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Impact of high moisture conditions on the serviceability performance of wood plastic composite decks

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ABSTRACT

Wood plastic composites (WPCs) are being increasingly used as alternatives to wooden decks. In the present study, it was verified the potential loss of stiffness of WPC deck boards as a result of moisture intake. It was also assessed the importance of moisture intake in the fulfilment of serviceability limit states. For these purposes, three different types of commercial WPC decks were studied, with high (WPCH), medium (WPCM) and low (WPCL) expected mechanical performance. Different experimental designs were followed to simulate full exposure to outdoor conditions and the effect of possible internal stress due to differential shrinkage and the swelling behaviour of fibres and the matrix. The results indicate a high loss of bending modulus of elasticity due to water absorption (between 40 and 50%) and shrinkage/swelling movements (between 22 and 29%). This level of stiffness loss has a direct impact on ensuring the compliance to the serviceability limit states. A strong negative linear relationship between water absorption and the loss of bending stiffness was established, which can be a helpful tool to assist manufacturers in defining the application rules and ensuring the expected service life of their products.

1. Introduction

Wood plastic composites (WPCs) consisting of natural plant fibres embedded in a polymer matrix are one of the different types of natural fibre composites (NFCs). The production and market share of these composites have grown significantly in the last decade. In 2012, the production of WPCs in Europe was 260,000 t, with decking being the major end-use of WPCs (174,000 t) [1]. The products available on the market for this end-use generally consist of wood flour or fibres embedded in a thermoplastic polymer (e.g. poly(vinyl chloride) (PVC), polypropylene (PP) or polyethylene (PE)). The increasing use of WPCs as decking is based on its image of sustainability as a product with the potential for incorporating waste materials (plastic or wood), and high durability when compared to untreated softwoods [2]. The latter characteristic makes this material an excellent alternative to the use of treated woods or tropical woods, which both raise environmental issues. However, recent studies have questioned some of the advantages of WPCs, compared to solid timber decks. A life cycle assessment study, comprising the use and disposal stages, showed that alkaline copper quaternary treated wood decks imply lower fossil fuel use and environmental impact when compared to a WPC (recycled wood fibre and a mixture of recycled and virgin high-density polyethylene (HDPE)) [3]. Additionally, studies have shown that WPCs can suffer physical and mechanical deterioration when exposed to outdoor conditions and there is a necessity for more thorough research of the moisture dynamics of these materials because of its direct impact on WPC durability [4]. Some of the factors affecting WPC performance are directly or indirectly related to moisture, stress levels, biodeterioration, photodegradation or a combination of these agents [5].

Short-term accelerated tests have shown that bending strength and the modulus of elasticity are more affected by exposure to high environment relative humidity (93%), than by temperature (23 to 40 °C) or UV exposure (0.85 mW/cm^2) [5]. The study used commercial extruded profiles composed of a HDPE matrix and natural flour. Regarding the modulus of elasticity, an average decrease of 34% was observed due to an exposure of 93% relative humidity condition in an environment of 23 °C and without exposure to UV radiation [5].

The composition of the material has a strong effect on its behaviour. The influence of wood flour size, the percentage of coupling agent, the percentage of lubricant and the PP plastic/wood ratio on the different physical and mechanical properties of WPC has also been shown [6]. Finer wood flour and a higher plastic/wood ratio decreases thickness swelling, which corresponds to a lower level of water absorption [6].

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Water intake is a crucial variable and is mainly a function of the percentage and size of voids, the type of fibre, the quality of the matrix, fibre loading, orientation of the fibres, the quality of adhesion in the fibre-matrix, exposed surface area and temperature [7,8]. A lower fibre-matrix adhesion quality generates void spaces where water can flow in. The contribution of the hydrophobic polymer for the water absorption capacity of the composite can be considered negligible. Long-term exposure to constant high moisture environments also accelerates the loss of mechanical properties and the risk of biodeterioration. Exposure to environmental conditions induces wetting and drying cycles, and generates internal stresses, leading to microcracks, which result in an increasing number of voids where water can flow in, thus decreasing the initial properties of the composite [9]. The increase in void presence, due to thermal or humidity cycle tests, has also been noticed in the matrix [10].

X-ray microtomography was used to assess the effect of soaking/drying cycles on a WPC (PP and wood flour in a ratio of 60/33) [9]. The study showed a void increase after re-drying (16% in the core and 8.4% in the surface layers) as a result of the differential expansion/contraction of the matrix and fibre, leading to a separation between these two components.

Water absorption for WPCs has been reported to typically be 0.7–2% after 24 h, 1–5% after a week, and up to 18–22% after several months [11]. Absorption can occur by diffusion (water flow under the influence of a concentration gradient), capillary transport (flow of water into the interface fibre/matrix) and transport by microcracks [12]. The latter two mechanisms are enhanced by aging. The rate of water absorption is accelerated by an increase in water bath temperature, but it does not influence the total amount of water absorbed [13].

An increase in water absorption with an increase in filler was observed for a variety of WPC samples, prepared by combining PP, low-density polyethylene (LPDE) and HDPE as the matrix and rice-husk flour (RHF) and wood flour as the filler [8]. In the same study, the enhancement of fibre/matrix adhesion using compatibilising agents, such as maleated polypropylene (MAPP) and maleated polyethylene (MAPE), was shown to contribute to lower thickness swelling and water absorption. The absence of this compatibilisation resulted in poor interfacial bonding and a decrease in the tensile and Izod impact strength, as filler levels increased. By comparing different matrices, before and after immersion, it was concluded that for the same matrix, a greater reduction of tensile strength and modulus is observed for higher filler levels [14].

Recently, numerous cases of WPC failures in service stress the need to ensure a suitable and safe performance during its expected working life [15]. Several reasons can explain the necessity for premature replacement of a WPC deck, these include design and construction errors, accidental or unexpected usage, and a possible significant decay in mechanical properties due to in-service water intake. Studies have shown that a significant loss of mechanical properties occurs due to water intake [13,16].

A HPDE/pine wood composite, with varying compositions, was exposed up to six years in different conditions (outdoor exposure to the sun and in shadow conditions) [17]. The study showed that wood moisture content can grow rapidly during the first four years and between the fourth and sixth years, a plateau seems to be achieved (between approximately 20% to 40%, depending on the type of composite and exposure) [17].

Scarce information is available on the impact of the loss of mechanical properties due to water absorption on the long-term expected performance of WPCs, mainly with regards to serviceability [18].

