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Influence of Climatic Factors on the Weathering of Coated Wood

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To evaluate a new test method for accelerated natural weathering of exterior wood coatings and European standardization a round robin test was carried out on nine different locations in Europe. Part of the evaluation consisted of investigating the relationship between the weathering results and the meteorological conditions on each site. The aim is to develop a climatic index, reflecting differences in severity of climate in different areas within Europe with respect to the weathering of coatings on wood. Preferably the relationship should be uniformly applicable to all coatings systems, making it possible to transfer test results from one location to another using this climatic index, in order to reduce the need for natural weathering tests on different sites. From the preceding literature study, in which the climate elements relevant for ageing effects of exterior wood coatings have been characterised, it was concluded that a climate index relevant to this purpose should be composed of global irradiation, total precipitation and number of days with more than 0.1 mm precipitation. For all tested coating systems together the correlation between the calculated climatic index and weathering results appeared to be very poor. No unambiguous relation could be found, which was valid for all systems. Thus, transferring weathering results from one location to another, independent of the coating system, does not seem possible on the basis of these results. When seperating the results obtained from the standardized coating 'Internal Comparison Product (ICP)', the relationship was considerably better. Transferring results by means of the ICP could therefore constitute a more suitable approach. Of the climate factors involved, only global irradiation showed reasonable correlation to the weathering results. Including the data on precipitation hardly improved the model.

Einfluss von Klimafaktoren auf die Verwitterung von beschichtetem Holz

Um eine neue Methode der beschleunigten Bewitterungsprüfung für Holz im Aussenbau im Hinblick auf eine europäische Norm zu beurteilen, wurde ein Ringversuch auf neun verschiedenen Standorten in Europa durchgeführt. Ein Teil der Arbeit bestand in der Untersuchung des Zusammenhangs zwischen den Resultaten der Bewitterungsprüfung und den meteorologischen Bedingungen an jedem Standort. Das Ziel war, einen (empirischen) Klimaindex zu entwickeln, der die Intensität des Klimas in verschiedenen europäischen Regionen in Bezug auf die Verwitterung von Holzbeschichtungen quantitativ beschreibt. Dieser Index soll möglichst einheitlich auf alle Beschichtungssysteme anwendbar sein, so dass es möglich wird, mit seiner Hilfe Testresultate von einem Standort auf einen anderen zu übertragen; dadurch soll der Aufwand für Bewitterungsprüfungen auf unterschiedlichen Standorten reduziert werden. Mit einer Literaturstudie wurde zunächst untersucht, welche Klimaelemente relevant sind für Alterungseffekte von Holzaussenbeschichtungen. Als Schlussfolgerung wurden die Klimagrössen Globalstrahlung, Gesamtniederschlag und Anzahl der Tage mit einem Niederschlag von mehr als 0.1 mm für die Formulierung eines solchen Klimaindex ausgewählt. Bei allen getesteten Beschichtungssystemen war die Korrelation zwischen dem errechneten Klimaindex und den Ergebnissen der Bewitterungsprüfung sehr schwach. Es wurden keine eindeutigen Zusammenhänge gefunden, die für alle Beschichtungen gültig waren. Daher scheint eine Übertragung der Resultate von Bewitterungsprüfungen von einem Standort auf einen anderen, unabhägig vom Beschichtungssystem, auf der Basis dieser Studie nicht möglich. Wenn die Bewitterungsresultate, die mit einem (für die EN-normierte Prüfung) standardisierten Beschichtungssystem 'Internes Vergleichsprodukt (ICP)' erzielt wurden, separat betrachtet, ist der Zusammenhang mit dem Index wesentlich besser. Die standortbezogenen Bewitterungsresultate mit Hilfe nur des ICP zu untersuchen, könnte daher ein besserer Ansatz sein. Hier zeigte von den einbezogenen Klimafaktoren nur die Globalstrahlung eine signifikante Korrelation mit den Bewitterungsresultaten. Ein Einschluss der Niederschlagsgrössen verbesserte das Modell kaum.

Annex I: List with abbreviations

ADHES/C	Adhesion, close to the defect
ADHES/R1	Adhesion, remote from (under) the defect
ADHES/R2	Adhesion, remote from the defect

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BLISTDENS	Blistering density
BLISTSIZE	Blistering size
CD	Colour difference (D65)
CHALK	Chalking
COLDIFF	Colour difference (D65)
CRACDENS/C	Cracking density, close to the defect
CRACDENS/R	Cracking density, remote from the defect
CRACSIZE/C	Cracking size, close to the defect
CRACSIZE/R	Cracking size, remote from the defect
DP	Number of days with precipitation more than 0.1 mm
FLAKDENS/C	Flaking density, close to the defect
FLAKDENS/R	Flaking density, remote from the defect
FLAKSIZE/C	Flaking size, close to the defect
FLAKSIZE/R	Flaking size, remote from the defect
GD	Gloss difference
GD%	Gloss difference, calculated as % of original gloss
GI	Global irradiation (kWh/m^2)
GLOSSDIFF	Gloss difference
GLOSSDIFF%	Gloss difference, calculated as % of initial gloss
MOULDENS/C	Mould density, close to the defect
MOULDENS/R	Mould density, remote from the defect
MOULSIZE/C	Mould size, close to the defect
MOULSIZE/R	Mould size, remote from the defect
PRECIMUL	PRECIP01 X PRECISUM
PRECIP01	Number of days with precipitation more than 0.1 mm
PRECISUM	Sum of precipitation (cm)
SP	Sum of precipitation (cm)
STAINDENS/C	Staining density, close to the defect
STAINDENS/R	Staining density, remote from the defect
STAINSIZE/C	Staining size, close to the defect
STAINSIZE/R	Staining size, remote from the defect

1
Introduction

A major disadvantage of natural weathering of coatings is the fact, that exposure conditions differ for every location, depending not only on the prevailing climate of a certain site, but also on the specific climatic conditions during the actual exposure period. In other words, results of natural weathering tests depend on *where* and *when* the tests are done and in principle cannot be transferred to or reproduced at other sites. If the performance and durability of an exterior wood coating system has to be fully investigated, it should therefore be exposed on several locations with explicitly different climatic conditions.

