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Investigations on ageing of wood-plastic composites for outdoor applications: A meta-analysis using empiric data derived from diverse weathering trials

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HIGHLIGHTS

- MOR and MOE are appropriate indicators to quantify a WPC's ageing.
- Accelerated weathering using xenon-arc light most degrades a WPC's strength.
- A PE-based matrix has a favourable effect on a WPC's durability.
- Strength losses are transferable to a WPC cladding design value.

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ABSTRACT

The successful development of durable wood-plastic composite (WPC) cladding is a challenge for the industry. Due to the organic fibres in the compound it is though doubtable if WPC performs satisfyingly in a façade application which is expected to last 50 years. This paper provides insights from a study to find out how ageing of WPC cladding can be assessed by relevant norms and which material components best support durability aspects. Based on these, a meta-analysis using 44 empirically generated data from 12 papers in the field of accelerated weathering, thermohygric conditioning and fungal decay of WPCs was conducted. It was found that high values of modulus of rupture (MOR) and Young's modulus (MOE) are considered key to an engineering design of WPC façades. Both parameters are appropriate indicators to describe the ageing of WPC cladding. Weathering of WPC decreases MOE more than MOR. Exposure to UV-radiation is more harmful than frost-thaw cycling. In order to minimize a loss in value in MOR and MOE, the use pf polyethylene in extruded panels with large-sized hardwood fibres under low content is recommended. Hence, these basic findings add higher value to a product development.

1. Introduction

In recent years deciders in building products and materials are more and more driven by durability and sustainability aspects. This is not only because norms and codes in the construction industry steadily take these criteria into account. In times of climate change, scarce fossil resources and increasing concerns about the vulnerability of the earth, architects and engineers feel more than ever morally responsible for the consequences of their decisions. But it is also up to the building product manufacturers to provide alternatives to conventional and less ecological products. The underlying philosophy is that a building material becomes more sustainable by increasing the share of biological components [1–5]. However, the case is more complex than it may first appear. The more hydrophilic organic ingredients are used in cladding products, the higher is water uptake and the less is the material's durability when impacts like frost and fungi occur [6,7]. Hence, manufacturers are faced this challenge when developing bio-based building products which are expected to last several decades in outdoor applications.

One example for bio-based materials is wood-plastic composites (WPC) which consists of wood fibres embedded in a

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petrochemical plastics matrix. So far the main applications are decking and cladding [8]. There is an emerging body of literature revealing the opportunities of WPCs in the building scope [9,10]. Basically, WPC uses up to 80% plant fibres and only 20% of fossil-based thermoplastics such as polypropylene (PP), polyethylene (PE) and polyvinylchloride (PVC) [11]. The high fibre share obviously relives the pressure on scarce resources. Furthermore, WPC supports the use of both recycled plastics and wood [2]. Even more, the compound itself can be recycled which follows the principle of cradle-to-cradle and which postpones the question of disposal to the future [12–14]. And finally, the production of WPC and its recycling is comparatively less energy consuming compared to conventional building materials such as metal or cementitious products. WPC is compounded by 180 °C whereas cement is sintered by 1200 °C. Taking a broader view, WPC provides interesting future aspects. The remaining 20% of petrochemical polymers can be substituted by bio-plastics such as polylactic acid (PLA) or polyhydroxyalkanoates (PHA) [15,16]. This turns current WPC into a Green-Composite which solely uses renewable resources. Products made from it are theoretically compostable. Hence, WPC offers new opportunities for the construction industry and specifically architects seeking a Green-Building Certificate will appreciate such a Green-Composite Façade (GCF) [17,18]. In this regard, WPC is viewed as being a transitional technology on the way to future green-composite building products [19].

The production volume of WPC worldwide was 2.43 million tons in 2012. Europe accounted for 260,000 tons and further increases to 450,000 tons are forecasted for the year 2020. Decking made 67% whereas cladding and fencing reached only 6% of the total amount in Europe [10,20]. Obviously besides decking, fencing could not yet emerge as market innovation. In addition to decking, which competes against less ecological tropical hardwood or maintenance-intensive domestic softwood, WPC cladding has to match materials which by experience performs satisfyingly over 5 decades. This life-time is determined by norms, such as EN 1990 [21] and EN 1991 [22], which provide 50-year wind loads as basis for the proof of the cladding's structural fitness. While to date, WPC cladding could not yet demonstrate if it indeed lasts 50 years in a façade application. It is undoubtable that each material will suffer from strength decreases provoked by ageing effects. The key is to find out about the expected strength loss of a WPC cladding even before it is installed at a building. Based on the literature reviewed, there is not yet any national or European approval for WPC cladding [23]. Such documents usually provide design values according to which a façade planner could demonstrate the 50-year structural resistance of the selected product in a target building under normative wind loads. However, some papers in the field of durability testing of WPC reported about strength decreases which at least give orientation in the assessment of a reasonable design value for the proof of structural fitness [24]. Based on the author's experience from the WPC industry, manufacturers are faced a lack of information about how to assess this long-term material degradation for their product. Therefore, the following questions are of paramount interest: (1) Which are the relevant norms to take into account when empirically investigating WPCs durability; (2) which are according these norms the most relevant impacts on WPC cladding during their life-time which significantly provoke ageing; (3) how can ageing become quantified from laboratory tests and (4) which aspects in WPC cladding product development have highest potential to optimize the product's long-term performance?

This paper reports about how these basic questions were successfully answered by research in legal regulations and material technology for WPC.

2. Normative regulations in the scope of cladding and WPC

2.1. Construction Products Regulation EU 305/2011

The European Regulation (EU) No 305 [25], known as Construction Products Regulation (CPR), entered into force as from 2011 and it forms the basis for the development of building products. According to the CRP, a cladding is a building product if its purpose it to rest permanently in a building or a part of it and if its properties moderate the building performance. A WPC cladding undoubtedly meets this criterion laid down in Article 2.1. Furthermore, the CPR defines seven basic prerequisites to be considered in a product development: (1) Mechanical resistance and stability; (2) Safety in case of fire; (3) Hygiene, health and the environment; (4) Safety in use; (5) Protection against noise; (6) Energy economy and heat retention; (7) Sustainable use of natural resources. Special attention is paid to safety aspects which are set down by the following: "*Buildings and building parts have to be erected in the way that they under no circumstances represent a danger for public safety, health and livelihood.*" A building part complies with these demands if it is stable. In terms of façades, the stability of a cladding product is regulated by norms, such as a harmonized European norm (EN) or a national norm. If such norms are lacking for a particular material, there is hence a possibility to regulate a cladding by building product approvals. This could either be a European Technical Assessment (ETB) in case of an EU-wide regulation or a national approval for a country-wise employment. Although there is no strict rule whether in case of the absence of an EN the producer has a choice between regulating a product as per state of the art or per ETB it is commonly assumed that the former can only be taken into account if the particular product is long-standing established in the building scope which in terms of WPC as a novel product cannot be the case. A study on how to regulate WPC cladding therefore should focus on norms and guidelines for the execution of product kit approvals with regard to a façade application.