The aim of the present study was to evaluate the influence of water intake on the loss of the modulus of elasticity and the implication of this loss for the serviceability limit state (SLS), considering the expected life span of WPC decks (ten years). This life span was used by the European Technical Approvals under the former Construction Products Directive and is supported by other studies [3].

2. Experimental work

2.1. Materials

Given the aim of this study, three commercial WPC deck boards were selected in order to test products with expected high (WPCH), medium (WPCM) and low (WPCL) mechanical short-term performance. Table 1 and Fig. 1 show the geometric characteristics of each tested product.

The identification of high and medium performance products was made by consulting the technical information available from each material. Two of the WPC tested presented CE marking (supported by technical specifications). The one showing higher bending performance was designated as WPCH and the other WPCM. The white-label WPC (no information available for the product) was designated as WPCL.

For each test program included in the present study (immersion in water and resistance to moisture), ten test pieces were cut from the deck boards of each WPC material. Each test piece maintained its original cross-section, as show in Fig. 1. The number of specimens included in each test exceeds the requirements of the recent EN 15534-4 standard [19] for bending tests (eight test specimens).

All pieces were conditioned in an environment of 20 ± 1 °C air temperature and 65 ± 5% relative humidity until a constant mass was reached (variation of mass less or equal to 0.1% after two successive weighing operations carried out at an interval of 24 h). The mechanical testing was also performed under such environmental conditions.

2.2. Proof-load test

To avoid the influence of variability between the boards, the apparent modulus of elasticity was measured in the same boards all through the testing procedures applied in the present study. For this purpose, a proof-load test was design. For the definition of the proof-load level, a selection of ten test pieces from each WPC type was tested until rupture, following a three-point bending test. The bending test followed the European standard EN 310 [20]. For each WPC type, it was determined that 40% of the ultimate load and the average value of all ten pieces would be used as the proof-load, Table 2. Bending tests were carried out in a Shimadzu mechanical testing machine using a 250 kN load cell with an accuracy of 1% in the range 1 kN to 250 kN. The tests were carried out under deformation-control at rates of 13, 12 and 18 mm/min for WPCH, WPCM and WPCL, respectively. The rates were chosen in order to obey to the criterion given in EN 310 [20] (rupture in the interval of 60 ± 30 s).

2.3. Chemical characterisation

Information about the matrix (thermoplastic) was available for WPCH and WPCM. For WPCL ("white-label product"), no information was available. To confirm/determine the matrix and the filler composition, analytical pyrolysis (pyrolysis coupled to gas chromatography with a mass spectrometer detector - Py-GC/MS) and Fourier transform infrared spectroscopy with an attenuated total reflectance accessory (FTIR-ATR) were used.

Py-GC/MS and FTIR-ATR allow elegant and efficient complementary ways for the characterisation of complex polymers that otherwise would require a combination of tedious and time consuming wet

Table 1
Geometries of the WPC boards tested.

WPC	Thickness (mm)	Width (mm)	Length/span (mm)
WPCH	24	140	550/500
WPCM	25	140	550/500
WPCL	25	150	550/500

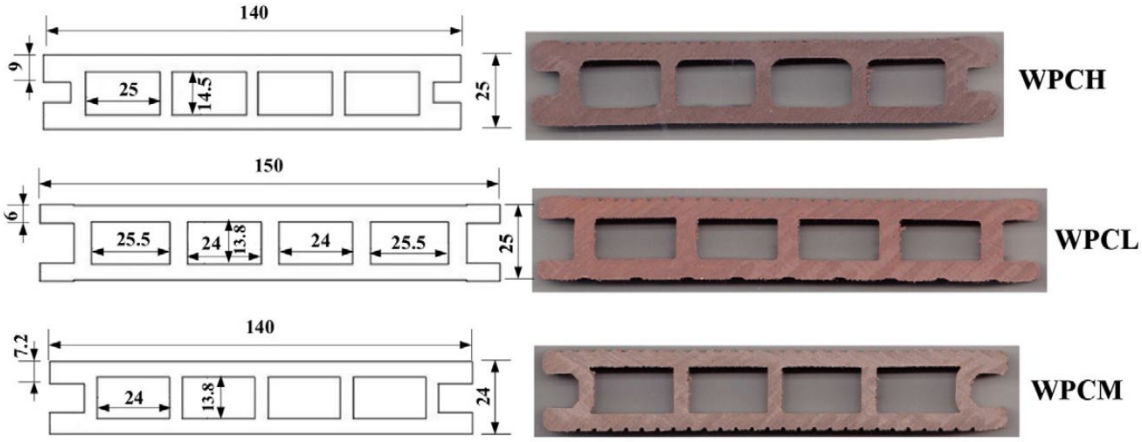

Fig. 1. Hollow cross-section profiles and dimensions (mm) for the three types of WPC boards tested.

chemical techniques. The former techniques have been successfully used alone [21], or in combination [22], for the characterisation of WPCs.

Each WPC's component content was accounted for by the total percentage area of all the component's identified pyrolysis products. For each WPC deck, the sample for analysis was collected by drilling the board with a power drill equipped with a 1 mm diameter drill taken perpendicular to the surface.

2.3.1. Py-GC/MS analysis

Py-GC/MS analyses were performed with a microfurnace pyrolyzer Frontier Lab PY-3030S equipped with an Auto-Shot Sampler (AS-1020E) attached to an Agilent GC 6890 with an MSD 5973 N mass selective detector. Pyrolysis runs were performed following the standard procedure for wood analysis [23–26]. The pyrolysis conditions were 600 °C for 10 s, with 90 to 110 μg of each WPC deck sample. The oven program was 4 min isothermal at 45 °C, rendered a heating rate of 4 °C min^{-1} up to 270 °C, which was then maintained for 60 min. The pyrolysis interface was kept at 320 °C and the GC/MS interface at 280 °C. Volatile pyrolysis products were separated using a DB 1701 capillary column (60 m × 0.25 mm, 0.25 μm film, J&W Scientific), with helium as the carrier gas (1 $ml.min^{-1}$), split 1:25, and they were identified by comparison of their electron ionization (EI) mass spectra with standards and with mass spectra libraries. The mass spectrometer was operated in EI mode at 70 eV, with a scan range from 25 to 550 *m/z* and the source temperature was 230 °C. PVC, PP and PE pyrograms were also obtained, in the same described conditions, for comparison.

