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Evaluation of Selected Accelerated Above-Ground Durability Testing Methods for Wood after Ten Years Exposure

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Abstract: Traditional benchmark wood durability testing methods such as stake tests take many years to give conclusive results, and in-ground tests do not always indicate the efficacy of preservatives in above-ground situations. To find test methods that would shorten the time required for wood evaluation for above-ground end uses, a series of different types of accelerated durability tests were set up. Five types of test: ground proximity, two types of decking, flat panels and double layer, were reassessed after ten years to determine whether the decay rankings given to the various types of preservative had changed over the extended exposure period. Exposure conditions varied between tests, with ground proximity being close to ground, and the double layer test carried out in very wet conditions, while raised decking and flat panel tests were relatively dry. In all of these tests, the preservative retention was 25% of the normal H3 retention. The results indicated that the ground proximity tests gave the fastest and most reliable results. Flat panels contained the next highest decay rates, followed by ground-level decking, double layer and raised decking. The evaluation and comparison of these five test methods after ten years' field exposure confirmed the trend and relative decay rate that was observed at four-year exposure. The use of a regression model for prediction showed a statistically significant overall relationship between decay scores in 2011 and 2017 (coefficient = 0.14 ± 0.07 , d.f. = 345.7, $t = 2.038$, $p = 0.042$). When resistance to decay was compared between preservatives, copper-chrome arsenate (CCA)-treated pine and naturally durable spotted gum samples were in better conditions than pine treated with any of the other preservatives.

Keywords: built environment; ground proximity test; service life prediction; testing methods; timber durability; wood product evaluation

1. Introduction

The prediction of the service life of a wooden commodity in built environment is the most significant consideration. Although several performance models are available for predicting the service life of a wooden products [1,2], the reliability and robustness of testing data which these models are based on are still in question [3]. It is acknowledged that the interrelationship between the key factors of fungal degradation, such as moisture, temperature and other biotic/abiotic agents, and their influences over time, is needed for the service life prediction of wooden commodities used in above-ground outdoor applications [3]. The standard above-ground durability tests often take a long time for decay to set in, and therefore it is difficult to calculate the expected service life [4].

Reducing the testing time for the durability of wood products is very desirable in the wood protection and timber industry for a return on their investment [5,6]. Although laboratory-based pure culture decay testing can be completed within 6 months, it is only useful as a screening test, not a substitute for field testing [7,8]. Laboratory-based decay tests have several limitations, including

not being subjected to natural weathering and UV and not being exposed to natural microbes in the environment [9,10]. Field exposure data are essential for wood products to be used for outdoor applications such as decking, cladding, window joinery [11], generally categorised as “Hazard” or “Used” Class 3. One of the main issues to be aware of in the Hazard Class 3 decay testing is the wide range of exposure that can occur within this class.

A number of outdoor exposure testing methods are used around the world [12], however it takes several years to get any meaningful results [13–15]. Each method has advantages and disadvantages for example, it was recognised that if above-ground test methods such as ‘Peg test’ [12] are used when specimens are too small it dries out very quickly, which can have an adverse effect on fungal establishment and growth and can delay the test results. However, the advantages of the ‘Peg test’ is that it is simple and easy to set up and the number of replicates can easily be increased so better statistical results can be produced. In Australia/NZ, three above-ground test methods—decking, L-joints and flat panels—are commonly used and were listed in Australasian Wood Preservation Committee (AWPC) protocols prior to 2015.

In this study, a series of above-ground exposure tests were installed in 2007 to determine which type of exposure test would give the most consistent results in the shortest time. The focus of the research was to accelerate the process of decay, but, at the same time, find the methods that are reliable and reproducible [16,17] and can contribute towards predicting the service life of the tested materials. To validate the design of various test methods, the relative order of failure of seven timber treatment/types in each test design was also compared in this study.

This manuscript evaluates and compares the condition of samples and relative durability ratings in five above-ground decay test methods after exposure periods of four and ten years. This was to determine which method gave the fastest results and whether rankings after four years remained the same after ten years.

2. Materials and Methods

2.1. Test Methods and Preservative Types

Several techniques were employed in the testing methods, including maintaining dampness in the test samples for a longer period, evaluating the effect of wetting and drying, and inoculating with known wood decay fungi rather than relying on natural incursions only [18–20]. The test methods used in this study included existing test systems, several “new” systems, plus the acceleration of some tests using pre-inoculated, untreated decay feeder blocks [21] or interior exposure in controlled conditions during cooler months of the year. The tests were reported and compared with Australian exposure sites after four years exposure. A full description of test methods was provided in Cookson et al. [22].

The timber used for the test samples was kiln-dried *Pinus radiata* sapwood from Pine Solutions Ltd. in Dandenong, Australia, and for the naturally durable samples, spotted gum (*Corymbia maculata*) heartwood from Burnetts sawmill in Bundaberg, Australia.