All further considerations in this paper consequently follow the requirements set out by a WPC-related harmonized norm, as best case. Such a document must contain further information about which product properties need to be declared to the market by the manufacturer.

2.2. Harmonized European WPC norm: EN 15534

As per April 2014 the European Norm (EN) 15534 [26] was introduced into the EU-member countries. Developed by the Mirror Committee CEN/TC 249/WG 13: wood-polymer composites (WPC), this norm specifies compounds which are made from natural fibres mixed with polymeric plastics. The used fibres are derived from plants and as such hemp, sisal, coconut, cotton, kenaf, jute, abaca, banana, leaf fibres, bamboo, rice, wheat straw etc. Polymers are expected to be virgin or recycled. The following Table 1 provides an overview about the norm series 15534 and Part 1 and 5 were applied in this study.

EN 15534 Part 1 contains information about which material properties need to be elaborated for WPC compounds and which synthesized test methods should be applied. EN 15534 in general represents a basic material norm rather than a product norm because it also contains criteria which are not relevant to cladding. Table 2 summarizes key material properties and threshold values given by this norm. Façade-oriented attributes which should be considered in a development process are marked in bold.

EN 15534 Part 5 is viewed as being at least application-oriented because it selects those material criteria from Part 1 which are applicable to the use of a WPC compound in façades. It is important to know that Part 5 explicitly excludes its application for cladding

Table 1
European Norm 15534 series for natural fibre-reinforced composites.

Norm	Content
EN 15534-1: 2014	**Composites made from cellulose-based materials and thermoplastics (usually called wood-polymer composites (WPC) or natural fibre composites (NFC)) – Part 1: Test methods for characterisation of compounds and products**
EN 15534-4: 2014	Composites made from cellulose-based materials and thermoplastics (usually called wood-polymer composites (WPC) or natural fibre composites (NFC)) – Part 4: Specifications for decking profiles and tiles
EN 15534-5: 2014	**Composites made from cellulose-based materials and thermoplastics (usually called wood-polymer composites (WPC) or natural fibre composites (NFC)) – Part 5: Specifications for cladding profiles and tiles**
EN 15534-6: 2015	Composites made from cellulose-based materials and thermoplastics (usually called wood-polymer composites (WPC) or natural fibre composites (NFC)) – Part 6: Specifications for fencing profiles and systems

Table 2
Material properties according to EN 15534-1.

Attributes	Test method as per...	Threshold value according to EN 15534
Physical properties		
Density	**ISO 1183-1**	
Moisture content	**EN 322:1993**	
Slip Resistance		
Slipperiness	CEN/TS 15676	
Pendulum test	EN 13451-1:2011 Appendix E	
Dimensional characteristics		
Mass, thickness, width and length	**Measuring tape**	**H: (1 000 ± 5)mm** **Ms: (500 ± 2)g**
Deviation from straightness	**Ruler and measuring tape**	
Cupping	Measurement device	
Mechanical properties		
Impact resistance (Charpy-Test)	EN ISO179-1	
Falling mass impact resistance	**EN 477**	**Max. failure one by 10 samples**
Tensile properties	EN ISO 527-2	
Flexural properties	**EN ISO 178**	**Deflection under 250N; ⩽5 mm**
Creep behaviour	3-point bending test	
Surface hardness (Brinell)	EN 1534:2010	
Nail and screw withdrawal	**EN 1383**	
Durability		
Resistance to artificial weathering **Resistance to natural ageing**	**Conditioning: EN ISO 4892-2: 2013, EN 927-6, EN ISO 16472;** **Assessment: EN 20105-A02 (Grey-scale), ISO 7724-1-2,-3** **Change in appearance** **Change in MOR (Modulus of Resistance)** **Change in slip resistance** **Chalking** **Peel strength**	
Moisture resistance		
Swelling and water absorption	**EN 317 and EN ISO 178:2010**	**⩽10% thickness; ⩽1,5% breadths; ⩽0,6% length;** **⩽8% mass increase**
Moisture resistance under cyclic conditions	**EN 321 (under modified conditions)**	
Moisture resistance – boiling test	EN15534-1; 8.3.3	⩽7% mass increase
Resistance against termites	**EN 117**	
Resistance against biological agents • **Basidiomycetes** • **Micro-fungi** • **Discolouring due to micro-fungi** • **Discolouring due to algae**	**Conditioning acc. EN 84:1997** **Assessment acc. EN V 12038 (under modified conditions)** **Change of bending strength acc. EN ISO 178** **ASTM D 3273 (under modified conditions)** **ISO 1686** **EN 15458:2007**	**Deflection under 250 N; ⩽0.6 mm**
Resistance to salt spray	EN ISO 9227	
Thermal properties		
Heat deflection temperature (HDT)	EN ISO 75-1,-2	
Linear thermal expansion	**ISO 11359-2**	**⩽50 × 10^{-6} 1/K**
Heat reversion	**EN 479**	
Heat build-up	**EN ISO 4892-1:2000, Test programme acc. EN 15534 specifications**	
Oxygen index (OI)	EN ISO 4589-2	
Reaction to fire	**EN ISO 11925-2** **SBI acc. EN 13823 and EN 13245-2:2008** **Assessment acc. EN ISO 11925-2, EN 13823**	
Other properties		
Degree of chalking	**EN ISO 4628-6**	
Change of gloss	**EN ISO 2813**	
Peel strength	**Apparatus**	

kits, comprising WPC panels, sub-construction and fasteners (EN 15534-5, Chapter 1). However, in addition to Part 1, this norm quantifies minimum values which ensure that the cladding product at least performs in a particular way which fits to its application, such as dimensional accuracy or maximal thermal linear expansion.

The list of measurable material attributes for WPC is long and they can be summarized by the following categories:

a) *Stability:* Tension and flexural stresses are indicators for the material resistance against external load impacts. Stresses at breaking, such as modulus of rupture (MOR) as well as Young's modulus of elasticity (MOE), are considered key traits in this field. By experience, the higher is MOR and MOE of a material the better it fits to a façade application. It should be noted that both values are characteristic in nature because they emerged from test series which results are statistically treated on a 5%-fractile base. Furthermore, the stability of façade coverings is also subject to the resistance of the fixation of single panels.
b) *Durability:* This aspect deals with strength decreases due to external impacts over the product's life-time. The effects are simulated by both artificial and natural ageing tests. In the former, samples are pre-treated under freeze-thaw cycling and under impacts of basidiomycetes. From both the loss of bending strength is measured. Natural ageing is investigated by the exposure of samples for one year to weathering conditions equal to South France. Here as well the loss of strength is measured afterwards. Category "Durability" therefore provides the basic tests to assess the material weakening due to (1) freeze-thaw cycling, (2) basidiomycetes and (3) UV-exposure.
c) *Serviceability:* Cladding is expected to keep its form and appearance at least for a considerable life-time and under changes which approach rather slightly. A constant geometrical appearance is ensured by low linear thermal expansions of the WPC panels, moderate creeping and little swelling due to water impacts. Discoloration is evaluated by xenon-light pre-treatment of samples and subsequent peeling tests of surface coverings.
d) *Safety:* Here, the fire resistance of wall panels is viewed as being most important in façade applications.
e) *Other criteria:* This category contains further characteristic traits and as such termite resistance, if WPC façades are erected in Mediterranean regions, the bulk density which allows the derivation of shear loads or the impact resistance which helps assessing the suitability of the cladding for hard-body attacks which for instance occur in hailstorms.