2.3.2. FTIR-ATR analysis

FTIR-ATR spectra (32 scans per sample, spectral resolution of 4 cm^{-1} and wavenumber range of 4000–400 cm^{-1}), using a diamond single reflection attenuated total reflectance (ATR) device, were recorded with a Bruker FT-IR spectrometer (Alpha) and a zero filling of two was applied. FTIR spectra of PVC, PP and PE were also acquired for comparison.

Table 2
Ultimate loads and proof-load levels associated with each type of WPC.

	WPC		
	WPCH	WPCM	WPCL
Ultimate load (kN)[a]	3.95 (0.30)	1.95 (0.10)	1.71 (0.19)
Proof-load level (kN)	1.58	0.78	0.68
Modulus of elasticity (kN/mm^2)[a]	5482 (361)	3266 (587)	2465 (420)

[a] Mean value (standard deviation).

2.4. Weight and dimensions

The weight of the test pieces was determined using a digital balance with a precision of ±0.1 g. The thickness and width were measured using a digital caliper with a precision of ±0.1 mm. Three measurements were done along the length of each board. The length was measured with two points using a ruler with a precision of ±1.0 mm.

2.5. Experimental designs

Two experimental designs were carried out for assessing the effect of moisture intake on a possible loss of serviceability performance of WPC decking boards: i) a water immersion test was completed to simulate deck boards fully exposed to outdoor conditions, where the boards are under water contact conditions for long periods of time; ii) a moisture cycling test was applied for assessing the loss of stiffness due to possible susceptibility to internal stresses due to differential movement of the fibre and matrix (shrinkage/swelling), capable of enhancing void volume and water absorption.

2.5.1. Immersion in water

The test pieces were initially subjected to the proof-load bending test to assess their modulus of elasticity. Afterwards, the test pieces were immersed in tap water at 20 ± 1 °C. Each fifteen days, the test pieces were removed from the water bath and subjected to proof-load bending, weighed and their dimensions measured. The water was replaced and this procedure continued until the test pieces showed constant mass (same criterion as described above). Subsequently, the test pieces were definitively removed from the water and left to dry until reaching a constant mass (variation of mass less than 1% in a period of 24 h). The drying was carried out in an environment of 20 ± 1 °C air temperature and 65 ± 5% relative humidity. After mass stabilisation, the pieces were again subject to a proof-load test, weighed and their dimensions measured.

2.5.2. Moisture resistance under cycling conditions

As for the previous test, ten test pieces from each WPC type were initially subject to the proof-load bending test to assess the state of the pieces before being subjected to the moisture resistance test according to EN 321 [27]. This test comprised three cycles, each one composed of three steps: a) immersion in water at 20 ± 1 °C for 70 ± 1 h; b) freezing at a temperature between −12 and −25 °C for 24 ± 1 h; c) drying at a temperature of 70 ± 2 °C for 70 ± 1 h.

At the end of each cycle, the test pieces were left for 4 ± 0.5 h in an environment of 20 ± 1 °C air temperature and 65 ± 5% relative humidity. In each cycle, after steps a) and c), the test pieces were subjected to a

proof-load bending test, weighed and their dimensions measured. After step a), before weighing, the boards were left in a vertical position to wipe off the water at the surface and within the hollow structure.

3. Results and discussion

3.1. Chemical characterisation

The WPCH pyrogram (Supplementary Fig. S1) shows the characteristic pyrolysis products of a softwood [28] and of a copolymer, polymethacrylate/poly(vinyl chloride) (P(MA-VC)) [29,30]. The pyrolysis products of the copolymer suggest that the mixture is roughly 1:1. The pyrogram of WPCM (data not shown) presented characteristic hardwoods syringyl (S) products [28] and PE pyrolysis products [31]. The WPCL pyrogram is dominated by PE pyrolysis products, but also shows traces of syringyl products (Supplementary Fig. S2). Table 3 lists the wood pyrolysis products identified and Table 4 shows the main pyrolysis products of each WPC board. The FTIR-ATR spectra (Figs. 2 and 3) were consistent both with the thermoplastic present and with the type of woody material detected by Py-GC/MS. Table 5 presents the main FTIR-ATR bands of the three analysed WPC deck boards, as well as PE, PVC and methyl acrylate (MA) diagnostic FTIR bands. The band at 1503 cm^{-1} confirmed the presence of hardwood in the WPCM and WPCL boards, and the band at 1509 cm^{-1} supported the presence of softwood in WPCH. The higher percentage of wood filler in WPCH (Table 3) explains the significantly higher modulus of elasticity of this material (approximately double) when compared to the other two types of WPC tested.

3.2. Water absorption effect on the modulus of elasticity

All WPC materials tested showed similar absorption behaviour with a steady increase of water absorption until reaching a plateau, as shown in Fig. 4. This same pattern was found in other studies comprising different WPC compositions [11,13]. A similar level of water absorption (from 10 to 12%) was attained by all materials tested. However, WPCH showed a water absorption plateau after only 1000 h of immersion, whereas for the other two types this same plateau was only attained after 3000 h. The time to stabilisation shown by WPCH is similar to values found previously at around 1200 h [13].

Table 4
Pyrolysis products (%) for each type of WPC.

Pyrolysis products (%)	WPC		
	WPCH	WPCM	WPCL
Wood pyrolysis products	34	6	7
Syringyl (S) units	(–)	(1)	(tr)
Guaiacyl (G) units	(7)	(1)	(1)
PE pyrolysis products	–	83	86
P(MA-VC) pyrolysis products	43	–	–
Other compounds' pyrolysis products	24	11	7

(tr): traces; —: not present.

Previous studies have shown that water immersion is positively related to the wood flour content, the immersion time, the type of polymer and possible fibre treatment [32]. The identification of a compatibilising agent (polymethacrylate) explains why WPCH showed a similar level of water absorption to the other two types of WPC tested, although WPCH showed a noticeable higher percentage of wood filler (approximately five times more).

The pattern obtained for water is followed by a similar decrease of the modulus of elasticity (Fig. 5). A variation in the modulus of elasticity between 40 and 55% is observed depending on the type of WPC tested. These result are similar to the ones (≈43% to 56%) obtained for a polypropylene/pine-flour composite (46% wood weight content) [13]. In this same study, it was observed, as in the present study, that during the first immersion stages, the water turned turbid, oily and dust particles started to appear in the water.