The aim of this research is to establish the existence of a correlation between the results of measurements and assessments made on the test panels on one hand and the climatic conditions on weathering sites – expressed as a *Climatic Index* – on the other. In the index the main climatic factors influencing natural weathering of exterior wood coatings had to be incorporated. Having found such a relation, the use of a Climatic Index for each location then makes it possible to transfer the results of one test site to another location with known climatic conditions. Thus the amount of testing needed for a good understanding of weathering resistance of a specific wood coating at other sites in Europe would be greatly reduced. Such a development would be of great benefit in the development of European standards on the performance testing of wood coatings.

The objectives of the present research are:

- determining the relevant climate elements, which interact with the wood substrate/coating system and cause the ageing effects of wood coatings;
- describing how these climate elements might quantitatively be characterised within the different European zones of climate;
- suggesting suitable climatic indices consisting of the relevant climate elements;
- relating the calculated climatic index of the sites to the results of the natural weathering test and suggesting a suitable method to transfer the results to other sites.

2
Theoretical background

The ageing processes of wood and wood coatings exposed to the weather are intensively studied. Comprehensive summaries on the present knowledge are given by Feist and Hon (1984) and – more practically – by the American Wood Handbook (Anon. 1987). Sell and Zimmermann (1995) state that, generally speaking, the most important interactions between the weather and coated wood are based on (photo)chemical, physical, and biological mechanisms as it is summarised in Table 1. All these elements of a climate and the resulting ageing mechanisms depend on and influence each other with great complexity and intensity which in turn depends to a major extent also on the properties of the coating and the wood substrate.

Thus, it is understandable that it is quite difficult – or even impossible – to quantify the intensity of the *single* elements of the weather with respect to their effect on the performance and durability of coatings on wood or coated wood, respectively. On the other hand, it is obvious that solar radiation i.e. UV (and parts of visible) light and global (thermally effective) radiation plus precipitation are dominant with respect to weathering mechanisms of, and within, coated wood. Therefore, a semi-quantitative or quantitative classification of weathering conditions is bound to incorporate these climatic elements.

During the last two decades, only a few comparative natural weathering studies of exterior wood finishes have been published. These studies had the main goal to compare the results of weathering tests with both different wood species and coatings exposed on climatically different exposure sites. Probably most different climates have been included in an "Australian test for decay in painted timbers exposed to the weather" (Beesley et al. 1983). About 25 sites in all climate zones of this continent and, additionally, 3 sites in the tropical Papua New Guinea were chosen for the exposure of test panels. However, in order to avoid any influences of the condition of the coating on the intensity of decay of the panels, the paint system has been renovated when weathering effects such as flaking and cracking have been observed. Thus, this study did not result in information about the influence of the extremely

Table 1. Overview the most important interactions between the weather and coated wood
Tabelle 1. Übersicht über die wichtigsten Wechselwirkungen zwischen Wetter und beschichtetem Holz

Mechanisms of ageing and disfigurement	Responsible elements of the climate	Effects on coated wood
Photochemical degradation, mostly of lignin	UV light and parts of visible light (short wave-length)	failure of the coating and discoloration and fissures of wood surface if coating is (partially) transparent
Physical mechanisms, particularly excessive changes of wood MC	thermally reactive part of sun radiation, air humidity, precipitation (partially)	dimensional changes, internal stresses, cracking of wood and coating
Erosion processes	rain, wind, driving rain	erosion of the coating film and subsequently of wood
Biological processes	mould fungi, 'blue stain', depending on presence of liquid water (rain) and high RH	

different Australian climates (from dry desert to tropical rainforests) on the durability of the coating.

From 1983 to 1985 a 24 months round robin test has been carried out by 4 European wood research institutes (Roux et al. 1988). The goal was to compare four different stains and paints, respectively, and non-coated samples of five different wood species. Despite substantial climatic differences between the four locations, the results of the exposure differed only little, although the changes of the wood moisture content measured monthly were significantly different. Since the intensity of wood moisture content changes is believed to be one of the key parameters of the intensity of weathering coated wood, this result is not easy to explain. A similar round robin test has been realised from 1984 to 1989 (Kropf et al. 1993; 1994) comparing the performance of exterior paints on weather-exposed wood surfaces in the United States and western Europe. Despite the differences in the performance of the different coatings tested on 4 wooden substrates, only little differences between the two sites have been observed, similarly to the comparison test mentioned above. Since 1990, three further European round robin tests have been performed in several countries within the framework of CEN standardization (Abrahams 1994; Abrahams and Graystone 1996; Svane 1992, de Meijer et al. 2001). Several locations were included, representing climatic regions ranging from northern maritime to mediterranean, and differing substantially in terms of annual duration of sunshine, annual sum of global radiation, annual sum of precipitation, and annual number of days with precipitation more than 0.1 mm. Although the averages of these climate characteristics on some of the sites are nearly two times as high as on others, the results of these round robin tests differed much less.

In the past, a few attempts were made to develop a classification system for climatic stresses of building structures. The major aim was to categorise the intensity of decay hazard for wooden constructions by means of the intensity of the climatic elements. As far as known, Scheffer (1971) was the first one proposing such a system of hazard classification for the climate regions of the USA. Based on the idea that decay risk would be mainly ruled by temperature and moisture influences, he developed an empirical equation for a climate index (CI) based on the air temperature and on the number of days per month with a certain minimum precipitation. Within the framework of the comprehensive Australian study mentioned above, Beesley et al. (1983) found a correlation, although weak, between the Scheffer CI and the incidence of decay of various painted test panels exposed to about 27 very different climates.