According to Part 5 of EN 15534, the manufacturer must execute initial tests and declare a particular list of selected compulsory and voluntary product traits. As a consequence, most product attributes are elaborated only once unless future changes in material formulation or production process would make a difference to former results. It is therefore plausible that findings from these tests should also serve a strength proof for a WPC façade carried out by engineers as demanded by EN 1990 [21] and 1991 [22]. However, it is important to note that all attributes are characteristic in nature which means that they represent a real reaction of the material after a natural or artificial pre-treatment. Hence, test results don't represent the future conditions under which the product must perform in its final destination.

Anyhow, the literature pertaining to WPC's durability sees in the existing WPC norm a measurement of limited suitability for quantifying the loss in material strength for the practice [27,28]. As a basic conclusion, EN 15534 describes durability tests which are not necessarily appropriate to assess the real product behaviour in practice but which are obligatory for manufacturers. It is therefore from highest interest to find a way how to assess WPC's real ageing behaviour from these initial tests which are anyway time-intensive and costly. The transfer of characteristic test results, such as MOR, into the practice is usually done by a simple conversion factor. However, there is no normative basis according to which such a factor can be elaborated for WPC [24]. Its development demands a deep knowledge in both the application and material technology.

2.3. Guideline for the execution of a building product approval: ETAG 034

ETAGs are European Technical Approval Guidelines which describe how approval documents should be carried out in case a harmonized norm is lacking. The ETAG 034 [29] was launched in July 2011 by the EOTA (European Organization for Technical Assessment) and it contains information about the deliverable initial tests, the conformity attestation and CE-marking of ventilated façade product kits. As already stated, a WPC cladding material is described by the EN 15534 which explicitly excludes its application for cladding kit product systems. As the study on hand attempts to regulate a WPC cladding for its application, it is essential to consider aspects from this ETAG even if the manufacturer doesn't seek an ETB. In addition to the EN, this guideline integrates aspects of performance behaviour due to interaction of single product components, such as fasteners, the coverings and the sub-construction. It is relevant to note that the application of this ETAG should be done in combination with material-related norms. Although the ETAG only covers a selected number of materials, such as fibre cement, pure plastics, ceramics, timber etc., it seems plausible to apply this guideline also to other materials for which an EN material norm already exists, like WPC.

The additional aspects under which cladding kits are investigated according to this ETAG can be summarized as follows:

(1) *Water tightness (protection against driving rain), chapter 5.3.1:* The water tightness of a mock-up of 1.20 m $\times$ 2.40 m is tested under artificial weathering using simulated wind-driven rain by 600 Pa. The cladding system is viewed as being water tight if on the backside no discernible water drops are visible.
(2) *Wind load resistance, chapter 5.4.1.1:* Cyclic wind suction is applied to a test surface of 1.5 m^2 with step-wise increase from 300 Pa up to cladding failure. The deformations and the failure loads are measured. This test is mostly executed in a suction chamber which makes this approach to a costly undertaking. However, the ETAG 034 also proposes using a foil bag at the rear side of the cladding and which becomes inflated by compressed air until failure.
(3) *Mechanical resistance of fasteners, chapter 6.4.2:* The pull-out resistance of fasteners, as screws, rivets or metal clips, through the WPC material can be elaborated using testing machines for tensile or bending strength. The rupture load and the deformations are measured from which the stiffness of the fixation points can be derived. Such insights are often applied in structural analysis by FEM simulations.
(4) *Durability, thermohygric product behaviour, chapter 5.4.5:* In addition to freeze-thaw cycling according to EN 15534, the ETAG demands a comparable test procedure applied to a 6 m^2 cladding surface. After artificial weathering, comprising also a spraying with water, the effects on the surface, such as peeling, cracking, erosion etc. is visually assessed and documented.

In addition to EN 15534, the ETAG 034 rather focuses on the performance of a complete façade section. However, neither the ETAG 034 nor the EN 15534 provide information on how the established durability-related test results can be condensed to a conversion factor which describes the material ageing. Such a factor would give orientation in a product development which primary aims to create highly durable WPC claddings.

2.4. Concept for the derivation of a design value from characteristic test results: EN 1990

EUROCODE EN 1990: Basis of structural design [21] is a base norm which regulates how structural calculations in the building scope should be carried out. Whenever a building element or a material is subject of strength proof, this norm specifies the treatment of material-related properties which were derived from performance tests. This is necessary because results from such tests solely show actual features of a particular series of test samples. It is doubtable if they could serve as reference for all imaginable cases under which WPC is used in practice. Therefore, results from such tests must be transferred from a characteristic level, representing the virgin state, to a design level serving for the code of practice. Of course, a material resistance after such a treatment must become inferior which takes into account all distortion effects within the test procedure, size effects resulting from small test samples and future large-scale applications, further deviations from the test conditions as temperature, humidity and specifically ageing effects within the application-related time frame. EN 1990, chapter 6.3.3 comprises such aspects by a single factor, which is:

$$\text{Conversion Factor}: \eta \leq 1.0 \quad (1)$$

To additionally compensate uncertainties in the previously determined conversion factor and for corrections pertaining to deviations between the material and the product made from it, EN 1990 recommends applying a partial safety factor γ_M.

Taking both factors into account, the resulting engineering design value R_d derived from material tests is as follows:

$$\text{Material Design Strength}: R_d = \eta^*(X_k/\gamma_M), \quad (2)$$

where X_k is the material property (EN 1990, 4.2) given as the 5%-fractile value from a test series using virgin specimen.

Hence, the factor η takes into account the difference between the bias of a virgin test sample and the same material in a future application close to its end-of live. Therefore it is at first necessary to determine the particular influences which most moderate this discrepancy. Based on the previous findings from the literature review in norms and regulations it seems plausible that (1) exposure to natural weathering, (2) fungal decay and (3) thermohygric conditions like freeze-thaw cycling have the highest impact on WPC ageing to be covered by η in Eq. (2). These tests measure the weakening due to particular pre-treatments which most widely and realistically catch the natural environment of a WPC cladding façade over its life-time.