The test methods are briefly described below:

1. Ground Proximity:

The dimensions of test specimens were 75 × 25 × 200 mm. The test method was as described by Archer et al. [23]. Test specimens were laid flat on top of two layers of 40 mm thick concrete blocks with a sheet of plastic “weed cloth” between the concrete blocks and the ground. The specimens were randomly arranged in five rows with about 10 mm gaps between samples on all sides. A 150 mm deep wooden frame covered with shade cloth was placed over the whole assembly (Figure 1).



Figure 1. Ground proximity test at installation with the shade-cloth and frame removed. The samples are placed on two layers of 40 mm thick pumice slabs with plastic weed mat underneath.

2. Double Layer:

The dimensions of test specimens were $75 \times 25 \times 300$ mm, which was different to the recommendation by Rapp and Augusta [24], to minimise the variation in test specimen sizes in this comparative trial. A plastic weed mat was placed on the ground and three rows of 90-mm-thick concrete blocks were placed on top of that. Three 100-mm-deep copper-chrome arsenate (CCA)-treated bearers were placed on the blocks. A 70×25 mm untreated pine strip was fixed on edge along the centre of the central bearer, while 70×25 mm H3.2 (Hazard Class H3.2, NZS 3640: 2003) [25]-treated strips were fixed along the outer edge of the outer bearers. Samples from each treatment group were in two layers, with five samples in the one layer, six in the other and samples overlapping those in the other layer by half the sample width. The samples were in close contact with untreated pine samples separating the treatment groups. One end of each sample was in contact with the central untreated strip, while the other end was in contact with the outer H3.2-treated strip (Figure 2). The whole assembly was surrounded by a 300-mm-deep frame covered with shade cloth;



Figure 2. Double layer test at installation. 100 mm square bearers supported on concrete blocks with plastic weed cloth underneath. The plastic strips between the samples and bearers were removed after a few weeks exposure. The batten along the centre was untreated pine, those on the outside were H3 treated. The whole assembly was surrounded by a 300-mm-deep frame covered with shade cloth.

3. Decking (ground-level):

The decking trials were set up as described in AWPC [26], with samples randomly arranged in two rows on 3/100 mm deep bearers. The dimensions of test specimens were $75 \times 25 \times 300$ mm. On the central bearer there was a 20-mm-thick untreated pine strip between the samples and the decking with a 40×20 mm untreated strip on edge, separating the ends of the two rows of decking. At the outer ends of the decking there was a 20-mm-thick, H3.2-treated strip between the samples and the bearers. There was a 5 mm space between samples. In the ground-level test, the bearers were placed directly on the ground in a grassed area;

4. Decking (1-m above-ground):

The 1-m above-ground decking sample sizes and set up was like ground-level decking, except for the 1-metre test the bearers were supported on posts 1 metre above the ground in the same grassed area (Figure 3);



Figure 3. Raised decking test at installation showing treated bearers and battens at the outer ends of the samples and untreated bearers plus separating strip in the centre. For the ground-level decking test, the treated bearers were placed directly on the ground, but other details were the same as for raised decking.

5. Flat panels:

A standard flat panel test was set up as described in AWPC (2015) [26]. The dimensions of test samples were $75 \times 25 \times 200$ mm. They had a keyhole-shaped slot cut in them close to one end. They were exposed on 45° sloping racks, facing north. The samples were randomly arranged in two rows, resting on an H3.2-treated batten at the upper end and on an L-shaped untreated pine support at the bottom end. A screw through the keyhole slot fixed the samples to the upper batten (Figure 4).



Figure 4. Flat panel test after installation. The upper rail holding the screws is H3-treated radiata pine. The lower L-shaped rail is untreated radiata pine.

In the Australasian Wood Preservation Committee Protocols for the Assessment of Wood Preservatives [26] results suitable for achieving registration can be obtained when timber treated to one quarter of the H3 reference preservative retention reaches less than 70% soundness. The preservatives used for the two decking tests, ground proximity, double layer and flat panel tests were all at 25% of the normal Australian H3 specification retention:

- Alkaline copper quaternary (ACQ), supplied by Osmose Ltd. as copper ammonium carbonate (CAC) and Didecyldimethylammonium chloride (DDAC). An aliquot of 360 mL of CAC and 227 mL of DDAC were added to water to make up 100 L of a preservative solution containing 0.055% active ingredients (CAC + DDAC);
- Copper-chrome arsenate (CCA), Tanalith O oxide supplied by Arch Wood Protection, Ltd. was shown by inductively coupled plasma mass spectrometry (ICP-MS) analysis to contain 9.2% Cu, 15.2% Cr and 12.4 As. Twenty litres of solution was made up using water and 32.27 g of Tanalith O to give a treating solution containing 36.8% m/m total active ingredients;
- Tebuconazole/propiconazole LOSP was Vacsol Azure supplied by Arch Wood protection Ltd. and shown by analysis to contain 0.048% (*w/v*) tebuconazole, 0.047% (*w/v*) propiconazole and 0.33% (*w/v*) permethrin, i.e., it contained 9.5 g/L total azoles;
- Tributyl tin naphthenate Lifewood H3 (235WR) supplied by Osmose Ltd. contained 1.1%–1.2% m/v tin, 0%–2% permethrin, 0%–5% dichlofluanide and >90% white spirits. The treatment solution supplied contained 0.38% m/v tin. (this is 25% of the H3 requirement in Australia but 50% of the H3.1 requirement in New Zealand);
- The high flashpoint kerosene was supplied by Arch Wood Protection, as Shell Mexcut 8 with a specific gravity of 0.8 at 15 °C and a flashpoint of 78 °C.

