Pilarski and Matuana [2005] found that freeze-thaw actions alone did not significantly affect the density of tested PVC/wood-flour composites. This at first speaks for UV-radiation as the most crucial impact on WPC density. In this context, many papers pertaining to WPC ageing trace the loss in density back to increasing material embrittlement ascribed to molecular chain scissions [Homkhiew 2014]. It can thus be theorized that if thickness swell is compensated by surface erosion as a result of rainfall and additionally the material`s weight decreases significantly then density must be lower after weathering. In this context, a higher standard deviation of values for aged samples underscores the damaging effects on WPC`s surface-near microstructure.

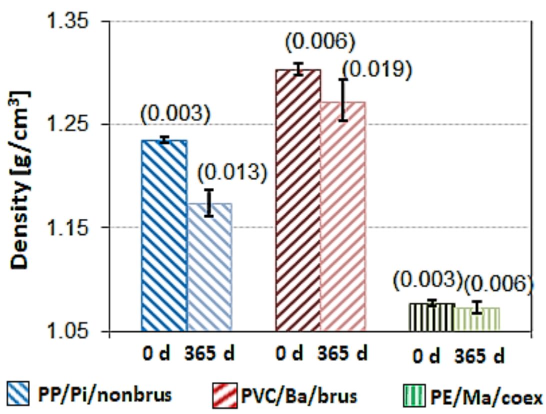

Fig. 6: Means (n=5) of densities before (0 d) and after weathering (365 d) of specimens (numbers in brackets indicate standard deviations).

From a broader perspective it can be argued that natural weathering in general changes physical traits of WPC to the worse. Once more type PE/Ma/coex revealed its superiority because values decreased only slightly and standard deviation was comparatively low. Here again a strong argument can be made that a surface protection best meets durability requirements. With regard to water uptake, as supposed throughout the last section, the high density of type PVC/Ba/brus effectively keeps saturation moderate compared to type PP/Pi/nonbrus with its 6% lower density.

3.4 Impact strength

As can be seen from Fig. 7 and 8, each compound type showed a decline of breaking energy after 365 days of exposure. However, this effect is statistically significant only if specimens were loaded at the front side and in dry state. It can therefore be concluded that after one year of natural weathering the material became more brittle whereby this change in ductility is more pronounced for the weathered surface near layers. The findings underscore the statements of Chaharmahali et al. [2008] wo see in furrowed and crazed surfaces a notch-similar effect with negative consequences for the material`s impact strength. The same comparison was drawn for water saturated specimens. As can be seen from Fig. 8, once again the weathered surface of the PP-based specimens leads to a 20% loss in breaking energy similar to the dry state (Fig. 7). This is in line with the findings about water absorption where this type showed the worst results relative to the other types. Even though density was at the center position this compound formulation revealed the least weather stability. A reason why in Fig. 8 the aged samples of type PE/Ma/coex even gained in impact strength compared to Fig. 7 might be traced back to a stabilizing effect from the water-filled pores being under pressure in saturation. This could also have contributed to the fact that in saturated state the difference between impacted front and rear side is not significant for p≤0.05 for all types.

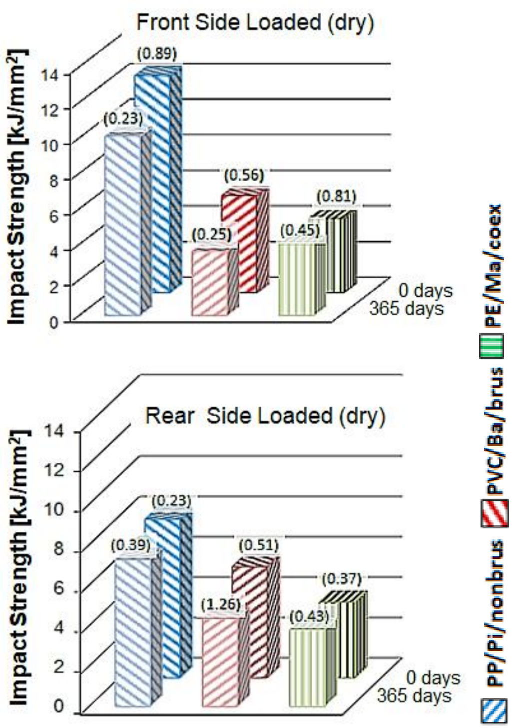

Fig. 7: Means (n=5) of impact strength before (0 d) and after weathering (365 d) of dry specimens (numbers in brackets indicate standard deviations).