3. Methodology

Introductory studies so far revealed three initial tests which are compulsive for WPC cladding manufacturers when regulating their product according EN 15534. All three tests use the material's bending strength as dependent variable to describe the ageing effect. Natural weathering should take place in Europe's Mediterranean region where the annual radiation dose is supposed to be 6,6 GJ/m^2 [26]. In addition to this, accelerated artificial weathering tests with laboratory light sources are proposed as alternative. This approach is far less time intensive and lasts 12.5–88.3 d depending on the norm and light source. Basic norms in this field are figured out in Table 2. WPC's reaction to water is measured by EN 321 [30] and it uses cycles of water soaking for 72 h, frost periods for 24 h and drying phases for 72 h. Mostly 3 cycles are passed where the first one has an extended phase for water immersion taking 28 d. This test in total takes 49 d. And finally, strength decrease due to fungal decay is measured according to ENV 12038:2002 [31] using *Coniophora puteana* (wet-rot), *Gloeophyllum trabeum* (brown-rot) und *Coriolus versicolor* (white-rot) in the specimen pre-treatment. The strength loss of incubated specimens is measured by bending tests of pre-dried and wet samples. By this comparison the effect of fibre deterioration becomes discernible because the water uptake alone also leads to strength decreases.

So far the preparative investigations on relevant regulations could satisfyingly answer the basic questions about which norms and tests could serve the assessment of WPC ageing behaviour. They build a theoretical framework according to which the decrease of the material's virgin strength under artificial climates becomes quantifiable. It can be argued that this framework is not appropriate to simulate a cladding's complete life-time because the number of frost-thaw cycles or the duration of radiation impacts as well as the intensity of exposure obviously cover only a share of the expected dose in a cladding's life. However, for a development of a WPC cladding's design value according to Eq. (2) it is more interesting to know which criteria have the highest effect on the ageing. WPC is a complex material and its performance mostly depends on the composite's ingredients and the production method which by today is dominated by extrusion and injection moulding. Current WPCs differ in the types and shares of fibres, plastics and additives used in the formulation. The production process itself is influenced by the composite's components and the end use of the product. The high number of possible compositions therefore makes it hard to predict a WPC's characteristics prior to development. Extensive previous literature review has witnessed that research in WPC is predominately settled in basic material investigations which employ single- to bi-variate analysis using only one kind of the three described impacts [19].

The study on hand therefore investigated relevant papers in the field of the three previously described durability tests. Results were assessed by a meta-analysis which tried to reveal how basic factors in WPC formulations and production processes affect the durability of current WPCs. To make the empiric results comparable among the papers, only those using bending strength MOR ad Young's modulus (MOE) as dependent variables under similar conditioning methods were selected. Following these requirements, in total 12 papers were examined, where 5 of them report about resistance to artificial weathering, 3 about fungal decay and another 4 about thermohygric impacts. Additionally, 9 papers were selected which examined further dependent variables such as water content or weight loss which by trend indicate the change of MOR and MOE as well. In terms of UV-impacts, the number of papers reporting about natural weathering of WPC was too small which is why the study focussed solely on artificial accelerated weathering trials. For the meta-analysis in total 44 variables could be derived from the 12 papers. Statistical calculations by SPSS Statistics and a ranking of all dependent variables tried to reveal which specimen showed minimal strength loss and therefore best support a façade strength calculation using R_d as per Eq. (2) and MOE for serviceability proofs.

4. Case study results and discussions

The following sections summarize the results from the meta-analysis for each type of conditioning method (1) accelerated weathering, (2) fungal decay and (3) thermohygric impacts. Tables 3, 5 and 7 provide an overview about the referenced papers, the

Table 3
Overview on the assessed papers in the field of Artificial Weathering (*AW*).

References	Formulation [%]	Independent variable	Production method	Conditioning method	Specimen code
Stark et al. [32]	50-Pine 50-HDPE. Incl. lubricants	Processing: Extrusion (*Ex*); Injection moulding (*IM*)	Extruded and injection moulded	Artificial accelerated weathering (*AW*) using xenon arc-light (300–400 nm) for 125 d by 0.06 kW/m^2	*AW*(*Ex*) *AW*(*IM*)
Beg/Pickering[34]	40-Pine 60-PP incl.3-MAPP	Fibre treatment: Bleached Pine (*BP*); Unbleached Pine (*uBP*)	Injection moulded	Artificial accelerated weathering (*AW*) using fluorescent light (340 nm) for 83.3 d by 0.06 kW/m^2	*AW*(*BP*) *AW*(*uBP*)
Falk et al. [33]	50/70-Wood 50/30-HDPE incl. Additives	Colour Pigments: Non-coloured (*nP*); Red-coloured (*rP*); Black-coloured (*bP*) Fibre Content: 50% (*50*); 70% (*70*)	Injection moulded	Artificial accelerated weathering (*AW*) for 62.5 d by 0.06 kW/m^2	*AW*(*nP/50*) *AW*(*rP/50*) *AW*(*bP/50*) *AW*(*nP/70*) *AW*(*rP/70*) *AW*(*bP/70*)
Kallakas et al. [35]	65-Birch 35-LDPP incl.5- APTES	Fibre fraction size: ⩽0.62 mm (*1*) 0.63-1.25 mm (*2*) 1.26-2.0 mm (*3*)	Injection moulded	Artificial accelerated weathering (*AW*) using fluorescent light (250 nm) for 21 d by 0.045 kW/m^2	*AW*(*1*) *AW*(*2*) *AW*(*3*)
Seldén et al. [36]	0/25/50-Conifer 100/75/50-PP incl.2-MAH (*M*) or without MAH (*nM*)	Fibre Content: 0% (*0*) 25% (*25*) 50% (*50*) Bonding Agent: MAH-PP (*M*) no MAH-PP (n*M*)	Injection moulded	Artificial accelerated weathering (*AW*) using fluorescent light (340 nm) for 56 d by 0.048 kW/m^2	*AW*(*M/0*) *AW*(*M/25*) *AW*(*M/50*) *AW*(*nM/0*) *AW*(*nM/25*) *AW*(*nM/50*)

Table 4
Test results in the field of Artificial Weathering (*AW*).

