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ORIGINAL

Modelling mould growth on coated modified and unmodified wood substrates exposed outdoors

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Abstract Mould growth on coated wood is today a genuine challenge for house owners. Environmentally sound wooden facades with long service lives and acceptable appearance are desired. The objective in this study was to investigate the accumulated mould growth on 13 different wood substrates with 3 surface coating systems by identifying the factors that contribute to the variation and to predict future performance. A generalized linear mixed model was fit to the data with the analysis showing that coating and exposure time both had highly significant influences on mould growth. Further, wood substrate was significant, but comparatively less than coating and exposure time. A smaller coefficient for mould coverage in the beginning of the exposure period gave the panels with one of the coating systems, BAP, a delay in mould growth, and the extrapolated values for years 6–12 indicate a longer aesthetic service life than panels with the two other coating systems. Coated heartwood as wood type was less susceptible to mould growth than coated mixed wood and coated sapwood. Acetylated pine as wood substrate and aspen as wood species had lower resistance to mould growth than the other wood substrates and wood species, respectively.

Introduction

An increase in coated wood attacked by surface moulds in above ground applications has been observed over the last 15–20 years in Norway and Sweden.

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Together with government-imposed restrictions on the type and amount of biocides and solvents in finishes, this has challenged researchers, producers, specifiers and home owners to find combinations of wood species, wood modifications, wood preservatives and surface coating systems that are minimally susceptible to surface mould growth and have long service lives.

Performance and service life are product characteristics that need documentation before a building product is sold and used. Service life prediction is of specific interest due to the need for calculating the total lifelong cost of a construction. There is presently a major focus on predicting the performance and service life of wooden products including wooden cladding in façades. The service life of coated wooden components in such an application is related to a number of factors (Bjurman and Herder 1992; Bravery 1988; Brischke et al. 2006; Eaton and Hale 1993; Viitanen and Ahola 1997a, b; Williams et al. 2000; Williams and Feist 1994):

- Macro- and microclimate
- Time
- Handling, storage, installation and maintenance
- Building design
- Interactions with other materials in an envelope or wall system
- Preservative treatment/modification
- Surface coating system: type, additives and fungicides
- Wood properties: species, heartwood/sapwood, density, growth rate, knots, grain orientation and amount of extractives
- Material climate: wood moisture content and wood temperature.

Wood types with limited swelling and shrinking properties often have the best paint-adhering performance (USDA Forest Service 1999). Furfurylation, acetylation, and thermal modification are three relatively new processes developed for wood enhancement that provide protection against fungal attack and possess enhanced properties such as less shrinkage and swelling (Boonstra et al. 1998; Kamdem et al. 2002; Lande et al. 2004a, b; Larsson 1998; Brelid et al. 2000; Rowell et al. 1985; Sailer et al. 2000; Schneider 1995; Viitaniemi et al. 1995; Westin et al. 1998, 2002). It was therefore expected that coated modified wood would perform better than untreated wood in the long-term. However, considering surface mould growth, research has shown that coated acetylated wood did not in fact perform better than uncoated non-acetylated wood when exposed outdoors (Nienhuis et al. 2003; Wakeling et al. 1992). Further, studies by Jämsä et al. (2000) and Ahola et al. (2002) revealed that heat-treated wood did not prevent fungal growth any differently than untreated wood on the coated surface when tested outdoors. Vernois (2001) concluded that paints and finishes used for untreated wood are not recommended for heat-treated wood substrates because of reduced paint adhesion, which is probably caused by exudation of resins from resinous species. To our knowledge no studies have been published on the performance of coated furfurylated wood used in outdoor applications.

It is critical that a surface coating is compatible with the underlying wood substrate. Williams et al. (1987) stated that the long-term behaviour of a paint film will primarily be determined by the wood/paint interface. Penetrating surface coatings for wood are generally less durable than film-forming coatings (USDA Forest Service 1999). Traditionally, water-borne acrylic/alkyd coating systems for wood have been reported to be more susceptible to fungal growth than solvent-borne alkyd coating systems (Bjurman 1996; Weissenborn et al. 2003). Recent studies have shown that new water-borne acrylic(/alkyd) coating systems can be less susceptible to mould growth than solvent-borne alkyd coatings (Gobakken and Jenssen 2007) which is also directly related to the fungicide type used in the paint system. Another aspect that may influence the susceptibility to mould growth is the way the wood material has been dried. The concentration of nitrogen and low-molecular hydrocarbon compounds was higher on the surface of sawn timber than on the inside after kiln drying (Boutelje 1990; Theander et al. 1993). Mould was shown to grow more rapid on kiln dried surfaces than on resawn surfaces (Terziev et al. 1994) and this was also the case for coated kiln dried wood surfaces (Viitanen 2001).