Given the fact that the present research is mainly dealing with surface weathering effects, it must be concluded that Scheffers' climate index is not satisfactory here, mainly because it does not include the UV radiation which is decisive for the ageing of wood surfaces and wood coatings. Unfortunately, even a thorough computer research of the relevant literature did not generate information on a specific climate index for coated wood consisting of data upon UV radiation, global (thermally effective) radiation, and rainfall. Sell and Zimmermann (1995) describe the increasing availability of European climate data on sun radiation and precipitation. However, compared with global radiation and precipitation, the collection of UV-radiation data constitutes a problem, because they are not readily available for every location. Since UV(-A) radiation correlates well with global radiation it was decided to leave UV-radiation out. The remaining climate data were then more or less empirically combined. To obtain a suitable climatic index the following equation was proposed:

$$C.I. = \frac{I_{global}}{20} + \frac{n_r \times R_{sum}}{500} \qquad (1)$$

with:

$C.I. =$ Climatic Index
$I_{global} =$ global irradiation on planes tilted 45°, facing south (kWh/m^2)
$n_r =$ number of days with precipitation more than 0.1 mm
$R_{sum} =$ annual sum of precipitation (cm)

The numbers 20 and 500 are introduced as denominators in the fractions to weigh the relative importance of radiation and rainfall, and to keep the resulting climate index for the European sites around 100.

3 Methodology

3.1 Natural weathering test

As part of a larger round robin test, pine sapwood *(Pinus sylvestris)* panels with eight different coating systems were exposed to the weather on nine locations spread over Europe for a period of one year, inclining 45° and facing south. The actual exposure took place from December 1995 until December 1996, with some minor differences between the sites.

The selected coating systems included both high- and low quality products and they were chosen to reflect different European traditions. A brief description is given in Table 2. According to prEN 927-3 (draft version of 1995, named 927-2 at that time) for each coating system eight panels were prepared, half of which was coated with the system under consideration, and the other half with an Internal Comparison Product (ICP). Of each eight panels, two (1 system, 1 ICP) were kept indoor as unexposed references. The panels had dimensions of 375 × 120 × 20 mm. To accelerate the natural weathering an artificial defect was inflicted in the middle of one flat side by milling a circular recess (diameter 25 mm, depth 5 mm) through the coating. In order to avoid introducing extra variation, panel preparation, application of coatings, and initial and final assessments of all panels were all done by one institute.

On the panels the following measurements and assessments were made: 60°-gloss and colour (D65) difference, blistering, cracking, flaking, chalking, adhesion, mould growth, and staining, according to prEN 927-3. Cracking, flaking, mould growth, and staining were all assessed with regard to both density and size of the defects. Also, they were assessed close to, as well as remote from the artificial defect in the panel, as was adhesion.

With regards to gloss an extra variable was calculated: gloss difference %, expressing the loss of gloss as a percentage of the initial value, thus eliminating structural differences in gloss between the coating systems. In the following statistical analyses only the data for panels known to have actually been exposed were included. ICP-panels were recoded in such a way that they constituted a 9th coating system in addition to the eight coatings tested.

3.2 Climatic data

Of the climatic data needed, global irradiation on 45° tilted planes would coincide well with the actual weathering position of the panels, but proved impossible to obtain for most locations. Instead the global irradiation on horizontal planes (0°) was used, which is a more commonly measured meteorological phenomenon. As expected, available data showed that both types of radiation data are closely related, so this choice would not influence the calculation of the proposed climatic index.

The actual weather data for the exposure period partly came from the project partners themselves and were partly requested from several national meteorological services.

In Table 3 the collected data are presented, including a climatic index calculated on the basis of the actual data

Table 2. Description of coating systems
Tabelle 2. Beschreibung der Beschichtungssysteme

Code	Binder type	Paint type	Colour	Carrier
PUL	poly-urethane	clear laquer	none	solvent
PUP	poly-urethane	opaque paint	white	solvent
ACP	acrylate	opaque paint	white	water
ACS	acrylate	semi-transparent stain	'teak'	water
AAP	alkyd/acrylate	opaque paint	white	water
ALS	alkyd	semi-transparent stain	'teak'	solvent
ALP	alkyd	opaque paint	white	solvent
ALP2	alkyd	opaque paint	white	solvent
ICP	alkyd	semi-transparent stain	red-brown	solvent

Table 3. Meteorological data (known Multi-Year-Averages in italics)
Tabelle 3. Metereologische Daten (Mehrjahresmittel MYA kursiv)

Institute	Country	Weather Station	Total radiation KWh/m^2		Precipitation cm		# days with precipitation > 0.1 cm	C.I. (eq.1)
			Actual	*M.Y.A.*	Actual	*M.Y.A.*		
Scotlab	UK	Drumalbin Glasgow	900		89.0	*110.9*	200	80.6
DTI	UK	Rosklide Kastrup	1020	*1015*	36.5	*60.2*	98	58.2
BRE	UK	London Heathrow	1009	*921*	42.5	*59.3*	151	63.3
Forbairt	IRL	Dublin Airport	938		80.6	*76.4*	199	79
WKI	DE	Braunschweig	973	*972*	51.7		135	62.6
VTT	FIN	Helsinki Airport	949		75.4	*64.7*	160	71.6
EMPA	CH	Zurich Reckenholz	1103	*1086*	98	*109*	164	87.3
SHR	NL	Deelen Airport	938		62.8	*76.5*	136	64
Catas	IT	Capriva Del Friuli	1335		164.5	*96.7*	162	120

according to equation 1. As stated before, these figures refer to the known actual exposure periods as much as possible, mostly from January to December 1996. It can be seen that there are considerable differences between the sites, with global irradiation ranging from 900 to 1330 kWh/m^2, total rainfall from 35 to 165 cm and number of days with precipitation more than 0.1 mm from 100 to 200. Also the deviations from the multi-year-averages are quite clear, which supports the conclusion that actual data should be preferred above averages. The location of the different test sites is given in Figure 1.