References	AW-Duration [d]	AW-Intensity [kW/m^2]	Specimen Code	MOR, non-weathered [MPa]	MOR, weathered [MPa]	Decrease Δ_{MOR} [%]	MOE, non-weathered [MPa]	MOE, weathered [MPa]	Decrease Δ_{MOE} [%]
Stark et al. [32]	125	0.06	*AW*(*Ex*)	39.6	26.9	**32.0**	3600	2052	**43.0**
			AW(*IM*)	24.5	16.2	**34.0**	3300	1584	**52.0**
Beg/Pickering [34]	83.3	0.06	*AW*(*BP*)	41.0	34.0	**17.0**	4450	3950	**11.3**
			AW(*uBP*)	39.0	34.0	**13.0**	4500	4000	**11.2**
Falk et al. [33]	62.5	0.06	*AW*(*nP/50*)	57.5	38.0	**34.0**	3000	2100	**30.0**
			AW(*rP/50*)	53.1	42.8	**20.0**	2953	2250	**14.0**
			AW(*bP/50*)	47.0	44.5	**5.5**	2531	2390	**5.5**
			AW(*nP/70*)	57.5	38.0	**34.0**	3000	2100	**30.0**
			AW(*rP/70*)	58.5	45.4	**22.5**	3445	2460	**29.0**
			AW(*bP/70*)	53.1	42.7	**20.0**	3093	2390	**23.0**
Kallakas et al. [35]	*21*	0.045	*AW*(*1*)	23.8	22.2	**6.5**	1000	880	**12.0**
			AW(*2*)	21.8	21.2	**2.7**	910	880	**3.3**
			AW(*3*)	20.7	20.4	**1.5**	830	840	**0.0**
Seldén et al. [36]	*56*	0.048	*AW*(*M/0*)	60.6	54.5	**10.0**	1990	no data	n.d.
			AW(*M/25*)	63.4	52.6	**17.0**	3240	2755	**15.0**
			AW(*M/50*)	65.7	51.3	**22.0**	5270	4005	**24.0**
			AW(*nM/0*)	66.2	58.3	**12.0**	2180	2090	**4.1**
			AW(*nM/25*)	54.4	44.6	**18.0**	3110	n.d.	n.d.
			AW(*nM/50*)	48.0	36.0	**25.0**	4980	n.d.	n.d.

Table 5
Overview on the assessed papers in the field of Fungal Decay (*FD*).

References	Formulation [%]	Independent variable	Production method	Conditioning method	Specimen code
Ashori et al. [39]	60-Poplar 40-HDPE. incl. 2.6-, 3.8- Additives	Fungicide Agent: 0.6% IPBC (*I*); 0.6% TBZ (*T*) 0.9% IPBC+0.9% TBZ (*I+T*) No agent (*nA*)	Injection moulded	Inoculation: 84 d by white-rot (T-versicolor) fungus and oven-dried before testing	*FD*(*I*) *FD*(*T*) *DF*(*I* + *T*) *DF*(*nA*)
Schirp/Wolcott [41]	49/70-Maple 45/24-HDPE incl.6% Additives	Fibre Content: 49% (*49*); 70% (*70*)	Extruded	Inoculation: 84 d by white-rot (T-versicolor) fungus and oven-dried before testing	*FD*(*49*) *FD*(*70*)
Naumann et al. [40]	50-Wood 50-HDPE incl. additives	Flame Retardant: Clariant-AP422 (*422*); Clariant-AP760 (*760*); Structol SA0832 (*S*); Expand.Graphite (*eG*) No retardant (*non*)	Extruded	Inoculation: 112 d by white-rot (T-versicolor) fungus and oven-dried before testing	*FD*(*422*) *FD*((*760*) *FD*(*S*) *FD*((*eG*) *FD*(*non*)

compound formulation used, the independent variable, the applied production method of specimen, the conditioning method and a specimen code connected to the dependent variable MOR and MOE. The Tables 4, 6 and 8 show the absolute results for MOR and MOE and their losses in value. Finally, the results from the statistical analysis are depicted in Figs. 1–3.

4.1. Results from the literature review about accelerated weathering

The variables used in the papers depend on 7 influences ranging from processing method to bonding agents. Stark et al. [32] investigated how the manufacturing method affects the strength decrease of HDPE-based WPCs. Additives and their potential to

Table 6
Test results in the field of Fungal Decay (*FD*).

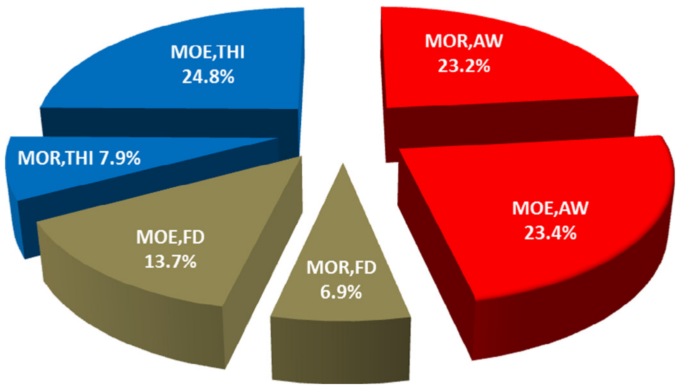
References	FD-Duration [d]	Specimen Code	MOR, non-weathered [MPa]	MOR, weathered [MPa]	Decrease Δ_{MOR} [%]	MOE, non-weathered [MPa]	MOE, weathered [MPa]	Decrease Δ_{MOE} [%]
Ashori et al. [39]	84	*FD(I)*	44.3	35.9	**19.0**	4360	2877	**34.0**
		FD(T)	34.3	28.7	**16.6**	3686	2395	**35.0**
		FD(I+T)	43.0	40.8	**5.1**	4282	3437	**19.7**
		FD(nA)	47.4	31.7	**33.1**	4424	2466	**44.3**
Schirp/Wolcott [41]	84	*FD(49)*	26.9	26.3	**2.2**	1979	1497	**24.4**
		FD(70)	14.7	11.98	**18.5**	1004	797	**20.6**
Naumann et al. [40]	112	*FD(422)*	no data	n.d.	n.d.	5425	4449	**18.0**
		FD(760)	n.d.	n.d.	n.d.	6056	4784	**21.0**
		FD(S)	n.d.	n.d.	n.d.	5487	3786	**31.0**
		FD(eG)FD(non)	n.d.	n.d.	n.d.	6573	4765	**27.5**
			n.d.	n.d.	n.d.	4120	2966	**28.0**

Table 7
Overview on the assessed papers in the field of Thermohygric Impacts (*THI*).

References	Formulation [%]	Independent Variable	Production Method	Conditioning Method	Specimen Code
Adhikary et al. [43]	50-Pine (*50*) 50-Plastics	Type of Plastics: HDPE (*PE*); Recycled HDPE (*rPE*); PP (*PP*); Recycled PP (*rPP*) Bonding Agent: 3% MAPP (*MA*) no MAPP (*nMA*)	Injection moulded	Cycles: Water soaking until equilibrium; 1 d freezing; 1 d thawing. In total 12 cycles	*THI(50/PE/nMA)* *THI(50/rPE/nMA)* *THI(50/rPE/MA)* *THI(50/PP/nMA)* *THI(50/rPP/nMA)* *THI(50/rPP/MA)*
Pilarski/Matuana [44]	25/38/50-Wood 75/62/50-PVC incl.5- Additives	Fibre Content: 25% (*25*); 38% (*38*); 50% (*50*) Fibre Species: Maple (*Ma*); Pine (*Pi*)	Extruded	Cycles: Water soaking until equilibrium; 1 d freezing; 1 d thawing. In total 12 cycles	*THI(25/Ma)* *THI(38/Ma)* *THI(50/Ma)* *THI(25/Pi)* *THI(38/Pi)* *THI(50/Pi)*
Wang et al. [45]	50-Rice Hull 50-PE (*PE*)	–	Extruded	Cycles: Water soaking for 2.5 d; 1 d freezing; 1 d thawing. In total 6 cycles	*THI(-/PE)*
Tamrakar/Lopez [46]	46-Pine 54-PP incl. 13-Additives	–	Extruded	Cycles: Water soaking for 20 d; 1 d freezing; 1 d thawing. In total 4 cycles	*THI(-/PP)*

Table 8
Test results in the field of Thermohygric Impacts (*THI*).

