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# An analytic algorithm-based method to assess the long term structural performance of wood-polymer composites

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ABSTRACT

Wood-polymer composites (WPC) increasingly gain in popularity in the building industry. However, such bio-based materials suffer from weathering which limits their lifetime. To learn more about the difference between natural and artificial ageing, compounds from 12 research papers were analyzed with regard to their strength development depending on exposure duration and fiber loading. In total 117 comparisons were drawn between data from both types of durability testing from which the acceleration and deceleration factors were derived. It was found that for usual WPC formulations weatherometer trials according to EN ISO 4892 represent 7.35 times longer periods under natural conditions. Further, the quality of data was an enabler for the development of algorithms which comprehensively detected that lifespan for 30%-fiber loaded compounds is 1.7-times longer compared to those with 45% fiber share. Hence, the findings point out that compound development for WPC needs strong orientation on the intended application.

## 1. Introduction

Wood-plastic Composites (WPC) represent a new generation bio-based building materials which contain up to 80% fibers from natural feedstock [1]. This makes it sustainable and helping preserving scarce crude oil reserves [2]. By today, cladding and decking count to the main applications where WPC is used outdoor under load impacts [3]. Products are mainly manufactured by extrusion technology where the compounds are re-melted, pressed through a die and cooled down afterwards in a water bath. Formulations for usual WPC compounds show a mix of thermoplastics, such as polyethylene (PE), polypropylene (PP) and polyvinylchloride (PVC) in which mostly wood fibers and wood flour are encapsulated. Since fibers are hydrophilic and plastics are hydrophobic, coupling agents as maleic anhydride grafted polypropylene (MAPP) is used for better bonding [4]. This significantly enhances stress transfer into the material [5]. Further, the addition of particular additives for coloring, stabilizing and improving special material properties are employed depending on the application [6]. In outdoor environment, color pigments should be inorganic since high weathering resistance becomes essential [7]. Structural safety is of paramount interest in the building scope and durability in most cases is expected to comprise decades. Hence, WPC formulations must be invented under intensive material and performance testing. In this regard, Friedrich [8] researched ageing effects for WPC compounds by meta-analysis using 44 empiric data collected from publications in this field. It was found that under UV-radiation applied in weatherometers, the strength decrease expressed by indicators like modulus of rupture (MOR) and modulus of elasticity (MOE) makes in average 25%. Exposure duration varied between 21 days and 125 days and ageing manifests itself as a function of exposure time. Particularly in façades mechanical stability is a key parameter for the structural engineer's design. However, it is yet not satisfyingly investigated if MOR- and MOE-declines of WPC material are the only factors which give an idea about the long-term product performance. Large scale laboratory testing by multi sampling with several plastics-based cladding products under simulated wind suction pointed out that mostly not the bending rupture of the panel itself but pull-out of fixations through the WPC material is the basic mode of WPC façade failure [9]. Although testing for a cladding fastener's resistance is well described for WPC by the material base norm EN 15534-1 [10], penetrating insights about this specific material and product characteristic are still lacking. However, investigations in MOR-related WPC ageing at least attempt to understand how the material reacts on endogenous physical impacts like UV and humidity. If pull-through resistance dominates the WPC cladding application, then bending resistance somehow plays its role as well. In this context, again Friedrich [9] revealed from relevant testing that WPC bending resistance around the fixation's head close to the panel's edge significantly influences the large scale façade performance. However, testing oversize façade sections in weatherometers is not possible since the interior of such chambers is simply too small.