Adan (1994) and Sedlbauer (2002) have described and developed prediction models for occurrence of spore germination and growth of certain mould species on the surface of various materials. Both scientists have studied materials and applications intended for indoor environments based on data on temperature, relative humidity and time. Viitanen (1997), Ritschkoff et al. (2000), and Hukka and Viitanen (1999) presented a model that described the material response and found the critical conditions for mould growth on surfaces of wood exposed to a known humidity and temperature. The model is based on data from a limited number of wood substrates conducted in the laboratory on small samples. Our current study explores a model for samples made of a variety of wood substrates and different coating systems exposed outdoors. The authors focus on the occurrence of spore germination and on the differences in mould growth development on the different substrates over extended periods to natural exposures that will provide input data for service life prediction. In South-Norway the degree of mould growth on painted wood will increase primarily during late summer and early fall (Gobakken and Jenssen 2007). Some surface coating systems prevent mould growth very well for the first few years when exposed outdoors followed by a noticeable increase (Gobakken and Jenssen 2007; Gobakken and Westin 2008). Further, other surface coating systems can have a constant increase in mould growth from day one of exposure and then flatten off after 2–3 years when reaching some kind of “steady state” or the maximum rating (5) used in standard EN 927-3 (2000). The shape of the curve and the slope coefficient that describe the degree of mould growth according to time can be characteristic for a specific combination of wood substrate and surface coating system. This is valuable input when searching for combinations with less mould growth susceptibility and when identifying the factors that significantly affect mould growth on painted wood. Performance data from in-service studies, field tests and laboratory tests are necessary to ensure the quality of the input data when modelling service life prediction; data from this study will be valuable for predicting service life of coated wooden cladding. In this study, three very different surface coating systems and 13 wood substrates were tested. This study expands on earlier work by Gobakken and Westin (2008) where the susceptibility of mould on the surface of coated modified wood substrates was investigated following outdoor exposure for 3.5 years. Panels were intentionally not cleaned or repainted during the test period. By testing various combinations of surface coating systems and wood substrate outdoors wood species, wood type (sapwood, heartwood, mixed), treatment, wood substrate and surface parameters have been evaluated, and the degree of surface mould development over time has been monitored.

The objectives were to study the accumulated surface mould growth on coated wooden panels by (1) identifying and quantifying the fixed factors that contributed to the variation in surface mould and (2) predicting the future performance of combinations of wood substrates and coating systems. The latter was accomplished by fitting a model to the field data collected. The authors wanted to investigate if wood substrates with documented fungal restrain would have an impact on the fungal colonization on a coated surface. Predicting future performance encompasses multiple goals, including both development of a better understanding of the mould growth process and its measurement, as well as having a model development and evaluation process for ongoing monitoring of surface mould growth and possibly other surface characteristics such as cracking, blistering, and flaking that may gradually decline over time.

Materials and methods

Test materials, exposure and evaluation

Thirteen different wood substrates were placed in the field study (five modified and eight unmodified substrates), including

1. Acetylated Scots pine
2. Furfurylated Scots pine
3. Heat-treated Scots pine
4. Oil heat-treated Scots pine
5. Heat-treated Norway spruce
6. Copper-organic preservative treated Scots pine (Wolmanit CX8)
7. Metal-free preservative treated Scots pine (Laquin Seal)
8. Untreated Scots pine sapwood
9. Untreated Scots pine heartwood
10. Untreated Norway spruce
11. Untreated Siberian larch heartwood
12. Untreated European oak heartwood
13. Untreated aspen sapwood.

Expanding on the study of Gobakken and Westin (2008), the present study adds an additional year of exposure. The wood samples were collected from various stands, sawmills, and wood working companies in Sweden and Finland to ensure it contained a variety of wood substrates. The acetylation was conducted according to the procedure described by Larsson (1998). Furfurylated Scots pine was processed by impregnation with a 22% solution of furfuryl alcohol in water (30 parts FA in

100 parts water + acidic catalysts and process additives) which corresponds to a weight percent gain (WPG) of 20. The thermally modified wood panels were taken from 4-m long beams of Scots pine and Norway spruce heat treated by the Thermowood process used in 2003 by Stora Enso with a process peak temperature of 220°C. Oil heat-treated Scots pine was processed by autoclaving with rapeseed oil and heating up to 200°C before drying.

Each substrate was tested in combination with three paint systems:

Internal comparison product (ICP): ICP is a solvent-borne red-pigmented semi-transparent alkyd paint which is required as internal standard paint for EN 927-3 (2000) testing and its composition is defined in the standard. The active fungicide is tolyfluanide (0.72% w/w).

White system paint (WSP): WSP consists of a solvent-borne primer and a water-borne acrylic top coat. The fungicides are tolyfluanide (<0.5% w/w) in the primer and isothiazolon (<0.05% w/w), 3-iodo-2-propynyl butylcarbamate (IPBC), (<0.4% w/w) and bronopol (<0.02% w/w) in the top coat.

Brown semi-transparent acrylic paint (BAP): BAP consists of a water-borne stain with a water-borne acrylic top coat. The fungicide is IPBC at a concentration of 0.2% w/w in the stain and 0.25% w/w in the top coat.

Table 1 shows the number of panels of each wood substrate and coating system per exposure period measured. Each wood substrate is described by species, sample composition (sapwood, heartwood, or a mixture of both) and treatment. The number of samples for each wood substrate, coating and year is specified.

The dimensions of the wood panels were 20 × 100 × 375 mm and each panel was coated on the top face and sides with one of the three paint systems. The panels were installed horizontally at a 45° angle in rigs facing south (EN 927-3 2000) in SP Trätek's test field in Bogesund, Sweden, in March 2003. Evaluation of mould coverage was done at 1 year (March 2004), 2.5 years (September 2005), 3.5 years (August 2006) and 4.5 years (September 2007). Mould coverage on the samples was evaluated according to EN 927-3 (2000). The assessment was made visually and by the use of a stereo microscope (10× magnification). The rating system ranges from 0 (no growth) to 5 (heavy growth) given by the pictorial rating scale in standard EN 927-3 (2000). The rating is based on a stepwise increase in mould growth coverage and pattern.