WPCH shows less variability, whereas WPCL shows a significantly higher variability, compared to the other composites. After removing the pieces from the bath and drying at atmospheric conditions (20 ± 2 °C temperature and 65 ± 5% relative humidity), a permanent drop in the modulus of elasticity is observed of ≈21% for WPCH and WPCM and ≈10% for WPCL, for a residual mass loss of ≈3% for all types of WPC tested.

Fig. 6 shows a strong correlation between water absorption and the decrease of modulus of elasticity for the three types of WPC boards tested. Once again, the WPCL modulus of elasticity seems less affected by the intake of water. However, this material showed, before being tested (dry material), a modulus approximately half of the one shown by WPCH. These results support the fact that the loss of stiffness is

Table 3
Identification of labelled peaks (from wood) (pyrograms shown as Supplementary material).

Label	RT (min)	Compound	ID	WPCH (%)	WPCM (%)	WPCL (%)
1		Carbon dioxide	CO_2			
2a	4.05 and 4.43	Acetaldehyde and furan	c	2.7 and 1.0	1.2 and –	1.1 and –
2b	4.64	2-Propenal	c		1.2	1.0
3	4.88	Propanal-2-one	c	3.8		0.6
4	6.08	2,3-Butanedione	c	2.6	0.5	0.4
5a	7.14	Hydroxyacetaldehyde	cH			0.5
5b	7.85	Crotonaldehyde	c	1.0		0.2
6	8.84	Acetic acid	c	3.6	1.0	0.7
7a	9.49	Hydroxypropanone	cH		0.3	0.4
7b	14.68–15.18	(2H)-Furan-3-one, 3-furaldehyde, butanedial, and 2-hydroxy-3-oxobutanal	c			0.1, 0.1, 0.2, and 0.2
8	15.89	2-Furaldehyde	c	4.7	0.4	0.5
9	21.55	2-Furaldehyde, 5-methyl	c	1.1		
10	23.61	4-Hydroxy-5,6-dihydropyran-(2H)-2-one	cP	1.5		
11	26.20	Guaiacol	g	1.9		
12	29.84	Guaiacol, 4-methyl	g	0.7		
13	34.61	Guaiacol, 4-vinyl	g	0.7	0.5	1.2
	36.29	Syringol	s		0.3	
14	38.70	Guaiacol, 4-propenyl	g	0.9		
15	39.54	Vanillin	g	1.2		
16	41.94	Acetoguaiacone	g	1.0		
	42.93	Syringol, 4-vinyl	s		0.3	
17	43.26	Guaiacyl acetone	g	0.6		
18	46.13	1,6-Anhydro-β-D-glucopyranose (levoglucosan)	cH	3.5		
	46.48	Syringol, 4-(1-propenyl)	s		0.3	

c: cellulose; cH: hexose; cP: pentose; g: guaiacyl lignin; ID: identification; RT: retention time.

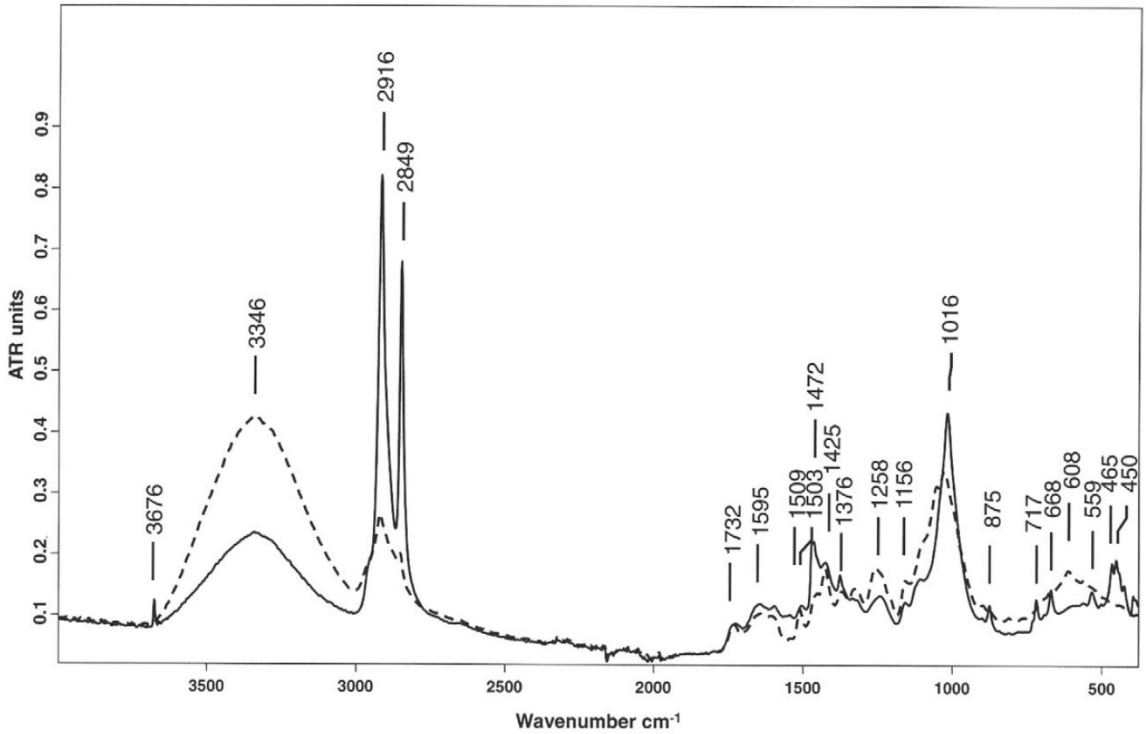

Fig. 2. FTIR-ATR spectra of WPCH (dashed line) and WPCM (solid line).

independent of exposure time and temperature, but is entirely a function of the percentage of water absorption, in line with previous conclusions [13].

This strong correlation indicates that by taking into account the water absorbed by a WPC in-service, it is possible to predict the loss of stiffness. This result is significant since it can help designers to select the proper material for the desired application conditions.

The strong variation of the modulus of elasticity and water absorption is not followed in terms of variation in the dimensions, as shown by Fig. 7. The variation of dimensions is more anisotropic in the case of WPCH and WPCM. In these two cases, the thickness accounts for the majority of the variation (around 6%), with half in the width (around 3%) and an almost insignificant amount in the length (below 1%).