Reference	THI-Duration [d]	Specimen code	MOR, non-weathered [MPa]	MOR, weathered [MPa]	Decrease Δ_{MOR} [%]	MOE, non-weathered [MPa]	MOE, weathered [MPa]	Decrease Δ_{MOE} [%]
Adhikary et al. [43]	12	*THI(50/PE/nMA)*	14.4	10.1	**29.9**	1340	1120	**16.4**
		THI(50/rPE/nMA)	15.6	14.2	**9.0**	1410	810	**42.5**
		THI(50/rPE/MA)	25.5	23.2	**9.0**	1880	630	**66.5**
		THI(50/PP/nMA)	14.7	10.8	**26.5**	1680	1360	**19.0**
		THI(50/rPP/nMA)	17.4	13.3	**23.6**	1720	1050	**38.9**
		THI(50/rPP/MA)	39.6	32.3	**18.5**	2340	950	**59.4**
Pilarski/Matuana [44]	12	*THI(25/Ma)*	36.6	35.1	**4.2**	2040	1697	**16.8**
		THI(38/Ma)	46.4	43.7	**5.9**	3380	2631	**22.1**
		THI(50/Ma)	31.6	26.8	**15.2**	2540	1678	**33.9**
		THI(25/Pi)	40.3	39.4	**2.2**	2350	2116	**10.0**
		THI(38/Pi)	43.6	39.9	**8.5**	3330	2727	**18.1**
		THI(50/Pi)	37.6	32.9	**12.5**	3340	2345	**29.8**
Wang et al. [45]	6	*THI(-/PE)*	13.6	12.9	**5.5**	1610	940	**41.6**
Tamrakar/Lopez [46]	4	*THI(-/PP)*	22.5	21.4	**8.0**	3700	2000	**46.0**



Variable	$\bar{x}$ [%]	SD [%]
$\overline{MOR}_{AW,FD,THI}$	26.1	19.3
$\overline{MOE}_{AW,FD,THI}$	36.5	26.7
$\overline{MOR}_{AW}$	39.8	18.0
$\overline{MOE}_{AW}$	40.1	25.6
$\overline{MOR}_{FD}$	11.8	7.6
$\overline{MOE}_{FD}$	23.5	6.0
$\overline{MOR}_{THI}$	13.5	8.1
$\overline{MOE}_{THI}$	42.5	33.6

Fig. 1. Shares of *AW*, *FD* and *THI* in total strength losses.

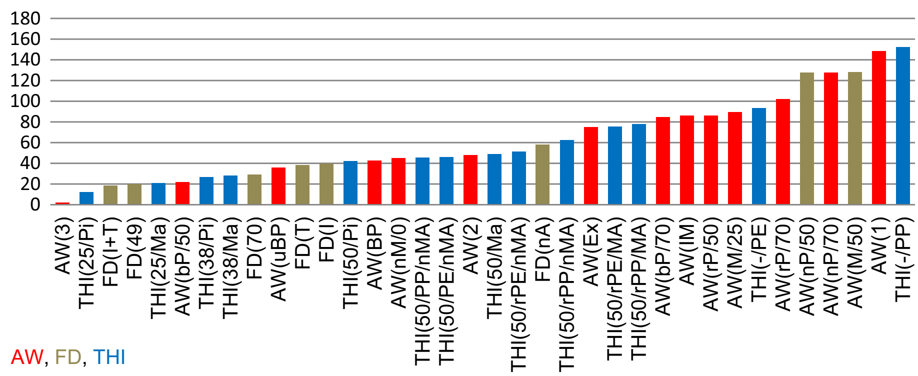


Fig. 2. Sum of percental losses for MOR and MOE per specimen and ranking of results.

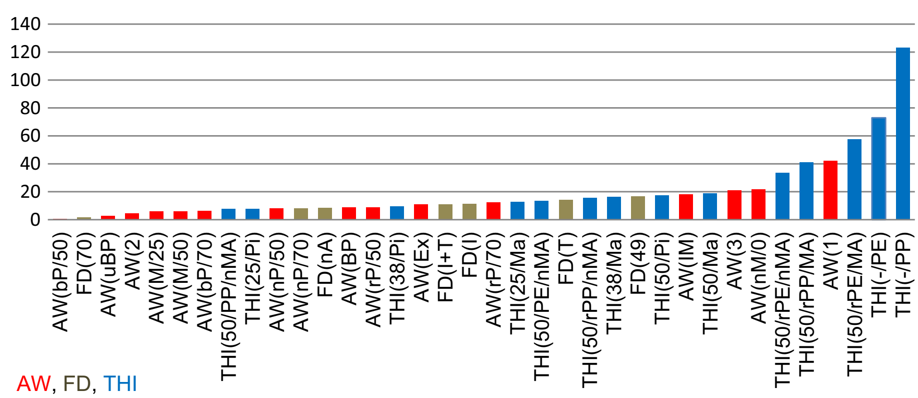


Fig. 3. Difference in percental losses for MOR and MOE per specimen and ranked results.

improve the strength loss was subject of a paper by Falk et al. [33]. The fibre played a major role in investigations by Beg and Pickering [34] who examined the influence of bleaching fibres against ageing. In addition, Kallakas et al. [35] touched on fibre fraction size and Seldén et al. [36] on fibre content.

The production method obviously does not significantly affect the MOR decrease whereas injection moulding tends to decrease MOE more than extrusion as can be seen from Table 4. As far as the fibres are concerned, the findings clearly show that bleaching has less influence on the results from accelerated weathering. However, bleached fibres tend to degrade more than unbleached ones. It can also be seen that strength loss in MOR and MOE is more for smaller fibres and higher fibre content. And obviously, dark colour pigments have a tendency to slow down ageing indicated by both MOR and MOE losses. Overall, it can be concluded that although there is a positive effect on WPC cladding preservation over its life-time, bleaching and the use of thicker fibres is much less effective. On the contrary, it is recommended using dark pigments, low fibre content and extrusion as production method. These development principles thus most probably lead to the "fittest" WPC cladding in terms of accelerated weathering.