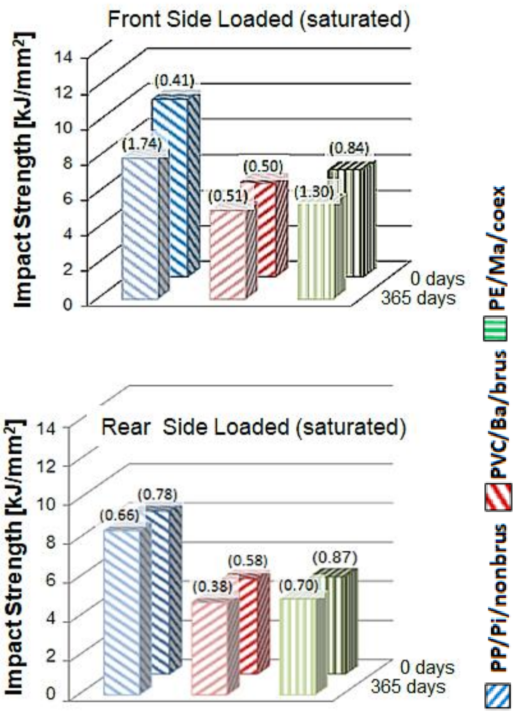

Fig. 8: Means (n=5) of impact strength before (0 d) and after weathering (365 d) of saturated specimens (numbers in brackets indicate standard deviations).

With regard to type PVC/Ba/brus it can be argued that a high initial density of the compound is a guarantor for longer weather resistance even though the surface of specimens was brushed and from the outset PVC is more brittle than PP and PE. The reason why brushing did not excessively translate into comparatively lower impact strength declines is explained by the fact that the specimens` long side was coincident with direction of brushing which also complied with main fiber orientation. This provided highest stability in the pendulum testing. Therefore, it can be postulated that increasing density offsets disadvantages from brushing in terms of weathering. Finally, similar to water uptake, the coextruded top-layer of type PE/Ma/coex effectively compensates for low density and protects the compound from quickly becoming brittle. Hence, without this measurement such a low-density compound is expected to significantly degrade under weathering and even more if a high amount of fibers is embedded.

3.5 Bending strength

With regard to modulus of rupture (MOR), Fig. 9 reveals that this strength declined by some 20% after 365 days in dry state and only 8% in wet state. All results are significant for p≤0.05. The figures also reveal that the average loss of MOR under both moisture contents is 38%. This gives credit to Badji et al. [2017] who measured 16% decrease after one year in South-France and to Thirmizir et al. [2011] who found about 15% to 23% loss after 6 months weather exposure in Malaysia. However, the loss is comparatively higher in virgin state of specimens. Similar to impact strength, two conclusions can be derived from these findings: (1) If pores in the WPC material were water-filled then the drop in MOR is comparatively less which speaks for the fact that water saturation somehow provides stability to the compound under external loading. (2) With progressing WPC ageing under weathering, polymer chain scission and cross-linking, as explained by section 1, make this stabilization effect less effective since the polymer matrix and particularly the interface with the swelled fibers became fissured and hence the water-filled pores much less yield the pressure under bending. With regard to specimen type 3, the protective effect from a co-extruded top-layer against initial water absorption is no longer evident after 365 days. This is because the specimens` rear side was planed and in the long the water will sufficiently penetrate from the back which leads to some 15% saturation at least for such non PVC-based compounds.