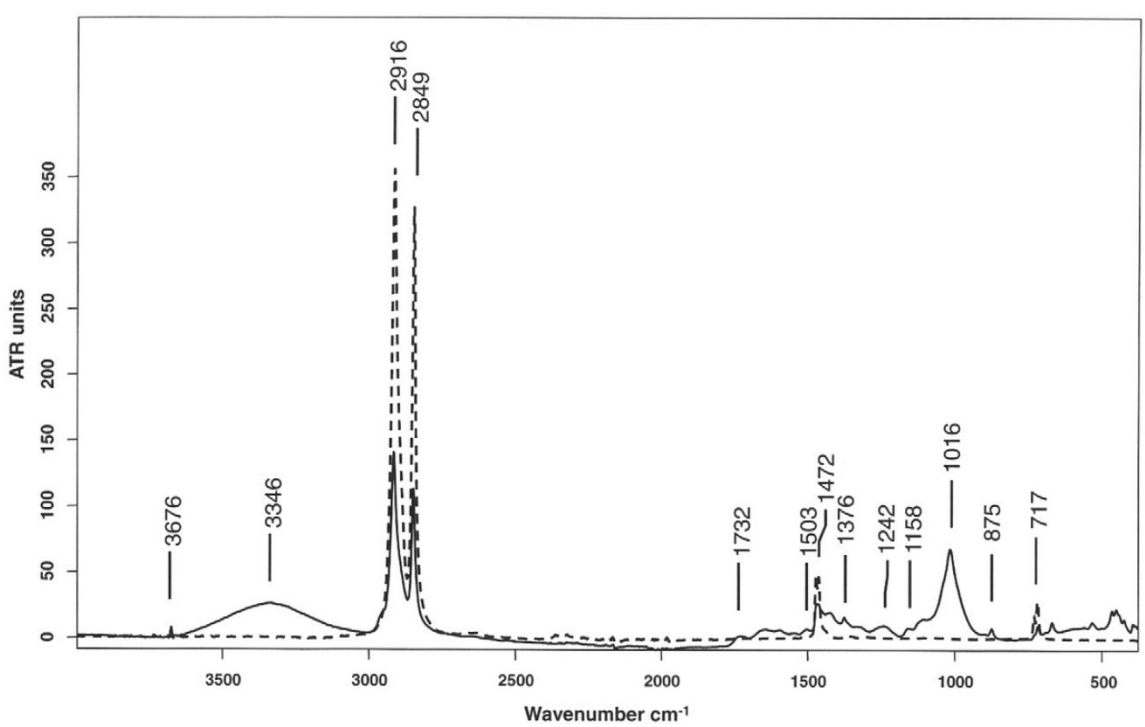

Fig. 3. FTIR-ATR spectra of HDPE (dashed line) and WPCM (solid line).

Table 5
FTIR-ATR band assignments.

Wavenumber (cm^{-1}) range of maxima	Bond type	WPCH	WPCM	WPCL
3676	O—H stretching, talc [22]		3676	
3346–3347	O—H stretching, wood [28]	3346	3346	3347
2916	C—H asymmetrical stretching, wood, PVC, PP and PE (mainly) [31]	2916	2916	2916
2849	C—H symmetrical stretching, wood, PVC, PP and PE (mainly) [31]	2849	2849	2849
1732	C=O stretching, wood [28]	1732	1732	1732
1509–1503	Aromatic skeletal vibrations [28]	1509	1503	1503
1472	C—H deformation, wood [28] and PE (mainly) [31]		1472	1472
1425	C—H deformation, wood [28] and PVC [29]	1425	1425	1425
1377–1376	C—H deformation, wood [28] and PP (mainly) [31]		1376	1377
1258	C—O—C stretching, P(MA-VC) [30]	1258		
1156	C—O—C stretching, wood [28] and C—H deformation and wagging, PP (mainly) [31]	1156	1156	1156
1016	C—C deformation, wood [28] and PVC [29,31]	1016	1016	1016
897	C—H deformation, wood [28] and PP [31]	897	897	897
876–875	C—C deformation, wood [28] and PVC (mainly) [29]	875	875	876
717	C—Cl stretching, PVC [29] or C—H rocking, PE [31]	717		
608	C—Cl stretching, PVC [31]	608		

3.3. Variation of the modulus of elasticity during moisture resistance testing

Along the different cycles, and comparing the same steps, a constant trend toward the increase of water content and decrease of the modulus of elasticity is observed (Fig. 8) at the end of the drying step of the third cycle, losses in the modulus of elasticity of 22, 26 and 29% for WPCH, WPCM and WPCL, respectively, were observed. At the end, and after reconditioning of the test pieces, permanent residual mass losses of 0.31, 0.17 and 0.27% were observed for WPCH, WPCM and WPCL, respectively. These results are similar to the ones obtained previously [33,34]. However, considerable permanent losses of the modulus of elasticity of 13.7, 10.7 and 14.4% were observed for WPCH, WPCM and WPCL, respectively. These losses are similar to the ones obtained for PVC/pine-four (9.96%) and PVC/maple-flour (16.8%) after five freeze-thaw cycles for a concentration of 50 phr (parts per hundred parts of resin) [33]. This same study showed that the increase of wood flour content increases the loss of stiffness due to the increase of water absorption. Also, in the same study, as the number of cycles increases, an increase of the loss of stiffness is observed. In the present study, the close relationship between wood content and loss of stiffness is not apparent. However the decrease of the modulus of elasticity with the increase number of cycles is apparent in the present study, as illustrated in Fig. 8.

The loss of mass is considerably lower than that observed in the immersion test corresponding also to a lower loss of the modulus of elasticity, with the exception of WPCL. In this case, the loss in the modulus of elasticity is in the same range.