Initially, ten replicates were installed in the field and three to six of them were evaluated after year 1. Since the set of panels from year 1 was washed before reinstalling in the rigs, another set of panels, not evaluated in year 1, was evaluated the following years to study the accumulated surface mould growth with as minimal surface maintenance as possible. Exceptions occurred in five groups (SPmixAC-ICP, SPsapMFP-ICP, SPmixHT-BAP, SPmixAC-BAP, and SPhrtUNTR-BAP) where some of the initial panels were not washed and were then subsequently evaluated in years 2.5, 3.5, and 4.5.

Statistical methods and model development

A rating is characterized as an ordinal measure indicating an amount of mould growth and coverage on a given panel and ideally indicates a percentage of

Table 1 Number of panels of each wood substrate/coating/year rated for mould growth

Species	Sap/heart/mix	Treatment	Wood substrate	WSP				BAP				ICP			
				Year 1	Year 2.5	Year 3.5	Year 4.5	Year 1	Year 2.5	Year 3.5	Year 4.5	Year 1	Year 2.5	Year 3.5	Year 4.5
Scots pine	Mixed	Acetylation	SPmixAC	3	3	3	3	3	5	5	5	6	6	6	5[a]
Scots pine	Sapwood	Furfurylation	SPsapFU	6	3	3	3	6	3	3	3	6	3	3	3
Scots pine	Mixed	Heat treated	SPmixHT	3	3	3	3	3	3	3	3	6	3	3	3
Scots pine	Mixed	Oil heat treated	SPmixOHT	3	3	3	3	6	3	3	3	6	3	3	3
Norway spruce	Mixed	Heat treated	NSmixHT	3	3	3	3	3	3	3	3	6	3	3	3
Scots pine	Sapwood	Cu-org. pres.	SPsapCOP	3	3	3	3	3	3	3	3	6	3	3	3
Scots pine	Sapwood	Metal-free pres.	SPsapMFP	6	3	3	2[a]	6	3	3	3	6	3	3	3
Scots pine	Sapwood	Untreated	SPsapUNTR	6	3	1[a]	1[a]	6	3	3	3	6	3	3	3
Scots pine	Heartwood	Untreated	SPhrtUNTR	3	3	3	3	3	3	3	3	3	3	3	3
Norway spruce	Mixed	Untreated	NSmixUNTR	4	3	3	3	8	3	3	3	8	3	2[a]	3
Siberian larch	Heartwood	Untreated	SLhrtUNTR	6	2	2	2	3	3	3	3	6	3	3	3
European oak	Heartwood	Untreated	EOhrtUNTR	6	3	3	3	6	3	3	3	6	3	3	3
Aspen	Sapwood	Untreated	ASsapUNTR	3	2	2	2	3	3	3	3	6	3	3	3

[a] Fewer samples because some specimens had fallen down from the test rigs and were not evaluated

coverage on a continuous scale. Because of the difficulty of such a measurement system, the ordinal measuring system for human evaluators has been the traditional method of visual surface characterization in wood coating systems. This pictorial scale is based on an increase in percentage of mould coverage and also takes into account the mould growth pattern. For example, two panels with the same percentage mould coverage may have a very different visual expression which can affect the aesthetic service life. The panels are typically exposed over a specified period of time and measured at time intervals with counts and/or averages of ratings at each time interval indicating performance. In other fields with ordinal rating systems, such as the health sciences and plant and soil sciences, statistical modelling that accommodates the ordinal nature of the measurement while also trying to account for the natural and experimental variability in the experiment have been developed and applied (Ananth and Kleinbaum 1997; Molenberghs and Verbeke 2005; Schabenberger 1995; Schabenberger and Pierce 2001).

In situations with an underlying continuous variable of interest, common models used for characterizing the observed ordinal data are cumulative logit models which are also known as proportional odds logistic regression models (Agresti 2002). A logit is defined as the logarithm of the probability (p) of some event, such as the observation of a low mould rating of 0, divided by the probability ($1 - p$) of the complement of the event, such as observing a higher rating than 0 (i.e., $\mathrm{logit}(p) = \log(p/(1 - p))$). Models of this type explicitly model nonlinearity and dependent, non-normal residual distributions commonly associated with ordinal rating situations (Schabenberger and Pierce 2001). They incorporate the multinomial probability distribution thus capturing the probability constraints such that when the probability of one rating increases, the sum of the others will decrease.

Based on a subset of the experiment described in Table 1, panel mould ratings were tabulated previously in Gobakken and Westin (2008), where comparisons of the magnitude of differences in average ratings did not fully account for the probability distribution of the ratings. Given that ratings occur on an ordinal scale, defined as $m_0 = 0 < m_1 = 1 < m_2 = 2 < m_3 = 3 < m_4 = 4 < m_5 = 5$, the cumulative logit is defined, in our case, as the logarithm of the probability of a rating less than or equal to m_i divided by the probability of a rating greater than m_i, $i = 0, 1, 2, 3, 4, 5$. Plots that display observed cumulative logits against experimental factors or possible covariates are useful for model development and evaluation (Friendly 2000); however, it should be kept in mind that additional variation due to repeated measurements may alter their interpretation. Ideally the plots would exhibit proportionality between rating levels and predictors. The observed logits were calculated with a small offset to include all rating levels on the plots.