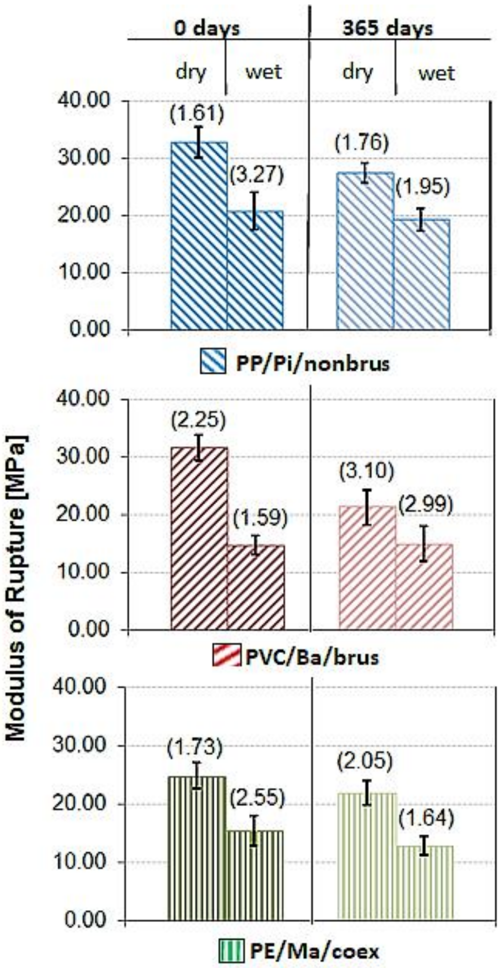

Fig. 9: Means (n=5) of Modulus of Rupture [MPa] before (0 d) and after weathering (365 d) of dry and saturated specimens (numbers in brackets indicate standard deviations).

4 CONCLUSIONS

The target of this study is to estimate the effect of natural weathering on wood-polymer façades showing differences in compound formulation and surface quality. To measure ageing effects on physico-mechanical performance of WPC cladding over time, water uptake until saturation, density and impact as well as bending strength were determined before and after a one-year outdoor trial. It was found that density and water uptake show a reciprocal behavior meaning that the higher the compound`s density the lower is the degree of water saturation and the compound initially soaks less water. In practical terms the findings also demonstrate that WPC façades lose weight in the long run. Results also turn out that a disadvantageous low density can effectively be compensated by a co-extruded fiber-free surface finishing. Ageing, expressed by loss in impact and bending strength, is more pronounced when specimens show a furrowed and crazed surface after weathering. This not only reduces the cross-section of the WPC-profile but also provokes a higher decline of density due to interfacial degradation and the creation of voids in the compound. By trend, this effect is worsened the larger the fibers are. Also in this regard, durability in general is higher if a WPC`s surface becomes protected by a weather-stable top layer. Nevertheless, this research also attested a tendency for impact strength increase under saturation which likeliest comes from the water-filled pores. However, this effect is not useful in façades under freeze-thaw impacts. Therefore, if for optical reasons a WPC cladding`s surface becomes brushed in order to make it wood-like, then density should be higher to offset negative consequences on the product durability. From the cost aspect, a co-extruded top-layer appears to be equally durable and allows for the implementation of much higher fiber shares under lower compound density. Although investment costs in such upgraded extrusion lines are higher, the savings from lower plastics content and higher production speed are expected to compensate well and even make the compound more sustainable.

5 SUMMARY

This paper reports from investigations on the ageing behavior of WPC compounds showing different surface finishings. After a one-year outdoor trial in Central European weathering it was found by physico-mechanical testing that the application of a co-extruded plastics layer on the WPC cladding surface effectively delays ageing effects such as furrowing and crazing. In contrast to PE- and PP-based WPC, the use of high density PVC-plastics as filler matrix not only enhances the long-term stability of compound density and water uptake but also compensates for a brushed surface which otherwise would be disadvantageous in terms of natural weathering resistance. WPC obviously could become even greener if more fibers were added to the formulation and additionally co-extrusion is applied to the profile`s surface. This also opens up new possibilities of façade designs and further outdoor applications.