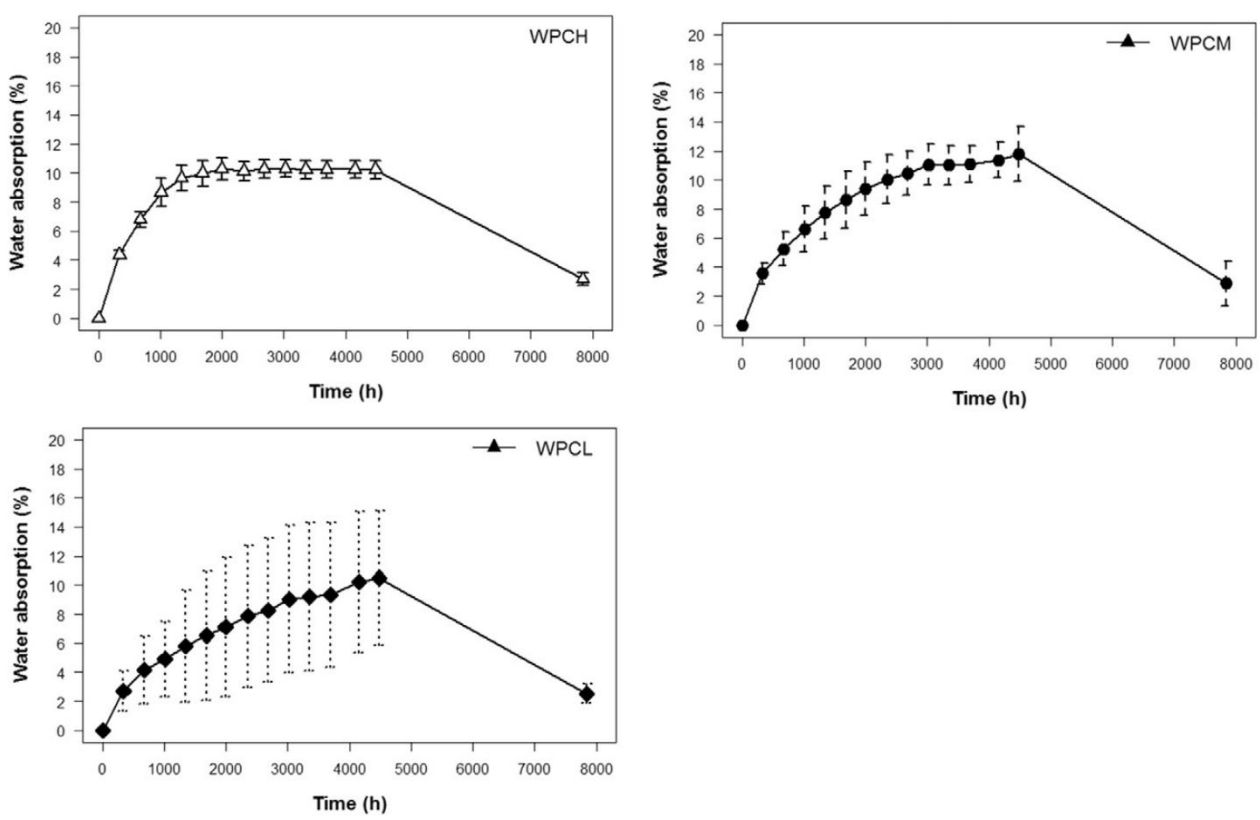

Fig. 4. Variation of water absorption during water immersion.

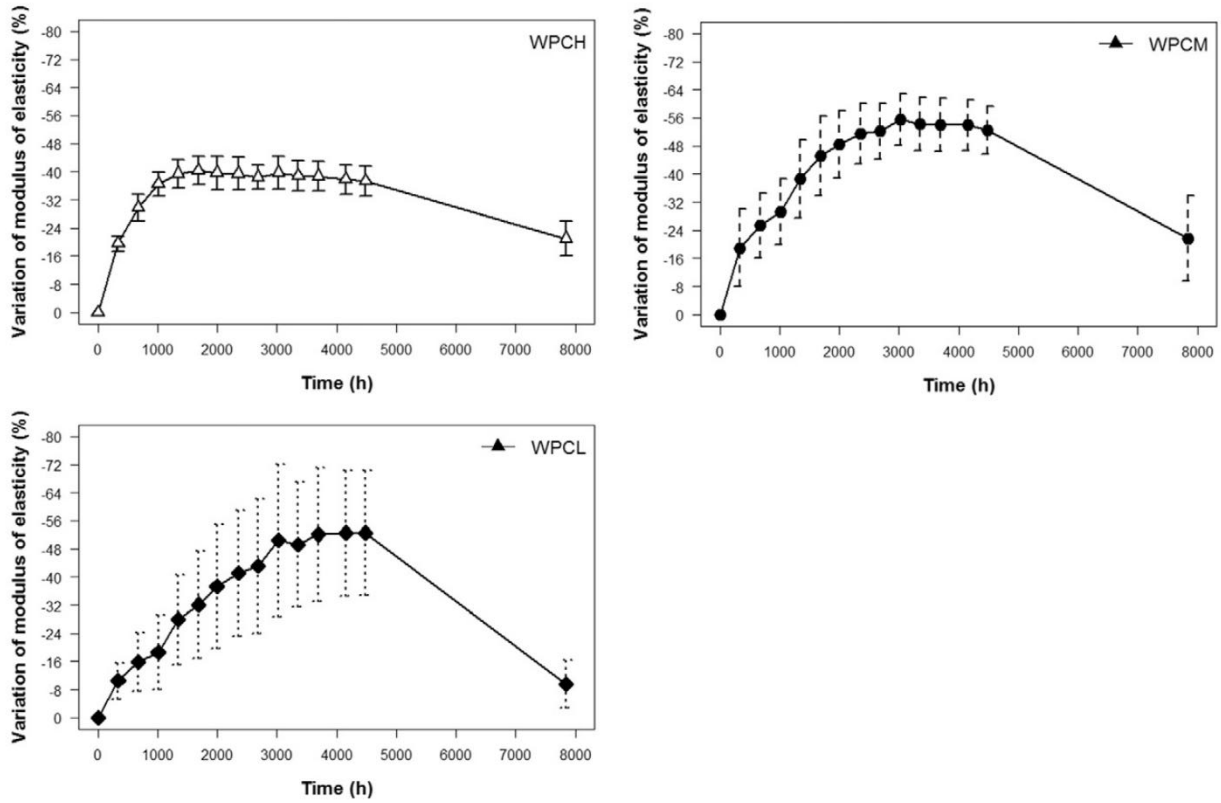

Fig. 5. Variation of the modulus of elasticity during water immersion.

3.4. Moisture effect on serviceability limit states (SLSs)

WPC decks are in general compared to wood decks and thus, Eurocode 5 [35] rules for SLSs were followed. The final deflection (w_{fin}) is considered to be composed of a precamber deflection (in the present study this is not applicable) (w_c), an instantaneous deflection (w_{inst}) and the creep deflection (w_{creep}).