4

Results and discussion

Data handling consisted of two steps: statistical evaluation of assessment differences between sites being significant, and if so, establishing a correlation, if any, between climatic data and weathering results. The calculated means for each variable per system and per site are presented in a previous publication (Creemers et al. 1998) Annex I gives a list with abbreviations for the criteria assessed, which is equally useful when studying the tables with statistical data in this paragraph.

4.1

Evaluation of differences between sites

In statistical evaluations the method of Analysis of Variance (ANOVA) is widely used. This method is based on assumptions of a normal distribution and homogeneity of variance of data. However, neither for the visual assessments nor for gloss and colour difference these assumptions could be met completely when looking at differences per system and per site. No data transformation could solve the problem, even when only considering the ICP with its larger number of observations.

For colour difference and gloss difference(%) the problem was mainly caused by unequal variances of the data over the sites. However, their overall frequency distributions were close to normal, which led to the decision to treat them as if being normally distributed. Consequently, the visual assessments were analysed with non-parametric tests, which do not require a normal data distribution or homogeneity of variance.

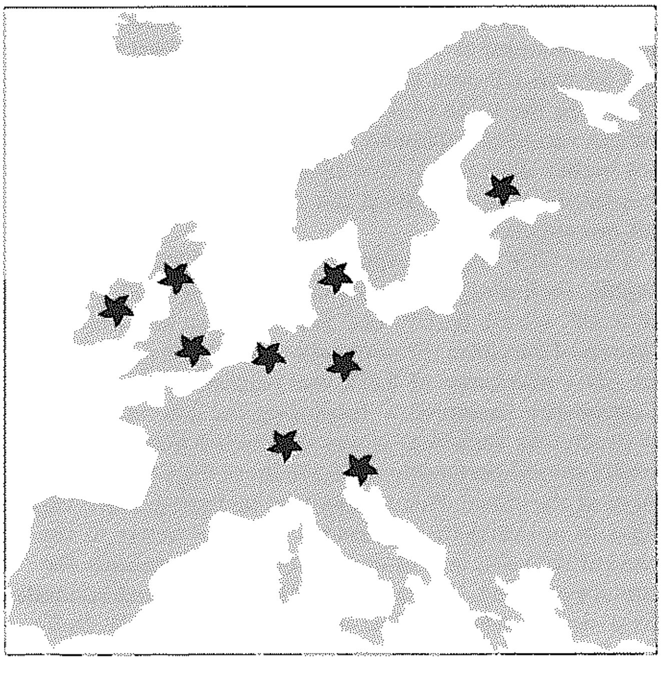

Fig. 1. Location of different test-sites
Bild 1. Lage der verschiedenen Testgebiete

4.1.1

Colour and gloss difference

Evaluating colour difference (CD), gloss difference (GD), and gloss difference % (GD%) with the ANOVA-method means trying to assess statistically the contribution of several variables (effects) to the variation in these factors. The more variation in a factor can be attributed to a certain variable, or, more commonly spoken, the more variation 'is explained' by the variable, the more this variable is likely to be the major cause of this variation. This likelihood is furthermore expressed as 'significance at the α%-level', with α mostly ranging from 5 to 0.1, the lower the value, the more likely.

In doing this for all systems with *site* as the only influencing variable, site proved to be a significant effect even at the 0.1%-level, but only accounting for 11, 20, and 29% of the variation respectively. Combining site with coating *system* as a second main effect greatly improved the model with 87, 71, and 62% of the variation explained. Although still significant, the contribution of 'site' as an effect however either slightly diminished or remained at about the same level, while 'system' contributes considerably more (see Table 4).

4.1.2

Visual assessments

Because of the non-compliance with the assumptions for ANOVA a non-parametric statistical test had to be used to study the visual assessments for significant differences between sites. When evaluating several independent samples this comes down to the so-called Kruskal-Wallis test, using the test statistic χ^2 (Chi-Square). The larger χ^2 is, the smaller the resulting significance becomes, and the more probable it is that there really are differences between sites. These differences may exist among several sites, but it is also possible that there is only one site differing from all the others. In this test a significance less than 0.05 points strongly towards differences existing. Results are shown in Tables 5a and b, including checks for CD, GD and GD%, and the test carried out for all exposed panels of systems 1–8 as well as ICP-panels only.

Apart from CD, GD and GD% there are several assessments which show significant (< 0.05) differences over the sites, amongst which are blistering density, chalking, cracking density close to the defect and mould density. The distinction between using the data for all exposed panels of systems 1–8 or for ICP-panels only does improve the evaluation slightly in terms of higher and more significant χ^2-values.