6 ACKNOWLEDGMENTS

This research did not receive any specific grant from funding agencies in the public, commercial or not-for-profit sectors. I gratefully acknowledge the collaborative work in WPC research projects with my students from the course FS15 and PM15C at the Baden-Württemberg Cooperative State University in Mosbach and in the European COST ACTION CA16114 "REthinking Sustainability TOwards a Regenerative Economy".

7 REFERENCES

[Adhikary 2010] Adhikary, K.B.; Pang, S.; Staiger, M.P.; Effects of the Accelerated Freeze-Thaw Cycling on Physical and Mechanical Properties of Wood Flour-Recycled Thermoplastic Composites. PolymComposite, 2010, 31, 185-194.

[Badji 2017] Badji, C.; Soccalingame, L.; Gara, H.; Bergeret, A.; Benezet, J.C.; Influence of weathering on visual and surface aspect of wood plastic composites: Correlation approach with mechanical properties and microstructure. PolymDegradStab, 2017, 37, 162-172.

[Beg 2008] Beg, M.D.H.; Pickering, K.L.; Artificial weathering of unbleached and bleached Kraft wood fibre reinforced polypropylene composites. PolymDegradStab, 2008, 93, 1939-1946.

[Berdahl 2008] Berdahl, P.; Akbari, H.; Levinson, R.; Miller, W.A.; Weathering of roofing materials - An overview. ConBuildMat, 2008, 22, 423-433.

[Butylina 2012] Butylina, S.; Hyvärinen, M.; Kärki. T.; A study of surface changes of wood-polypropylene composites as the result of exterior weathering. PolymDegradStab, 2012, 97, 337-345.

[Carus 2015] Carus, M.; Eder, A.; Bioverbundwerkstoffe Naturfaserverstärkte Kunststoffe (NFK) und Holz-Polymer-Werkstoffe (WPC). Location: Fachagentur Nachwachsende Rohstoffe e.V., 2015.

[Carus 2018] Carus, M.; Partanen, A; Natural fibre-reinforced plastics: establishment and growth in niche markets. Location: nova-Institut, 2018.

[Catto 2016] Catto, A.L.; Montagna, L.S.; Almeida, S.H.; Silveira, R.M.B.; Santana, R.M.C.; Wood plastic composites weathering: Effects of compatibilization on biodegradation in soil and fungal decay. IntBio-teterBiodegr, 2016, 109, 11-22.

[Chaharmahali 2008] Chaharmahali, M.; Tajvidi, M.; Najafi, S.K.; Mechanical Properties of Wood Plastic Composite Panels Made From Waste Fiberboard and Particleboard. PolymComposite, 2008, 29, 606-610.

[Chaochanchaikul 2013] Chaochanchaikul, K.; Rosarpitak, V.; Sombatsompop, N.; Photodegradation profiles of PVC com-pound and wood/PVC composites under UV weathering. ExpressPolymLett, 2013, 7, 146-160.

[Chavooshi 2014] Chavooshi, A.; Madhoushi, M.; Navi, M.; Abareshi, M.Y.; MDF dust/PP composites reinforced with nanoclay: Morphology, long-term physical properties and withdrawal strength of fasteners in dry and saturated conditions. ConBuildMat, 2014, 52, 324-330.

[Fabiyi 2008] Fabiyi, J.S.; McDonald, A.G.; Wolcott, M.P.; Griffiths, P.R.; Wood plastic composites weathering: Visual appearance and chemical changes. PolymDegradStab, 2008, 93, 1405-1414.

[Friedrich 2016] Friedrich, D.; Investigations on ageing of wood-plastic composites for outdoor applications: A meta-analysis using empiric data derived from diverse weathering trials. ConBuildMat, 2016, 1142-1152.

[Friedrich 2018] Friedrich, Daniel: Welfare effects from eco-labeled crude oil preserving wood-polymer composites: A comprehensive literature review and case study. JCleanProd, 2018, 188, 625-637.