As already mentioned, the literature research also identified further papers which could not take part in the meta-analysis but which gave additional valuable insights. Xiaxing et al. [37] report about the use of anti-oxidants and light stabilizers (HALS) as antiageing-agents in WPCs. During one year natural weathering in China their results initially showed slight strength increases by 3.7% and after the natural conditioning the values went down by

7–10% for both MOR and MOE. Fibre species were independent variables in a test undertaken by Fabiyi and McDonald [38]. In addition to all other papers, their study was using MOR and MOE only for the characterization of specimens prior to accelerated weathering. However, results can be interpreted in the light of the previous papers because the higher is the initial strength the more is the final strength after weathering. According to their paper, hybrid poplar and Douglas fir provoke higher MOR and MOE values compared to white oak and ponderosa pine.

4.2. Results from fungal decay tests

Tests reports pertaining to how WPC decays are scarce most probably due to the long duration of appropriate experiments. However, among the selected three papers valuable insights about the effect of fungicide agents were provided by Ashori et al. [39] and about the addition of flame retardants by Naumann et al. [40]. Fibre content played again a major role when assessing ageing effects as examined by Schirp and Wolcott [41].

The test results show that MOE in general suffers more from fungal decay than MOR. As expected, preservatives significantly prevent a compound from fungal-related strength decreases. The higher is the concentration of mixed IPBC (propynyl butylcarbamate) and TBZ (2-thiazol-4-yl-1H-benzo-imidazol), the more is their preservation effect on the compound. Another basic conclusion drawn from Naumann et al. is that also flame retardants potentially enhance a WPC's resistance against fungal decay. Although data was published only for MOE it can be concluded from all results that a comparable effect can be expected for MOR. Thus, flame retardants in façades have a double effect which maybe makes the costly use of particular fungicides avoidable. However, the results indicate that not each type of retardant has the same potential. In terms of wood fibres, results from Schirp and Wolcott reveal that effects from fibre contents influence MOE more than MOR and the higher the share the more degradation occurs. However, reducing the content in order to preserve WPC from fungal decay is more effective for MOR than for MOE. From a broader view, the calculated strength decreases by Schirp and Wolcott are much lower than the others which might come from the maple hardwood fibres whereas in the other papers softwood as poplar and spruce or pine was used. And finally, *FD*(*nA*)-specimen were injection moulded whereas *FD*(*49*)- and *FD*(*non*)-specimen were extruded. All these three specimen groups showed nearly similar fibre content und they used the same plastics. Therefore, it can be theorized that losses in MOE caused by fungal decay are higher for injection moulded WPCs. An explanation by the author could be that extrusion in general covers the profile's surface with a thin plastics layer whereas fibres of moulded parts have contact to the exterior. To sum up, the "fittest" WPC against fungal decay most probably has a fungicide agent inside, a minimum of fibre content and should be extruded. Alternatively to the fungicides, the addition of flame retardants is beneficial to both fire resistance and protection against fungi.

In other papers pertaining to fungal decay, water uptake or mass decrease turn out to be appropriate indicators for the loss of strength. In this context, Clemons et al. [6] report that extruded specimens absorbed significantly more water than injection moulded ones. This is in contrast to previous findings because a higher water content would lead to more strength decrease in extruded products and not in injection moulded ones. In general, specimens which were soaked in water absorbed much less compared to boiled ones. Furthermore, the more water was absorbed the less is flexural strength. As far as strength decrease by fungal decay is concerned, the material's weight loss correlated well with losses in MOR. Using water uptake as indicator was also recommended by Fabiyi et al. [42]. 5 fibre species were tested and hybrid poplar and ponderosa pine showed highest weight losses whereas high lignin containing fibres, such as from Douglas fir, are hydrophobic and therefore reduce water uptake. It was also confirmed by them that hardwood, like black locust or white oak, enhance a WPC's durability. In addition to this, the weight loss by fungi was 2–3 times higher when using fibres from hybrid poplar and pine which gives credit to the conclusions drawn from Table 6. The last paper in this context was from Karta et al. [7] which examined the effect of different fibre sizes and the addition of zinc borate. In general, water absorption increased with the fibre content and weight loss by fungi was higher for WPC with smaller fibre size. This is coincident with the findings from the last section. However, the addition of zinc borate significantly reduces mass loss after inoculation which speaks for an appropriate use as fungicide particularly in WPC with high fibre content.

4.3. Results from the literature review about thermohygric conditioning

Research in the ageing behaviour due to thermohygric impacts was mainly driven by aspects about the used fibres and type of plastics. A paper from Adhikary et al. [43] in this context reports about recycled and virgin HDPE and PP. The effect of recycled plastics and the addition of bonding agents were of major interest. In addition, Pilarski and Matuana [44] investigated content and fibre source and their compound was the only using PVC in the matrix. Finally, Wang et al. [45] gave insights about rice hull as fibres and Tamrakar and Lopez [46] report about a conventional softwood-PP-mix which was exposed to thermohygric climate changes.

As can be seen from Table 8, the use of recycled plastics does not per se lead to comparative lower MOR values for both PP- and PE-based WPCs before and after weathering. Although it appears that recycling of plastics even contribute positively to initial strength values, their effect on MOE after weathering is significantly worse. It can also be seen hat a rPP-based matrix provokes higher MOR and MOE than using rPE. However, the story is different when specimens were exposed to thermohygric impacts. Here, PP significantly reduces MOR more than does PE. The effect on MOE is rather small. And finally, the addition of MAPP to recycled plastics lead to significant higher MOR-, but smaller MOE-values. MAPP's influence on strength preservation is only for rPP positive. However, its effect on MOE is basically worse. The use of maple hardwood instead of pine softwood makes at first no difference to initial MOR and MOE values. Surprisingly, the result does not change significantly after weathering. In addition, the strength decrease for both MOR and MOE correlates well with the fibre content. Specimens used by Adhikary et al. [43] were the only injection moulded. However, a comparison with the other papers under normalized values could not indicate a significant difference between the two production methods. Also the use of rice hulls does not reveal a disadvantageous effect compared to the other fibre sources. From a broader view, the use of PVC seems not significantly differ from initial strengths of PP- and PE-based compounds. However, in terms of weathered samples PVC appears to have a much better effect on MOE which speaks for a higher durability. All in all it can be concluded that the "fittest" compound under thermohygric impacts should use PE or PVC rather than PP and it should have the lowest fibre content possible. MAPP as bonding agent at least lead to higher MOR strength after weathering although it has no preservative effect.

4.4. Results from the statistical analysis

The last sections investigated how each of the three conditioning methods effects a particular WPC composition. To gain a broader overview about simulated ageing of WPC, a statistical analysis was conducted to answer the following questions: (1) How is the average degradation for MOR and MOE when taking into account all 44 variables, (2) how does each method contribute to the ageing of WPC?, (3) does ageing effect both dependent variables to the same extend?, (4) which are the basic conclusions for the development of suitable WPC cladding?