Table 4. Analysis of variance: Effects of site and coating system on CD, GD, and GD% (all systems)
Tabelle 4. Varianzanalyse: Einfluß des Standorts und der Beschichtung auf die Parameter CD, GD und GD% (für alle Systeme)

Factor	Variable/effect	% of variation explained	Significance
colour difference (CD)	SITE	9	< 0.1
	SYSTEM	76	< 0.1
	Site/System Combined	87	< 0.1
gloss difference (GD)	SITE	20	< 0.1
	SYSTEM	51	< 0.1
	Site/System Combined	71	< 0.1
gloss difference % (GD%)	SITE	28	< 0.1
	SYSTEM	33	< 0.1
	Site/System Combined	62	< 0.1

Table 5a, b. Results of Kruskal Wallis tests for all systems (a) and for ICP only (b)
Tabelle 5a, b. Ergebnisse des Kruskal-Wallis-Tests für alle Beschichtungssysteme (a) bzw. nur ICP (b)

Dependent Variables	Statistics	
	Chi-Square	Significance
System 1–8		
ADHES/C	5.450	0.709
ADHES/R1	15.952	0.043
ADHES/R2	9.377	0.312
BLISTDENS	94.773	0.000
COLDIFF	13.527	0.095
CHALK	4.859	0.000
CRACDENS/C	74.403	0.000
CRACSIZE/C	58.959	0.000
CRACDENS/R	6.161	0.629
CRACSIZE/R	30.345	0.000
FLAKDENS/C	8.627	0.375
FLAKSIZE/C	10.910	0.207
FLAKDENS/R	0.704	1.000
FLAKSIZE/R	6.250	0.619
GLOSSDIFF	24.488	0.002
GLOSSDIFF%	31.622	0.000
MOULDENS/C	37.766	0.000
MOULSIZE/C	15.338	0.053
MOULDENS/R	27.236	0.001
MOULSIZE/R	3.952	0.861
STAINDENS/C	6.500	0.591
STAINSIZE/C	30.431	0.000
STAINDENS/R	16.778	0.033
STAINSIZE/R	21.957	0.005
System 9 (ICP) only		
ADHES/C	69.210	0.000
ADHES/R1	19.441	0.013
ADHES/R2	12.309	0.138
BLISTDENS	187.630	0.000
COLDIFF	169.121	0.000
CHALK	52.891	0.000
CRACDENS/C	90.038	0.000
CRACSIZE/C	51.299	0.000
CRACDENS/R	15.623	0.048
CRACSIZE/R	31.015	0.000
FLAKDENS/C	0.000	10.000
FLAKDENS/R	0.000	10.000
GLOSSDIFF	137.488	0.000
GLOSSDIFF%	137.305	0.000
MOULDENS/C	149.543	0.000
MOULSIZE/C	18.556	0.017
MOULDENS/R	177.621	0.000
MOULSIZE/R	7.765	0.457

4.2
Correlating weathering results to climatic data

4.2.1
Colour and gloss difference

Regression analysis was carried out for CD, GD, and GD% with global irradiation (GI), sum of precipitation (SP) and number of days with precipitation more than 0.1 mm (DP) as predictors. The correlation coefficient R is a measure how well the resulting regression line fits the data. Its values preferably are close to +1 or −1, values close to 0 being an indication of no relation at all. If all panel data are taken into account (Table 6, left column) GI proves to be the best predictor for all three properties, as including SP and DP hardly improves the correlation coefficient. Using the three predictors in the form of the proposed climatic index: GI + (SP × DP) also does not raise the level of correlation. The absolute value of R ranging from 0.276 to 0.528 can hardly be called impressive. Excluding the ICP, resulting in lower values of R (Table 6, middle column) shows that this system is of marked importance in the regression analysis. If the regression analysis is done for ICP-panels only, eliminating a system effect, the results are considerably better (see Table 6 right column). The overall outcome is the same, GI being the best predictor and SP and DP only slightly improving the model. But even then the value of R^2 (R-squared), which is a measure for the variation explained by the model is in the best case not higher than 0.652. This means that there is still about one-thirds of the variation not covered by the model and left unexplained.

These (ICP) regressions were searched more thoroughly, including all interaction factors GI × SP, GI × DP, SP × DP, GI/SP, GI/DP, and SP/DP. Using stepwise inclusion of variables the correlations could be raised a little: for CD a maximum of 0,870 was reached. However, from 'Collinearity Diagnostics' (exploring the inter-correlation of predicting variables) it was concluded that the final model should preferably not have more than two variables, three at the most. This means that including more variables to optimise the regression (i.e. fit it better to the present data set) would at the same time diminish the model's stability, i.e. the possibility to give good estimates for a similar situation, but with another data set. In Tables 7a, b, and c therefore only regression coefficients (including 95%-confidence intervals) are presented for the predictors used so far. The form of the equations is:

Table 6. Correlation coefficients using data of all systems and excluding ICP
Tabelle 6. Korrelationskoeffizienten für alle Daten außer ICP

Predictors	Properties								
	All systems			System 1–8			System 9 (ICP) only		
	CD	GD	GD%	CD	GD	GD%	CD	GD	GD%
GI	0.276	0.423	0.517	0.067	0.332	0.433	0.782	0.693	0.710
GI + SP + DP	0.298	0.430	0.527	0.165	0.363	0.458	0.808	0.698	0.715
GI + (SP × DP	0.281	0.430	0.528	0.145	0.362	0.456	0.784	0.695	0.712

$$Y = \text{Constant} + b_1X_1 + b_2X_2 + b_3X_3 \ , \qquad (2)$$

as in the first case:

$$CD = -6.681 + 0.0125{}^{*}\mathrm{GLOBIRR} \qquad (3)$$

The t-value associated with the coefficients is a measure for the usefulness of the corresponding predictor. As a guide regarding useful predictors, one should look for t-values well below −2 or above +2. Doing this, it becomes clear that in all cases global irradiation is the most important variable. The coefficients associated with precipitation variables have relatively low values. In this respect the proposed climatic index (consisting of predictors: Constant, GLOBIRR, PRECIMUL) does not perform better than any other combination.

When CD and GD are plotted against GI, SP, and DP, it becomes clear that the relationship between the climate and the colour and gloss measurements is completely clouded by the large differences between the tested coating systems. The plots also show the relation of these weathering results to precipitation to be less pronounced than to GI (Figure 2). All these data are based on testing a linear relationship. Curve-fitting procedures using logarithmic, exponential, quadratic, or cubic effects could not improve the estimates.