[Homkhiew 2014] Homkhiew, C.; Ratanawilai, T.; Thongruang, W.; Effects of natural weathering on the properties of recycled polypropylene composites reinforced with rubberwood flour. IndCropProd, 2014, 56, 52-59.

[Hung 2012] Hung, K.C.; Chen, Y.L.; Wu, J.H.; Natural weathering properties of acetylated bamboo plastic composites. PolymDegradStab, 2012, 97, 1680-1685.

[Kartal 2013] Kartal, S.N.; Aysal, S.; Terzi, E.; Yilgör, N.; Yoshimura, T.; Tsunoda, K.; Wood and Bamboo-PP Composites: Fungal and Termite Resistance, Water Absorption and FT-IR Analyses. BioResources, 2013, 8, 1222-1244.

[Kenichi 2015] Kenichi, E.; Noboru, S.; Surface deterioration of wood plastic composites under outdoor exposure. JWoodSci, 2015, 61, 143-150.

[Kumari 2007] Kumari, R.; Ito, H.; Takatani, M.; Uchiyama, M.; Okamoto, T.; Fundamental studies on wood/cellulose-plastic composites: effects of composition and cellulose dimension on the properties of cellulose/PP composite. JWoodSci, 2007, 53, 470-480.

[Messiry 2013] Messiry, M.E.; Theoretical analysis of natural fiber volume fraction of reinforced composites. AEJ, 2013, 52, 301-306.

[Mohamadzadeh 2012] Mohamadzadeh, M.; Haftkhani, A.R.; Ebrahimi, G.; Yoshihara, H.;.Numerical and experimental failure analysis of screwed single shear joints in wood plastic composite. MaterDesign, 2012, 35, 404-413.

[Petchwattana 2012] Petchwattana, N.; Covavisaruch, S.; Chanakul, S.; Mechanical properties, thermal degradation and natural weathering of high density polyethylene/rice hull composites compatibilized with maleic anhydride grafted polyethylene. JPolymRes, 2012, 19, 9921-9930.

[Pilarski 2005] Pilarski, J.M.; Matuana, L.M.; Durability of Wood Flour-Plastic Composites Exposed to Accelerated Freeze-Thaw Cycling. Part I. Rigid PVC Matrix. JVinylAdditTechn, 2005, 11, 1-8.

[Tamrakar 2011] Tamrakar, T.; Lopez-Anido, R.A.; Water absorption of wood polypropylene composite sheet piles and its influence on mechanical properties. ConBuildMat, 2011, 25, 3977-3988.

[Thirmizir 2011] Thirmizir, A.; Ishak, M.; Taib, R.M.; Rahim, S.; Jani, S.M.; Natural Weathering of Kenaf Bast Fibre-Filled Poly(Butylene Succinate) Composites: Effect of Fibre Loading and Compatibiliser Addition. JPolymEnviron, 2011, 19, 263-273.

[Zhou 2016] Zhou, X.; Huang, S.; Chen, L.; Effect of Antiaging Agents on the Outdoor Natural Weathering of Bamboo Powder/Polypropylene Foamed Composites. JVinylAdditTechn, 2016, 22, 311-319.

Norms and standards

ASTM D 1435-2013: Standard Practice for Outdoor Weathering of Plastics.

DIN EN 15534-1-2018: Composites made from cellulose-based materials and thermoplastics - Part 1: Test methods for characterisation of compounds and products.

DIN EN 15534-5-2014: Composites made from cellulose-based materials and thermoplastics - Part 5: Specifications for cladding profiles and tiles.

DIN EN ISO 1183-1-2013: Plastics - Methods for determining the density of non-cellular plastics.

DIN EN ISO 179-1-2010: Plastics - Determination of Charpy impact properties - Part 1: Non-instrumented impact test.

DIN EN ISO 62-2008: Plastics - Determination of water absorption.

EN ISO 178:2013-09: Plastics - Determination of flexural properties.

Regulation (EU) No 305/2011 of the European Parliament and of the Council laying down harmonized conditions for the marketing of construction products and repealing Council Directive 89/106/EEC.