Repeated ratings over time can complicate analysis if there is an additional dependency due to the particular panel that is repeatedly being measured. Modelling and evaluation of these dependencies are discussed in Agresti (2002), Schabenberger and Pierce (2001), and Molenberghs and Verbeke (2005). In particular, the following cumulative logit model that models the probability of low mould growth ratings versus high mould growth ratings as a function of the fixed effects, including wood substrate, coating and exposure time, and a random effect due to repeated measurements was assumed:

$$\text{logit}[p(Y_{ijkl} \leq m|X_i, C_j, t_{ijk}, Z_l)] = \beta_m + \beta_i X_i + \beta_j C_j + \beta_3 \ln(t_{ijk}) + b_l Z_l$$

where Y_{ijkl} = mould coverage rating for panel $ijkl$, $m = 0,1,2,3,4$ (ratings for mould), X_i = substrate group i (species/wood/modification type), C_j = coating j, t_{ijk} = exposure time k (1, 2.5, 3.5, and 4.5 years), b_l = random effect for panel l, Z_l = panel l from treatment group ij, β = model parameters.

This generalized linear mixed model assumes the random effects for panel l, b_l, are independently, normally distributed with mean zero and variance τ^2. The model was fit in SAS® V9.1.2 using the procedure NLMIXED (SAS 2004) following Molenberghs and Verbeke (2005). The NLMIXED procedure modelled the probabilities of levels of mould coverage having lower ordered values. The experiment is not a full factorial design for wood species, wood types (heartwood/mixed/sapwood) and surface treatments, therefore the tested combinations of these groups were identified as substrate groups (or wood substrates). The model includes fixed effects for the categorical predictors, which are substrate group and coating system, and a fixed effect on the logarithm of exposure time. Hypotheses of interest were tested with linear contrasts between appropriate coating system and substrate groups in SAS, including comparisons between coating systems, wood type, wood species, and pair-wise comparisons between substrate groups. The contrasts give estimates of differences between the log cumulative odds, while the exponentiated estimate is an estimate of the odds ratio, both of which are independent of rating system (SAS 2004). A difference in log odds detectably different than zero is indicative of an odds ratio different than unity. Because cumulative probabilities of lower mould coverage values were modelled, an odds ratio greater than unity indicates the first part of the hypothesis has higher probability of lower ordered mould ratings than the second part of the hypothesis. Correspondingly, an odds ratio less than unity indicates that the second part of the hypothesis has a higher probability of lower ordered mould ratings than the first part. There are multiple model fitting methods available for generalized linear mixed models, even within SAS, including those that fit the marginal model, such as general estimating equations (with proc GENMOD) and data approximation via iterations of linear mixed methods [with proc GLIMMIX, see Molenberghs and Verbeke 2005, or The GLIMMIX Procedure (SAS 2006) for details].

Initial models included two random effects modelled as cluster effects to try to capture the variation due to different specimens being measured after 1 year exposure and the specimens with repeated measurements in years 2.5, 3.5, and 4.5. This effect is also confounded with using different evaluators for rating the first year compared to year 2.5, 3.5, and 4.5. Further modelling reduced this to a single cluster effect. Initial model development included data from year 1, year 2.5 and 3.5, and the fixed time effect was polynomial. Following the 4.5-year evaluation, the data was used as a test data set. Rough assessment of the predicted versus the observed average 4.5-year rating indicated the above model form was more parsimonious and the model was refit and is discussed here. Further assessment of the model included comparison of parameter estimates from the above model to parameter estimates from binary logistic regressions, comparison of estimates obtained by other fitting methods and predictive characteristics of the model. In particular, the revised model was used to extrapolate average performance at 6, 8, 10, and 12 years of exposure. Although extrapolation of this extent is quite risky and uncertain, long-term behaviour of the models is of keen interest in the progress towards realistic service life prediction modelling.

Alternative models for modelling ordinal responses include variations of cumulative logit models that allow non-proportionality, other cumulative link models, such as cumulative probit and cumulative complementary log–log, and other models that do not use cumulative probabilities. See Agresti (2002) for a discussion on alternative models, including models that treat the response as a continuous variable. For repeated discrete data, such as occurs in this experiment, there are several related methods of model representation and parameter estimation that have nuances and differing assumptions that can influence model development and fitting (Molenberghs and Verbeke 2005). Several alternatives were considered in the course of model development. It is anticipated that as additional data becomes available, further testing and refinement of the model will be carried out, such as better assessments of certain interactions and fitting of partial proportional odds in situations that may not be adequately characterized by the current data set.

Results

In an attempt to characterize the distributions for statistical comparisons, a mixed effect proportional odds model was fit to the data on mould growth on various coated wood substrates over a period of time. Observed cumulative logit plots (Fig. 1a–c) show the approximate pattern of logits across the substrate groups, coating groups, and years of exposure. The declining logits with exposure time indicate that the probability of lower ratings is decreasing relative to higher ratings, as expected. Other factors that can affect the appearance of the plots include excluded variables, such as possible interactions, and dependencies between observations.

A proportional odds model that assumes the logits of the probability of mould ratings are functions of the independent variables wood substrate, coating, and exposure period was fit as described in "Materials and methods". The logit plots (Fig. 1a–c) give an indication of the suitability of this proportional odds model with approximate parallelism across the log axis of exposure and approximately equal differences between the same logits associated with each pair of substrate types and with each pair of coating types.

The logit plot (Fig. 1a) of mould ratings for each wood substrate shows that wood substrates ASsapUNTR and SPmixAC tended to have a lower percentage of zero ratings and that half of the wood substrates have not progressed to maximum mould coverage ratings (5) yet. It also appears that the probabilities of 2 or lower ratings is not that much higher than that of 1 or lower.

Further the logit plot of mould ratings for each coating system (Fig. 1b) showed that the panels with WSP coating experienced no zero ratings while those with BAP have not progressed to complete mould coverage ratings of 5.

The logits associated with mould ratings 0–4 tend to decrease with respect to exposure period. Mould rating 5 appeared after 3.5 years exposure time.