Table 7a–c. Regression coefficients (ICP data only)
Tabelle 7a–c. Regressionskoeffizienten für die ICP-Daten

Predictor	Coeff. (B)	t-value	95%Confidence Interval for B	
			Lower Bound	Upper Bound
Predicting: CD				
(Constant)	−6.681	9.896	−8.012	−5.361
GLOBIRR	1.25E-02	18.831	0.011	0.014
(Constant)	−14.694	−8.262	−18.198	−11.189
GLOBIRR	1.83E−02	12.135	0.015	0.021
PRECIP01	2.51E−02	5.142	0.016	0.035
PRECISUM	−2.38E−02	−4.019	−0.036	−0.012
(Constant)	−6.29	−8.804	−7.698	−4.882
GLOBIRR	1.18E−02	15.074	0.010	0.013
PRECIMUL	2.35E−05	1.626	0.000	0.000
Predicting: GD				
(Constant)	32.199	8.945	25.106	39.292
GLOBIRR	−5.13E−02	−14.543	−0.058	−0.044
(Constant)	17.848	1.761	−2.123	37.820
GLOBIRR	−3.83E−02	−4.447	−0.055	−0.021
PRECIP01	3.54E−02	1.268	−0.020	0.090
PRECISUM	−5.73E 02	−1.697	−0.124	0.009
(Constant)	30.841	8.035	23.278	38.403
GLOBIRR	−4.90E−02	−11.609	−0.057	−0.041
PRECIMUL	−8.00E−05	−1.020	0.000	0.000
Predicting: GDP				
(Constant)	43.203	9.537	34.278	52.129
GLOBIRR	−6.78E−02	−15.271	−0.077	−0.059
(Constant)	26.143	2.050	1.013	51.272
GLOBIRR	−5.18E−02	−4.787	−0.073	−0.030
PRECIP01	4.03E−02	1.149	−0.029	0.109
PRECISUM	−7.08E−02	−1.665	−0.154	0.013
(Constant)	41.273	8.551	31.763	50.784
GLOBIRR	−6.45E−02	−12.153	−0.075	−0.054
PRECIMUL	−1.14E−04	−1.152	0.000	0.000

4.2.2
Visual assessments

As the visual assessments are not normally distributed (in the statistical sense) the 'normal' regression analysis was not possible and a non-parametric statistical test had to be used. To establish the correlations between the climatic data and the visual assessments the Spearman rank-correlation test was used, with the test statistic ρ (Rho). Like the correlation coefficient R mentioned before, values of ρ close to −1 or +1 are a strong indication of a well defined linear relationship between the two variables tested. Values of ρ close to 0 suggest the absence of a linear relation. This ρ-statistic also can be significant at a certain level: the lower the level, the more probable the real existence of a relationship becomes.

When looking at all systems, including the ICP, the latter seems to have a large share in the correlations. Therefore the Spearman-test was carried out once for systems 1–8 (excluding ICP) and once for ICP only. Again, colour and gloss difference were included as a check. In Tables 8 and 9 the same assessments show significance as before namely blistering density, chalking, cracking density close to the defect and mould density. Using the data of ICP-panels (Table 9) increases the coefficients and thus the variation explained, but again they are not very high.

In general most and best correlations are found with global irradiation, with the exception of mould density, which shows high correlations with precipitation (Table 9). Contrary to the expectations however the coefficient is negative, i.e. more rain or more rainy days tend to lead to lesser mould growth, as can be seen in Fig. 3a and b for 'mould growth density close to the defect' in relation to SP and DP. The data for 'mould growth remote from the defect' are quite similar.

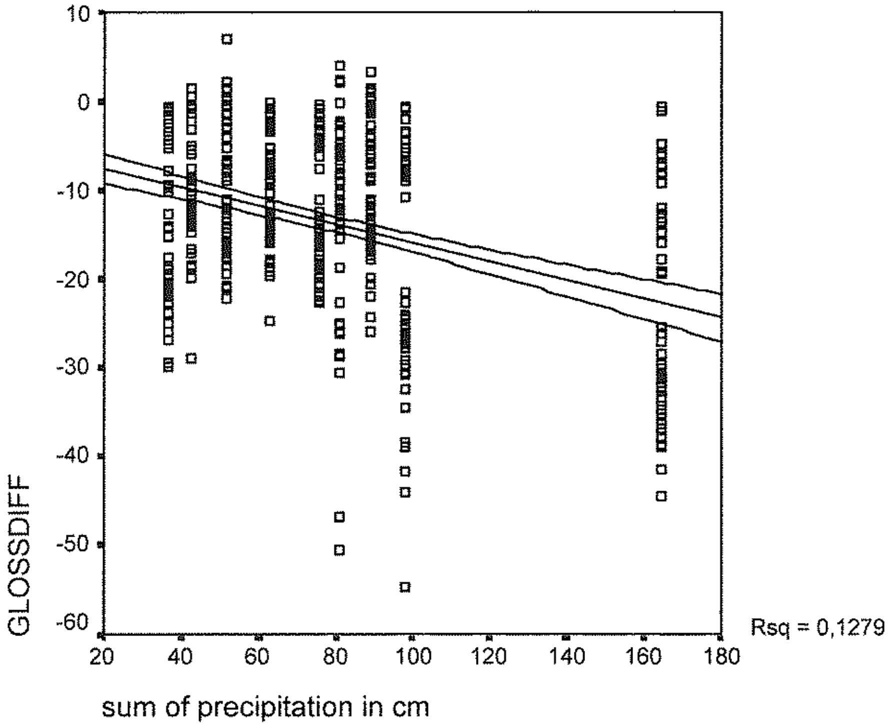

Fig. 2. Scatterplots of glossdifference (GD) against global irradiation (GI), and sum of percipitation (SP) for all systems (including linear regression line and its 95% confidence interval as well as Rsquared)