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**Nomenclature**

| | |
|---|---|
| MOR | Modulus of Rupture; [MPa] |
| $MOR{\downarrow}^{art\ (nat)}$ | Decline of initial MOR after artificial (natural) weathering; [%] |
| $t^{art\ (nat)}$ | Exposure time of specimens to artificial (natural) weathering; [h] |
| $\mu^{art\ (nat)}$ | Fiber content of WPC specimens from the artificial (natural) weathering group; [-] |
| i | Number of a specimen from the artificial weathering group which exact positon within the μ-t-matrix is determined by row number n and line number m where n belongs to fiber content μ and m to exposure time t |
| j | Number of a specimen from the natural weathering group which exact positon within the μ-t-matrix is determined by row number n and line number m where n belongs to fiber content μ and m to exposure time t |
| $\bar{MOR}^1{\downarrow}^{art}$ | Decline of $MOR{\downarrow}^{art}$ after 1st step adaption to the fiber content μ of a comparison value $MOR{\downarrow}^{nat}$; [%] |
| $\bar{MOR}^2{\downarrow}^{art}$ | Decline of $MOR{\downarrow}^{art}$ after 2nd step adaption to the exact $MOR{\downarrow}^{nat}$-value by modification of exposure time; [%] |
| $\bar{t}^{\ art}$ | Modified exposure time which provokes the value $\bar{MOR}^2{\downarrow}^{art}$; [h] |
| $\bar{MOR}^1{\downarrow}^{nat}$ | Decline of $MOR{\downarrow}^{nat}$ after 1st step adaption to the fiber content μ of a comparison value $MOR{\downarrow}^{art}$; [%] |
| $\bar{MOR}^2{\downarrow}^{nat}$ | Decline of $MOR{\downarrow}^{nat}$ after 2nd step adaption to the exact $MOR{\downarrow}^{art}$-value by modification of exposure time; [%] |
| $\bar{t}^{\ nat}$ | Modified exposure time which provokes the value $\bar{MOR}^2{\downarrow}^{nat}$; [h] |
| $\alpha^{dec}$ | Deceleration factor describing how many times longer t from artificial weathering becomes when matching the same MOR↓-value under natural weathering; [-] |
| $\alpha^{acc}$ | Acceleration factor describing how many times shorter t from natural weathering becomes when matching the same MOR↓-value in a weatherometer; [-] |
| ε | Difference in fiber content or exposure time of two specimens within the μ-t-matrix which both take a neighbor position to each other; [-] or [h] |
| $\bar{\alpha}^{\ dec}$ | Mean from a series of single α-values where each is the result from an exposure time-based comparison between the i-th $\bar{MOR}^2{\downarrow}^{art}$-value and each single $MOR{\downarrow}^{nat}$-value; [-] |
| $\hat{\alpha}^{dec}$ | Global deceleration factor as mean over all series which elaborated $\bar{\alpha}^{\ dec}$; [-] |
| $\bar{\alpha}^{\ acc}$ | Mean from a series of single α-values where each is the result from an exposure time-based comparison between the j-th $\bar{MOR}^2{\downarrow}^{nat}$-value and each single $MOR{\downarrow}^{art}$-value; [-] |
| $\hat{\alpha}^{acc}$ | Global acceleration factor as mean over all series which elaborated $\bar{\alpha}^{\ acc}$; [-] |
| u | Number of MOR↓-values from the artificial weathering group subjected to comparisons with v values from the other group |
| v | Number of MOR↓-values from the natural weathering group subjected to comparisons with u values from the other group |
| s | standard deviation; [-] |

Therefore, the exposure of small specimens to artificial weathering still represents the most practical and cost-efficient way how to quantify ageing of WPC. Nevertheless, if the scale-effect makes basic conclusions about a WPC façade's long term performance less reliable, then testing natural weathering against artificial conditions is acknowledged as a way to make the difference between both testing modes more discernible. In the further, weatherometers then should replace time consuming outdoor trials. If so, further information is essential about how many days of natural weathering equals a particular period in weatherometers where UV-dosage of 60 W is usually applied [11]. However, test results from outdoor trials strongly depend on local weather conditions and as such amount of consumed UV-radiation and humidity. Even if water spraying in weatherometers intends to simulate such realistic conditions, it is hard to determine the short-term exposure duration in climate chambers in order to predict a particular long-term outdoor performance. Factors which accelerate such multi-year exposures or decelerate artificial durations can only be derived from multiple outdoor and chamber tests in order to make conclusions maximal consistent. Further, it is necessary to assess reliability of empiric data in this field since the circumstances under which natural weathering trials were executed widely scatter.

To see clearer in this affair this paper reports from a study directed to investigate the acceleration- and deceleration factor for common and comparable WPC formulations derived from papers by comprehensive literature review. Since compounds differ by the nature and amount of additives, only those without any UV-stabilizers and comparable agents were taken for the meta-analysis. Further, formulations and their related strength decline under artificial and natural exposure were grouped by fiber content and exposure duration. By so, an extensive data basis was collected with which statistical significance, time lapsing and algorithms describing the time- and fiber-depending strength decline were derived under mathematical approach. The remainder of this paper is organized as follows: (1) the origin of empiric data and their quality is described, (2) the analytical model is synthesized, (3) basic findings and their bi-axial relationship between weathering type and fiber content are discussed and (4) a formula is presented which satisfyingly calculates future compound strengths in outdoor applications.

## 2. Methodology

### 2.1. Data source and quality

Independent from the location and type of weathering, at the first glance most papers pertaining to WPC ageing tell about significant strength decreases and compatibilizers, lubricants and UV-stabilizers reveal good potential to slow down ageing by better bonding between fibers and matrix during weathering. However, the review also pointed out that the type of plastics not excessively influenced MOR-drops but, besides additives and agents, fiber share and exposure time did so. Hence, the study on hand uses data from six papers in the field of accelerated weathering and the same number from studies about outdoor trials and each employed zero-samples as compounds which were free from any additives. In order to keep influences from different constituents to a minimum, all data in this study are derived from such zero-samples which consequently renounce on stabilizers and therefore are similarly equipped with plastics and fibers only. Table 1 and 2 provide an overview on all reported figures with which comparisons were drawn between MOR-drops. Thus, data were derived from two different weathering types and particularly natural weathering trials were distributed around the equator. As can be seen from both tables, *t*-tests among the variables MOR↓ and exposure time t or fiber content μ revealed high statistical relevance for each weathering type. Hence, data showed sufficient quality for mathematical processing.