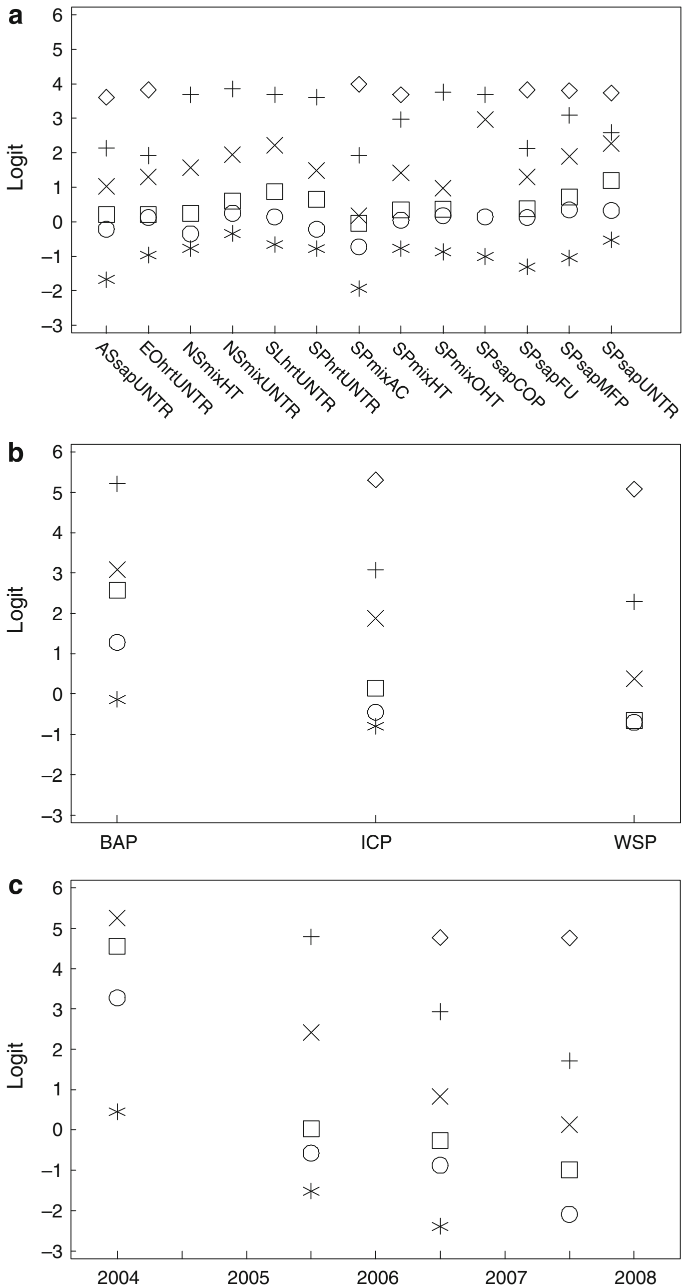

Fig. 1 **a** Logit plot of mould ratings for each wood substrate. See Table 1 for a description of the wood substrates. **b** Logit plot of mould ratings for each coating system. **c** Logit plot of mould ratings for year 1, year 2.5, year 3.5 and year 4.5. Mould rating; 0 *asterisk*, 1 *open circle*, 2 *open square*, 3 *multi symbol*, 4 *plus symbol* and 5 *open diamond*

The final model included fixed effects for substrate group, coating type, and the logarithm of exposure time. Table 2 lists the factors included in the model and indicates that all are highly significant. The random effect to account for repeated measurements does not appear significant ($\hat{\tau}^2 = 0.1783$, SE $= 0.2391$), but appears to possibly capture a small amount of correlation and was kept in the model.

Parameter estimates from this model as compared to binary models, indicated that the model generally captured substrate group, coating, and exposure time effects, with the possible exception for substrate SPsapCOP. This particular treatment group had significant effects in two of the binary models with significant coefficient estimates of the opposite sign, arising from the lack of any two ratings and a larger group of three ratings. The difference between this substrate group and the others can be seen in the logit plot of mould ratings (Fig. 1a).

Particular hypotheses of interest were tested, based on the model, by specifying contrasts that evaluated different coating systems, wood type, wood species and substrate groups. Table 3 shows the fixed effect differences for specific hypotheses of interest and highlights significant differences, based on a comparison-wise error rate of 0.05, between the different coating systems, wood types and wood species. A highly significant difference occurs between the panels coated with the BAP system and the ICP and WSP systems. Coating system BAP tends to have a higher probability of lower ordered mould values compared to the coating systems ICP and WSP, and further ICP resulted in lower ordered mould values than WSP. Heartwood substrates are significantly differentiated from the sapwood and mixed wood substrates, with heartwood substrates experiencing a higher probability of lower ordered mould values. Of the five wood species included in the study, the Siberian larch substrate resulted in lower ordered mould values with higher probability than the substrates with aspen, European oak and Scots pine. The odds ratio of the contrast between the Norway spruce substrates and the Siberian larch substrate indicates that the Siberian larch may have a higher probability of lower ordered mould ratings than the Norway spruce substrates, but the effect's non-significance indicates that the current study either does not have the ability to differentiate them or that they are not different.

Table 4 shows the pair-wise fixed effect differences (contrasts) between the various wood substrates that were significant. No adjustments for multiple comparisons were made to the *p* values.