Bild 2. Abhängigkeit von GD von GI und SP (s.Anhang) für alle Systeme. Angegeben sind auch die Regressionsgrade, das 95% Kongfidenzintervall sowie R^2

Table 8. Spearman's Rho correlations for systems 1–8 (ICP excluded)

Tabelle 8. Rho-Korrelation nach Spearman für die Beschichtungssysteme 1–8 (außer ICP)

	global irradiation Correlation Coefficient	sum of precipitation Correlation Coefficient	days with precipitation Correlation Coefficient	empa climate index Correlation Coefficient
ADHES/C	−0.113	0.094	0.118	0.084
ADHES/R1	0.021	0.140*	0.081	0.144*
ADHES/R2	0.046	0.106	0.048	0.104
BLISTDENS	0.296**	0.354*	0.082	0.348**
COLDIFF	0.081	−0.146*	−0.155*	−0.147*
CHALK	0.278**	0.105	−0.093	0.084
CRACDENS/C	0.438**	−0.058	−0.286**	−0.034
CRACSIZE/C	0.169*	0.154*	0.103	0.166*
CRACDENS/R	0.107	0.031	−0.034	0.033
CRACSIZE/R	0.405**	−0.025	−0.315**	−0.019
FLAKDENS/C	0.088	−0.074	−0.078	−0.058
FLAKSIZE/C	−0.159	0.002	−0.037	−0.028
FLAKDENS/R	0.022	0.020	0.007	0.020
FLAKSIZE/R	−0.284	−0.284	−0.057	−0.284
GLOSSDIFF	−0.185**	−0.227**	−0.140*	−0.242**
GLOSSDIFF%	−0.229**	−0.253**	−0.141*	−0.268**
MOULDENS/C	0.300**	0.162*	−0.013	0.162*
MOULSIZE/C	−0.214**	−0.112	−0.100	−0.127
MOULDENS/R	0.258**	0.159*	0.007	0.158*
MOULSIZE/R	−0.117	−0.027	0.003	−0.036
STAINDENS/C	−0.131	−0.131	−0.023	−0.131
BTAINSIZE/C	0.269**	−0.115	−0.269**	−0.115
STAINDENS/R	−0.065	−0.193	−0.184*	−0.198*
STAINSIZE/R	0.314**	−0.137	−0.314**	−0.137

** Correlation is significant at the 0.01 level (2-tailed)
* Correlation is significant at the 0.05 level (2-tailed)

5
Conclusions

On the basis of the results of this test no generally applicable correlation between climatic data and weathering data could be found which is independent of the type of coating tested. This means that transferring test results from one site to another by means of a climatic index is not an option in the development of standards. As the

Table 9. Spearman's Rho correlations (only ICP)
Tabelle 9. Rho-Korrelation nach Spearman (nur ICP-Daten)

	global irradiation Correlation Coefficient	sum of precipitation Correlation Coefficient	days with precipitation Correlation Coefficient	empa climate index Correlation Coefficient
ADHES/C	−0.063	−0.088	−0.064	−0.089
ADHES/R1	0.002	−0.014	0.049	0.020
ADHES/R2	0.006	−0.090	−0.037	−0.066
BLISTDENS	0.384**	0.255**	−0.244**	0.144*
COLDIFF	0.553**	0.229**	0.011	0.734**
CHALK	0.255**	0.255**	0.058	0.255**
CRACDENS/C	0.375**	0.023	−0.227**	0.043
CRACSIZE/C	0.120	0.151*	0.104	0.160*
CRACDENS/R	0.042	0.111	0.082	0.103
CRACSIZE/R	0.498**	0.133	−0.248	0.152
OLOSSDIFF	−0.631**	−0.345**	0.034	−0.373**
OLOSSDIFF%	−0.639**	−0.341**	0.040	−0.319
MOULDENS/C	0.408**	−0.435**	−0.699**	−0.481
MOULSIZE/C	−0.125	0.059	0.125	0.059
MOULDENS/R	0.474**	−0.475**	−0.763**	−0.477**
MOULSIZE/R	−0.001	0.118	0.116	0.118