For the determination of the final deflection, it was used the quasi-permanent combination of actions, see equation below, considering a permanent action (self-weight) and a variable action (imposed load).

$$w_{fin} = w_{inst,G}(1 + k_{def}) + w_{inst,Q,1}\left(1 + \psi_{2,1}k_{def}\right) \leq \delta_{Ld} \quad (1)$$

where $w_{inst,G}$ and $w_{inst,Q,1}$ are the instantaneous deformations for actions G (permanent) and Q_1 (variable), respectively, $\psi_{2,1}$ is the factor for the quasi-permanent value of the leading variable action, k_{def} is the relative deformation factor (creep) considering load and exposure conditions and δ_{Ld} is the limit value for deflection.

Few studies have been conducted on the creep behaviour of WPC materials, namely providing factors (k_{def}) to be used for verification of safety and serviceability. One result was found regarding the determination of the k_{def} factor for WPC materials considering a ten year deck service life. This value was taken from a published European Technical Approval (ETA-11/0037) [36] which is significantly higher (27.5) than those specified in Eurocode 5 for wood-based panels exposed to the exterior (2.50). However, this significantly higher relative creep, when compared to solid wood, is also confirmed by other studies [37]. Other

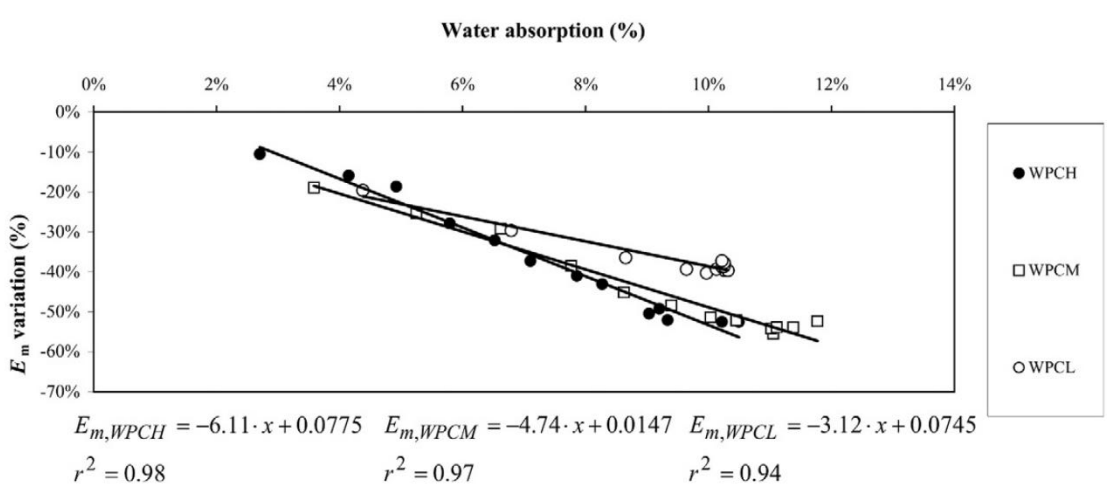

Fig. 6. Variation of the modulus of elasticity (E_m) as a function of water absorption.

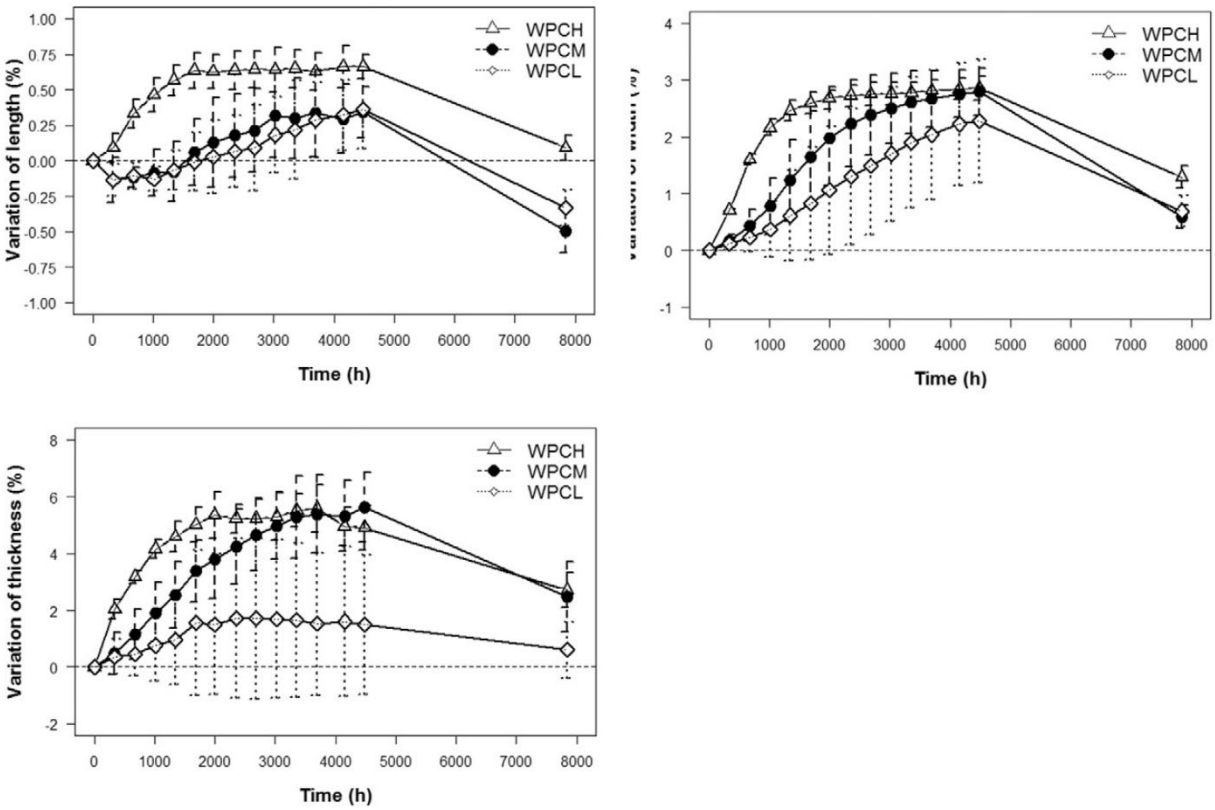

Fig. 7. Variation of dimensions during water immersion.

data ($\psi_{2,1}$ and Q) was taken from [38,39] being all data used for the analysis available as Supplementary Table S1.

The maximum loss of the modulus of elasticity expected for the different WPCs tested was defined considering the maximum water absorption percentage (11%) observed for the different WPCs when immersed in water.