The wood substrate SPmixAC appears significantly different from the other substrates, indicating the model predicts the odds of having higher mould ratings are greater than the other substrates. The differentiation amongst the other substrates is less clear, although the ASsapUNTR, EOhrtUNTR and SPsapFU tend to also have

Table 2 Type 3 tests of fixed effects

Effect	Numerator DF	Denominator DF	*F* value	$p > F$
Substrate group	12	293	6.65	<0.0001
Coating	2	293	107.37	<0.0001
Log (years exposure)	1	293	247.27	<0.0001

DF Degrees of freedom

Table 3 Linear contrasts between coating systems, wood types and/or wood species (degrees of freedom = 293)

Coating system/wood type/wood species	Estimate	Standard error	*t* value	Unadjusted *p* value	Odds ratio
BAP versus ICP	4.90	0.40	12.10	**<0.0001**	134.04
BAP versus WSP	7.90	0.54	14.64	**<0.0001**	2,685.25
ICP versus WSP	3.00	0.29	10.32	**<0.0001**	20.03
Sapwood versus heartwood	−0.55	0.27	−2.02	**0.0440**	0.58
Sapwood versus mixed	0.58	1.17	0.49	0.6231	1.78
Heartwood versus mixed	0.66	0.26	2.50	**0.0128**	1.94
Aspen versus European oak	−0.63	0.55	−1.14	0.2533	0.54
Aspen versus Norway spruce	−1.81	0.51	−3.57	**0.0004**	0.16
Aspen versus Scots pine	−1.34	0.45	−2.99	**0.0030**	0.26
Aspen versus Siberian larch	−2.23	0.57	−3.92	**0.0001**	0.11
European oak versus Norway spruce	−1.19	0.43	−2.77	**0.0060**	0.30
European oak versus Scots pine	−0.71	0.37	−1.94	0.0534	0.49
European oak versus Siberian larch	−1.61	0.50	−3.21	**0.0015**	0.20
Norway spruce versus Scots pine	0.48	0.29	1.67	0.0956	1.61
Norway spruce versus Siberian larch	−0.42	0.44	−0.96	0.3399	0.66
Scots pine versus Siberian larch	−0.90	0.38	−2.34	**0.0199**	0.41

Significant *p* values in bold

higher mould ratings. The wood substrates SPhrtUNTR, SLhrtUNTR, and SPsap-COP were concluded to have significantly lower mould ratings (based on odds) in 5 of 12 comparisons. Further, NSmixUNTR, SPsapUNTR, NSmixHT and SPmixHT appeared to have lower ordered mould ratings based on 4 of 12 comparisons.

The goodness of the model was evaluated on a number of factors, including the convergence characteristics of the fit, the significance of fitted parameter estimates, and a preliminary visual assessment of the model. The multiple plots used for assessment are based on the comparison of the observed average ratings versus the expected average ratings from the model (Fig. 2). The correspondence between the observed average ratings and the expected ratings from the model tend to support the model developed.

Although no true goodness-of-fit test has been conducted, drawing inferences from the model appear appropriate, with exposure time and coating system significantly effecting mould ratings, and substrate group to a lesser extent. The models were also used to extrapolate an average rating at 6, 8, 10 and 12 years and these results were included in Fig. 3. Based on extrapolated average ratings, mould coverage on the panels with WSP and ICP reaches maximum rating earlier than for panels with BAP. The expected mould rating for wood substrates with BAP show a smaller slope coefficient than for panels with ICP and WSP from the start until BAP had a structural break in the coating at year 2.5. From year 2.5 the slope coefficients were similar for all the three paint systems until the panels reached the maximum rating. From Fig. 3 it can also be inferred that panels with WSP all had a rating of one or above at year 1.

Table 4 Single degree of freedom contrasts between wood substrates (degrees of freedom = 293) with unadjusted $p \leq 0.05$

Wood substrates[a]	Estimate	Standard error	*t* value	Unadjusted *p* value	Odds ratio
ASsapUNTR–NSmixHT	−1.64	0.57	−2.90	0.0040	0.19
ASsapUNTR–NSmixUNTR	−1.99	0.57	−3.49	0.0006	0.14
ASsapUNTR–SLhrtUNTR	−2.23	0.57	−3.92	0.0001	0.11
ASsapUNTR–SPhrtUNTR	−2.50	0.58	−4.29	<0.0001	0.08
ASsapUNTR–SPmixAC	1.10	0.53	2.09	0.0374	3.00
ASsapUNTR–SPmixHT	−1.93	0.58	−3.32	0.0010	0.15
ASsapUNTR–SPmixOHT	−1.16	0.56	−2.07	0.0394	0.31
ASsapUNTR–SPsapCOP	−2.28	0.59	−3.88	0.0001	0.10
ASsapUNTR–SPsapMFP	−1.51	0.55	−2.75	0.0063	0.22
ASsapUNTR–SPsapUNTR	−1.82	0.57	−3.18	0.0016	0.16
EOhrtUNTR–NSmixHT	−1.02	0.50	−2.04	0.0424	0.36
EOhrtUNTR–NSmixUNTR	−1.36	0.50	−2.73	0.0067	0.26
EOhrtUNTR–SLhrtUNTR	−1.61	0.50	−3.21	0.0015	0.20
EOhrtUNTR–SPhrtUNTR	−1.87	0.52	−3.62	0.0004	0.15
EOhrtUNTR–SPmixAC	1.73	0.48	3.57	0.0004	5.61
EOhrtUNTR–SPmixHT	−1.31	0.51	−2.54	0.0115	0.27
EOhrtUNTR–SPsapCOP	−1.65	0.52	−3.17	0.0017	0.19
EOhrtUNTR–SPsapUNTR	−1.19	0.51	−2.36	0.0190	0.30
NSmixHT–SPmixAC	2.74	0.51	5.40	<0.0001	15.50
NSmixHT–SPsapFU	1.05	0.51	2.08	0.0384	2.86
NSmixUNTR–SPmixAC	3.09	0.51	6.04	<0.0001	21.89
NSmixUNTR–SPsapFU	1.40	0.51	2.76	0.0062	4.05
SLhrtUNTR–SPmixAC	3.33	0.52	6.46	<0.0001	28.05
SLhrtUNTR–SPmixOHT	1.07	0.51	2.10	0.0366	2.92
SLhrtUNTR–SPsapFU	1.65	0.51	3.24	0.0013	5.19
SPhrtUNTR–SPmixAC	3.60	0.53	6.76	<0.0001	36.51
SPhrtUNTR–SPmixOHT	1.34	0.52	2.54	0.0115	3.80
SPhrtUNTR–SPsapFU	1.91	0.52	3.64	0.0003	6.75
SPmixAC–SPmixHT	−3.03	0.53	−5.77	<0.0001	0.05
SPmixAC–SPmixOHT	−2.26	0.50	−4.52	<0.0001	0.10
SPmixAC–SPsapCOP	−3.38	0.54	−6.31	<0.0001	0.03
SPmixAC–SPsapFU	−1.69	0.49	−3.47	0.0006	0.18
SPmixAC–SPsapMFP	−2.61	0.50	−5.28	<0.0001	0.07
SPmixAC–SPsapUNTR	−2.92	0.52	−5.65	<0.0001	0.05
SPmixHT–SPsapFU	1.34	0.52	2.58	0.0105	3.83
SPmixOHT–SPsapCOP	−1.11	0.53	−2.10	0.0362	0.33
SPsapCOP–SPsapFU	1.69	0.53	3.20	0.0015	5.41
SPsapFU–SPsapUNTR	−1.23	0.51	−2.40	0.0169	0.29