The intensity of a pre-conditioning method is given by the duration and the dose of impact. Both parameters were applied according norms which do not yet consider the façade application. However, in the previous papers the intensity of imposed impacts differed significantly. In order to make results comparable, the losses from MOR- and MOE-values were normalized with orientation on the highest dose. It is noteworthy to point out that a low contribution of a single conditioning method to the total strength decrease of a WPC's MOR and MOE does not necessarily mean that it is underrepresented and its intensity should therefore become increased. In this regard, insights from this analysis give orientation in further durability-related research which should clarify how a cladding's life-time can be simulated by appropriate doses of impacts.

Results from the statistics are depicted in Figs. 1–3. It was found that the decrease of initial material strength is strongly correlated with the opposed impacts. This can be concluded from a Pearson correlation of $\rho_{MOR} = 0.96$ and $\rho_{MOE} = 0.94$ between the strength before and after conditioning. The average strength loss over all 44 variables is $\overline{MOR}_{AW,FD,THI} = 26.1\%$ and $\overline{MOE}_{AW,FD,THI} = 36.5\%$. Obviously, MOE decreases more under weathering impacts than MOR. Histograms witnessed that MOE-values were similar to Gaussian distribution whereas MOR-values differed significantly. It can be theorized that the behaviour of MOE is more predictable than is the case for MOR. Furthermore, data from each weathering method revealed the following mean values: $\overline{MOR}_{AW} = 39.8\%$, $\overline{MOR}_{FD} = 11.8\%$, $\overline{MOR}_{THI} = 13.5\%$ and $\overline{MOE}_{AW} = 40.1\%$, $\overline{MOE}_{FD} = 23.5\%$, $\overline{MOE}_{THI} = 42.5\%$. Obviously, MOR suffers most from *AW* and the least from *FD* and *THI* whereas MOE degrades most under *THI* and *AW*. *FD* plays an intermediate role in both cases. The standard deviations (SD) indicate that the values vary extremely around the arithmetic mean. This gives credit to the fact that WPCs in general can hardly become standardised by a small number of reference values and each formulation needs appropriate testing to determine its characteristics. Given the three conditioning methods were applied to the same compound, *AW* again is the dominating conditioning method as depicted in Fig. 1. The sum of shares now makes 100%.

The target of a WPC cladding product development is to keep the degradation for MOR and MOE moderate and if possible well-balanced. Otherwise, strength calculations by the use of a low MOR-design value become impaired by serviceability calculations under high MOE-values. To find out which of the tested composites in the meta-analysis best meet both criteria, at first the strength loss [%] for MOR plus MOE was calculated for each specimen code and the 44 results were ranked. According to Fig. 2, the *AW*-variables are located rather towards the right hand side which indicates that *AW* contributes most to ageing as already stated by the statistics. Secondly, the difference between the strength losses of both dependent variables, given as $|MOR - MOE|$, was ranked as well. Results from Fig. 3 confirm that in most cases *AW* equally influences MOR and MOE. The first two variables which best meet the development criteria of low and equal degradations are *AW*(*bP/50*) and *THI*(*25/Pi*). The former has a PE-based matrix with an average contend of unbleached fibres and the latter has PVC inside by even lower fibre content. Both were part of the identified "fittest" WPC in Section 4.1 and 4.3.

In a wider context it can be argued that all three weathering methods more or less are equally responsible for WPC's ageing which confirms that they should be applied in the elaboration of appropriate conversion factors. It does appear that accelerated weathering similarly effects MOR and MOE and comparably more than thermohygric conditioning. Fungal decay however takes an intermediate position.

The previous conclusions derived from each pre-conditioning method and from the statistical analysis can be summarized by the following recommendations. They fill the gap that exists for the development of durable WPC cladding and a design value for strength calculations:

(a) *Production process:* Extrusion has a promotive influence on MOE and does not significantly worsen MOR. This positively affects a WPC façade design.
(b) *Plastics:* PE has a tendency to much better cover weathering impacts which helps to keep the conversion factor η rather moderate. The beneficial use of PVC was only confirmed by THI-related tests.
(c) *Additives:* Some flame retardants have a fungicidal property and can effectively replace fungicides particularly for façades which have no permanent contact to earth. Anti-oxidants and light stabilizers are effective against UV-impacts, however dark colour pigments have a high potential to replace these costly agents. Darker façades therefore are expected to last longer than light coloured surfaces.
(d) *Fibres:* Thicker fibres from hardwood and Douglas fir in rather moderate contents are beneficial for a WPC's durability and this also reduces η and increases the design value R_d.
(e) *Life-expectations:* Given that fungal decay goes along with thermohygric climates and degradations under *AW* hardly differ from those provoked by *THI* plus *FD* it can then be argued that cladding will degrade equally in Northern and Mediterranean regions.

All listed principles thus have a value adding effect on the development of WPC cladding products which successfully answers question 3 and 4 from section 1 of this paper.

5. Conclusions

By today there is no applicable concept according which bio-based plastics can be developed for the purpose of high durability in façade applications as demanded by building codes. Therefore, this paper attempts to understand the ageing process of WPC. At first, relevant norms and guidelines in the field of WPC compound and façade application were reviewed to find out about the applicable durability-related tests for WPCs. It was found that three basic standard methods are mainly used in type tests which are (1) accelerated weathering by UV-radiation to degrade the plastics matrix, (2) fungal decay tests to impair the biological components in WPC and (3) thermohygric weather cycles to reduce bonding between fibre and matrix by swelled and frozen fibres. To evaluate the structural performance of WPC in façades, MOR is used for the derivation of appropriate design values which in conjunction with MOE build the basis for strength and serviceability calculations. Based on these insights, a literature research identified 12 papers which served a meta-analysis to find out about dependencies between material components or production methods and the strength loss due to the identified weathering methods. In total 44 selected variables were employed in an assessment which revealed that by trend extrusion, the use of PE as matrix, a low content of rather thick hardwood fibres and dark colour additives have a favourable effect on the WPC's durability. Notably, the use of flame retardants which are necessary anyway in this kind of application also enhances the resistance against fungal decay. All three kinds of weathering impacts decrease MOE more than MOR. Artificial accelerated weathering has the highest influence followed by thermohygric cycling and fungal decay. A conversion factor η which transfers test results to a MOR- and MOE-design value for the practice should therefore similarly consider all three conditioning methods. A partial ageing-factor pertaining to each method can be the ratio of MOR and MOE resulting from weathered- and non-weathered specimen. The partial factors then should become condensed to a global ageing-coefficient to be applied to Eq (2).

In closing, additional investigations are recommended to verify the revealed development principles by applying all three conditioning methods to the same specimens. Further studies should be directed to clarify how the three partial ageing coefficients should be condensed to a global value which best meets the durability expectations of façades.

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