By considering the uncertainty regarding k_{def}, a sensitivity analysis was carried out assuming a possible bandwidth variation of 10% around 27.5. Fig. 9 presents the long-term deflection as function of span compared to the limit values for deflection (solid red lines) and the maximum water absorption expected (dashed black line).

The long-term (ten years) behaviour of the WPC boards tested is highly dependent upon the type of material and water absorption behaviour. For a span of 450 mm, no material shows a suitable performance for a time window of ten years, considering the assumed level of absorption of the WPC when exposed to outside conditions (11%). WPCH shows a suitable performance, if it is accept a deflection limit state equal or superior to span/150, and if the maximum water absorption attained would be inferior or equal to ≈6%.

If the span is reduced to 400 mm (the span usually applied to WPC terrace deckings), WPCH is the only material that could deliver a suitable performance if a limit state corresponding to span/150 is accepted. If the span is reduced again to 350 mm, then WPCH shows a suitable performance for the most demanding deflection limit state considered (span/300). WPCM and WPCL (in this case for the lowest tolerance limit span/150) show suitable performances, only if the level of absorption in-service is lower than ≈8.5 or ≈5%, respectively. The results obtained were based on a k_{def} factor established for a material existing in the market with CE marking. Thus, from Fig. 9, the importance of the characterisation of WPC decks, including the evaluation of long-term

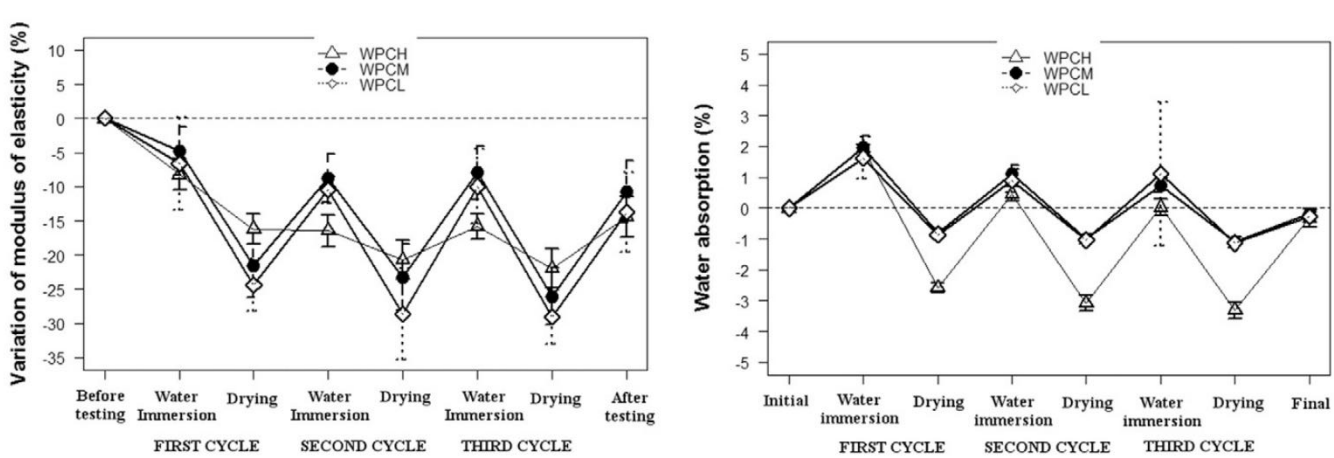

Fig. 8. Variation of the modulus of elasticity and water absorption during exposure to the moisture resistance test.

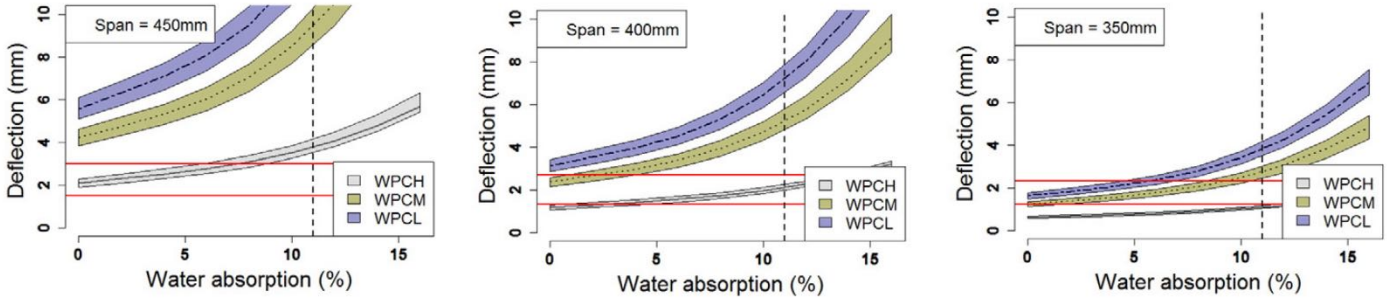

Fig. 9. Long-term deflection as function of different WPCs and spans, considering a variation of ±10% of k_{def}. (shadow region around the mean); red solid lines — limits for long-term deflection; black dashed line — limit of water absorption for the materials tested.

water absorption behaviour and short-term mechanical properties and creep behaviour, is clear. Only when these data are known, can a clear judgement about the claim of a ten year working life be supported. Otherwise, even a safe span of 350 mm could clearly not be sufficient, as is evident in the case of WPCL.

4. Conclusions

The increase of moisture content markedly affects the performance of all types of WPCs tested. The behaviour of WPC boards, when subjected to water immersion or shrinkage/swelling cycles, showed a strongly permanent loss in the modulus of elasticity. The level of water absorption (10 to 12%) observed for all WPC types, when immersed in water until saturation, represents a significant loss of bending modulus (40 to 55%). By considering current application rules for deck boards, this result has a direct impact on ensuring the compliance to the serviceability limit states (maximum deflection accepted) and, therefore, conditioning the application rules to be defined by manufacturers. The strong negative linear relationship obtained between water absorption and the loss of modulus can assist manufacturers in enhancing the design of their products, given the service conditions expected.

The results of the present study stress the importance of a proper characterisation of WPC boards (namely creep behaviour) to define suitable application rules and to achieve compliance with the expected service life.

The application of Py-GC/MS and FTIR-ATR analysis proved to be efficient tools for the characterisation of WPCs, allowing the identification of the matrix and additives, as well as the wood type, softwood vs. hardwood, also providing a rough semi-quantitative estimation of the polymer/filler content without prior calibration.

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.matdes.2016.04.030.

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