[a] Table 1 describes wood substrate groups or designations

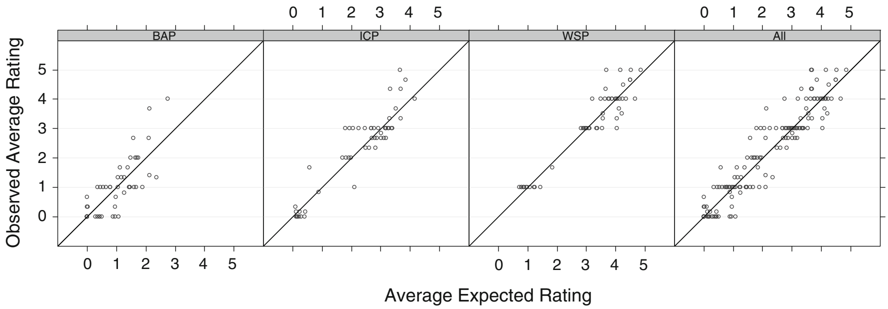

Fig. 2 Average expected rating versus observed average rating by each coating type and collectively for all groups

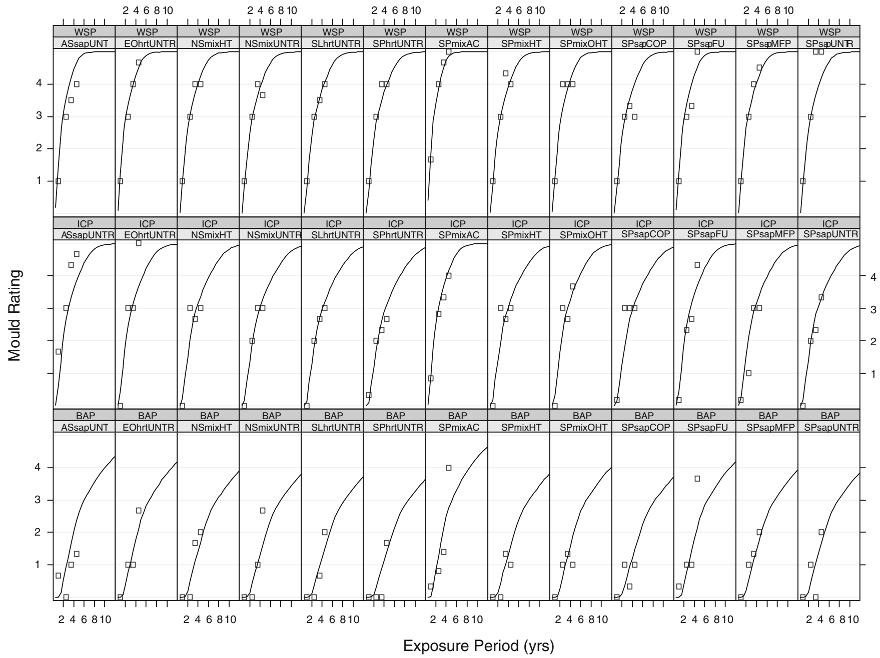

Fig. 3 Predicted and extrapolated average mould ratings (*solid line*) from the model versus observed mould ratings (*squares*) for each substrate group, coating system and year

Discussion

Model and statistics

Based on the final model fit to 4.5 years of exposure data, estimated average ratings as determined from the fixed effect portion of the model are in agreement with the typically calculated average mould performance rating for most WSP systems, some ICP systems and a few of the BAP systems (Fig. 3). Although not necessary for hypothesis comparisons within the current model context, projected average ratings exhibit reasonable behaviour. Logit plots and coefficient comparisons (not shown) did indicate that the proportional odds assumption is suspect for the SPsapCOP substrate. Another substrate, ASsapUNTR, appears to exhibit an interaction with the coatings. The general tests from Table 2 show that coating had a highly significant influence on mould rating differences, secondary to the highly significant effect of exposure over time. The substrate group differences are comparatively less significant than coating or exposure time, but are still highly significant. It is desirable to employ methods and models that will accommodate no increases in the number of subjects but increases in number of repeated measurements. At this time no statistical adjustments were made for the multiple testing situations.