** Correlation is significant at the 0.01 level (2-tailed)
* Correlation is significant at the 0.05 level (2-tailed)

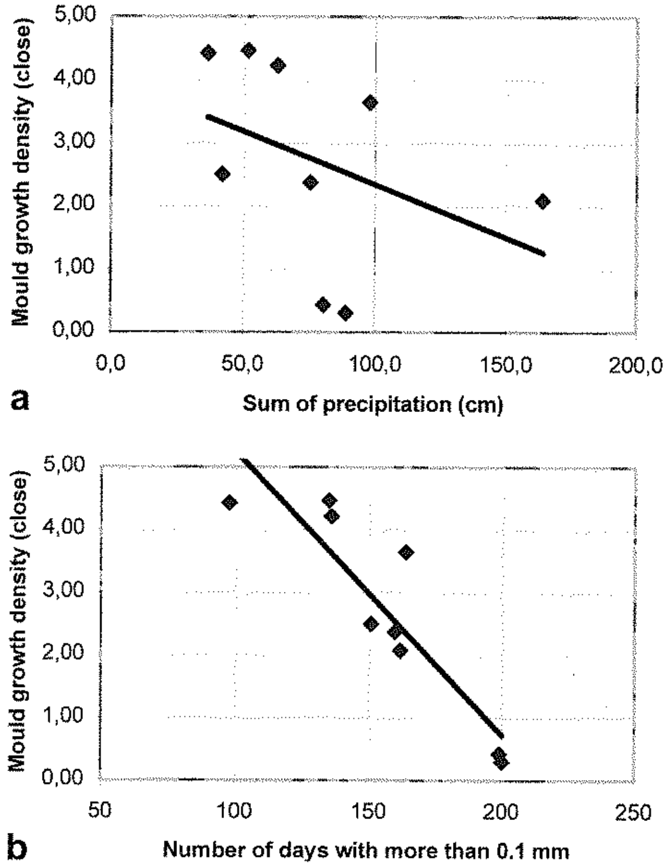

Fig. 3a, b. Relation of mould growth on ICP coating to sum of precipitation (a) and days with more then 0.1 mm (b)
Bild 3a, b. Beziehung zwischen Schimmelwachstum unauf IPC-Beschichtung zur Gesamtfällung (a) bzw. zu Tagen mit mehr als 0,1 mm Wachstum (b)

relation between weathering resistance of the ICP and the climate is, however, more pronounced, transfer of test results from one climate to another by means of the ICP is a more practical option.

The relation between climate and degradation is depending on the coating type, which leaves the possibility open that different relationships still may exist for different systems or different groups of systems. This immediately raises the question how the groups should be formed or how the properties and the limits should be chosen on the basis of which they are divided. However, although the differences between the systems attribute largely to the variance in the results, all systems were used on all sites, so apparently natural weathering on some sites gives more uniform results then on others, making it even more complex. These findings coincide with those from the preceding literature study. On the other hand it can be concluded that (global) irradiation is one of the most prominent stressing factors where natural weathering of exterior wood coatings is concerned, which clearly supports the proposal to incorporate solar irradiation into a climatic index. In the field of automotive coatings it has been shown that UV and solar exposure correlate well to photodegradation of coatings (Bauer 2000).

It is recommended to look further into the factors, which may classify the climate at a certain exposure site as 'severe'. Minimum (night) temperature, especially at the beginning of the exposure, may influence film forming in acrylic-based paints and, thus, performance at a later stage of the test. Time of wetness, and rapidity of moisture changes are other examples of possible measurements. This kind of observations should be made at the specific site and during the actual exposure period. Furthermore, the climate indices calculated for the sites in this project are really quite close to each other, probably mainly due to the relative little differences of the regional global radiation in north and central Europe. Therefore it is recommended to opt for larger differences in future research, e.g. by incorporating more south-European sites like Spain, Portugal or Greece.

The found negative correlation between mould growth and precipitation needs further study, since it does not seem to agree with the general assumption that mould growth is enhanced by high moisture contents (Viitanen 1996). Maybe the results have been distorted because of collecting and packing the panels under wet conditions at the end of the exposure period.

References

Abrahams IL (1994) Examination and analysis of results from CEN TC 139 WG 2 'Round Robin' II. 12 Months exposure. CEN TC 139 WG 2 document N 144

Abrahams IL, Graystone JA (1996) Natural weathering of exterior wood coatings: a comparison of performance at five European sites. Proceedings XXIII FATIPEC Congress, Brussels, Belgium

Anonymous (1987) American Wood Handbook. USDA Forest Service

Bauer DR (2000) Global exposure models for automotive coating photo-oxidation. Polymer Degradation and Stability 69: 297–306

Beesley J, Creffield JW, Saunders W (1983) Australian test for decay in painted timbers exposed to the weather. For Prod J 33: 57–63

Creemers J, De Meijer M, Sell J (1998) Influence of climatic factors on the weathering of coated wood, PRA conference Advances in exterior wood coatings and CEN standardisation, paper 14, Brussels

De Meijer M, Creemers J, Cobben W (2001) Relationships between the performance of low-VOC wood coatings and the dimensional changes of the wooden substrate. Surface Coatings Int. Part B 84: 77–85

Feist WC, Hon DN-S (1984) Chemistry of weathering and protection. In: R.M. Rowell (ed.). The chemistry of solid wood. Amer. Chem. Soc., Washington D.C. 401–451

Kropf FW, Sell J, Feist WC (1993) Vergleichender Bewitterungsversuch mit nordamerikanischen und europäischen Holzaussenanstrichen. Forsch.- u. Arbeitsberichte EMPA-Abt. Holz Nr. 115/27, 72 pp.

Kropf FW, Sell J, Feist WC (1994) Comparative weathering tests of North American and European exterior wood finishes. For Prod J 44: 33–41

prEN 927-3 1995 (draft version). Paints and varnishes – Coating materials and coating systems for exterior wood – Part 3: Natural weathering test

Roux M-L, Wozniak E, Miller ER, Boxall J, Böttcher P, Kropf F, Sell J (1988) Natural weathering of various surface coatings on five species at four European sites. Holz Roh-Werkstoff 46: 165–170

Scheffer Th C (1971) A climate index for estimating potential for decay in wood structures above ground. For Prod J 21: 25–31

Sell J, Feist WC (1986) U.S. and European finishes for weather-exposed wood – a comparison. For Prod J 36: 37–41

Sell J, Zimmermann T (1995) Comparability of weathering conditions within different European zones of climate – Literature study on the feasibility of a 'climatic index'. Report EC-project MAT 1 – CT 940062. EMPA Wood Department, Dübendorf, Switzerland

SPSS (1997) SPSS Base 7.5, incl. Applications Guide. SPSS Inc., Chicago

Svane P (1992) Round Robin test CEN TC 139/WG 2, N, DK, F and UK. Final Report (Document N 90). 6 p. and annex

Viitanen H (1996) Factors affecting the development of mould and brown rot decay in wooden material and wooden structures: Effect of humidity, temperature and exposure time. Dissertation, Swedish Univ. of Agricultural Sciences, Uppsala