These types of models are based on iterative fitting methods and can sometimes have difficulties converging and calculating model parameter estimates. The current model here converged quite rapidly and appeared stable, with starting estimates obtained from SAS's proc GLIMMIX. Difficulties in estimation were experienced with several of the more complicated model forms, likely the result of small sample sizes per treatment group. Hence these types of models require larger sample sizes to fully explore possible fixed and random effect structures. Although the model did not indicate large random effects, the mixed effect model was kept because it was felt appropriate for this incomplete data situation. Increased availability of statistical software for estimation of the generalized linear mixed models will likely increase their use and further the statistical community to develop more experimental design and model fitting strategies.

As stated extrapolation from the model exhibits reasonable monotonically non-decreasing behaviour between estimated asymptotes of zero and five; caution in interpreting longterm predictions from this model is necessary as confidence in these extrapolations has not been determined. Further experimental data as well as statistical modelling work in this area could help validate the models and/or lead to improvements.

Susceptibility to surface mould growth

After 4.5 years exposure time coating system BAP was significantly less susceptible to mould growth than ICP and WSP, and this reflects the results after 3.5 years reported by Gobakken and Westin (2008). A smaller slope coefficient for mould coverage in the beginning of the exposure period gave the panels with BAP a delay and the extrapolated values for year 6–12 indicate a longer aesthetic service life than panels with the paint systems ICP and WSP. BAP contains IPBC as the only fungicide. Other studies (Gobakken and Jenssen 2007; Weissenborn et al. 2003) also indicate that coating systems that predominantly contain IPBC in a relatively high concentration often have less mould growth than coating systems with other fungicide combinations. Scots pine heartwood, Siberian larch heartwood and copper-organic preserved pine as substrate groups had higher probability of resisting mould growth than the other substrate groups after 4.5 years outdoors exposure. Heartwood substrates appeared to have higher expected probabilities of lower ordered mould values when compared to mixed wood and sapwood substrates.

Heartwood in most trees is known to be less susceptible to decay fungi than sapwood, and Scots pine heartwood contains antifungal components and hydrophobic extractives which can suppress fungal growth (Scheffer and Cowling 1966). But it is known that a wood species or wood type can resist mould growth and at the same time not resist decay fungi (Yang and Bisson 2004) and visa versa. Although, in this study, heartwood substrate had less surface mould growth than sapwood and mixed wood. Further, copper is well known for its anti-fungal properties, mainly towards decay fungi, and copper compounds will over time migrate to the surface of copper-organic preserved wood. Alfredsen et al. (2008) found that copper containing preservatives also had less surface mould growth than non-copper containing samples. In the present study it was shown that mixed Norway spruce, Scots pine sapwood, heat-treated Scots pine and heat-treated Norway spruce substrates have higher expected probabilities to resist mould growth than the untreated aspen sapwood, European oak, acetylated Scots pine and furfurylated Scots pine substrates and were only slightly more susceptible than Scots pine heartwood, Siberian larch heartwood and copper-organic preserved pine. Heat treatment improves the durability and dimensional stability of wood and gives better coating performances (Boonstra et al. 1998; Jämsä et al. 2000; Rapp and Sailer 2000). This should give a surface with fewer checks and lower possibilities for fungal establishment, but this seems not to be the case in this study. Heat-treated Scots pine performed similar to non-heat-treated Scots pine sapwood and the same as Norway spruce substrates. Oil heat-treated Scots pine appeared to perform slightly worse. Jämsä et al. (2000) and Ahola et al. (2002) revealed that heat treating wood did not prevent fungal growth any better than untreated wood when it was surface coated and tested outdoors.

The acetylated pine substrate had higher calculated expected probabilities of higher mould ratings indicating more surface mould than the other substrate groups. Acetylated pine restrains growth of decay fungi and possess properties that extend the service life when used in above ground applications (Brelid and Westin 2007), but several studies support our findings that acetylated wood does not restrain blue stain fungi (Beckers et al. 1994; Edlund 2004; Nienhuis et al. 2003; Wakeling et al. 1992). Rather, the impression is that acetylation in some cases can promote mould growth on the surface of the wood. Aspen as compared to other wood species in the substrates tended to have a higher probability of having higher mould ratings with more surface mould than other wood substrates. One has to be aware of a possible interaction between ASsapUNTR and the coatings, which the authors were unable to assess with this model. Further, aspen is known as a less durable species (EN 350-2 1994) and was expected to be more susceptible to mould growth.

Conclusion

Service life of coated wooden materials used as external claddings, fences, noise barriers, etc. is expected to be several decades depending on the deterioration-influencing factors. Data from 4.5 years of accelerated outdoor exposure and projected average mould coverage ratings indicate that the aesthetic service life for coated wooden claddings are mainly determined by the coating system given that the climatic factors are more or less uniform. The slope coefficient for mould coverage over time will decide the time when the panel will reach end of service life and maximum mould rating. The results from this study should be considered as an initial step towards a better understanding of the wood substrate—coating processes and possible interactions when considering surface mould growth. Exposure of the panels in this study and regular evaluation will continue. Responses like cracking, flaking, blistering and adhesion of the paint film due to outdoor exposure will influence mould growth and should therefore be examined for a more complete model.

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