Ten pine samples, treated with each type of preservative plus water-treated pine and untreated spotted gum, were installed for decking, ground proximity, flat panel and double-layer test. Pine control samples were treated with water to ensure that any changes in the wood that may have been caused by saturating and re-drying of the wood using aqueous preservatives would be duplicated. Spotted gum heartwood is in Class 2 (durable) in the Australian Standard (AS5604: 2003 Timber—Natural durability ratings) [27] and would normally be used without preservative treatment in most exterior, above-ground situations.

Before treatment, the samples had an average moisture content of 10.5%. The moisture content of samples was determined by weighing sections cut from surplus samples, oven-drying them for two days and reweighing.

Schedules used for the treatment of samples were:

- Water and water-based preservatives—initial vacuum −95 kPa (0.95 bar) for 30 min, 1400 kPa (14 bar) for 60 min, no final vacuum, giving an average uptake of 650 kg/m³;
- Light organic solvent preservative (Tributyl tin naphthenate)—initial vacuum −55 kPa (0.55 bar) for 5 min, flood while maintaining vacuum, (about 10 min), release vacuum and drain, final vacuum of −90 kPa (0.9 bar) for 30 min, giving an average uptake of 60 kg/m³;
- HF kerosene schedule was similar to the LOSP schedule, except that the initial vacuum was −80 kPa (0.8 bar) for 5 min, giving an average uptake of 115 kg/m³.

Samples were weighed immediately before and after treatment. The surface of those treated with water-based preservatives was wiped with absorbent paper to remove surface liquid before being weighed after treatment. Preservative uptake was calculated by dividing the sample weight gain during treatment by the saturated volume of the sample and expressed as litres/cubic metre. After being air-dried in the laboratory, a stainless-steel tag containing the sample number and a treatment code was attached to each sample.

2.2. Assessment Methods

The tests were left in place, outdoors, after the four-year assessment at Whakarewarewa, Rotorua test site (New Zealand, with 1400 mm mean annual rainfall). Those remaining after ten years were re-assessed, but by that time the stakes and rot boxes had gone. While most of the embedded test samples remained, the support structures had collapsed and the samples were scattered on the ground, hence they were not assessed. The remaining tests were: ground proximity, double-layer, decking (ground level and 1 m above ground) and flat panels.

Assessments for decay only were done by a single experienced assessor using a blunt 3-mm-diameter probe, and sample ratings were based on the American Standard ASTM D-1758 [28] as follows:

Ratings for decay/insect damage

10 = No decay or insect damage;

T = “Trace” discolouration, decay suspected but not positively identified;

9 = Minor decay or damage at defects, less than 3% of the cross section;

8 = Minor but established decay, 3%–10% of the cross section;

7 = Well established pockets or extensive surface damage, 10%–30% of the cross section;

6 = Extensive established and deepening decay, 30%–50% of cross section;

4 = Deep and severe decay, more than 50% of cross section;

0 = Disintegrating, failed.

All samples were given a single decay rating. To determine the condition of any set of samples including failed samples (rated 0), ratings were averaged. For all tests, decay ratings apply to the most decayed part of the cross-section along the sample.

2.3. Statistical Analysis

Statistical analysis of the data obtained was carried out using the SAS PROC GLM program [29]. Differences in test and treatment effects were confirmed by a linear model (Table S1).

Further, statistical analysis was undertaken using R. Mixed effects models used the lme4 package (R package version 3.6.2, <https://www.R-project.org>). Decay scores in 2017 were predicted from a mixed-effects regression.

3. Results

The average decay rating of the five test methods using various preservatives are given in Table 1.

Table 1. Decay Ratings after 4 years exposure at Whakarewarewa, Rotorua.

Treatment	Decking Ground Level	Decking 1-m Above-Ground	Ground Proximity	Double Layer	Flat Panel
Water	7.2	9.5	4.2	4.5	9.7
HFK	7.5	9.7	6.3	5.9	7.8
ACQ (1/4) *	10.0	10.0	7.4	9.1	9.3
CCA (1/4) *	10.0	10.0	9.4	10.0	10.0
Azoles (1/4) *	9.9	9.8	7.5	9.5	9.9
TBT (1/4) *	9.9	9.8	7.0	9.7	10.0
Spotted Gum	9.9	10.0	9.7	9.9	10.0

* Preservative retentions were one quarter of that required in New Zealand for treatment to the H3 specification. HFK = high flashpoint kerosene; ACQ = Alkaline copper quatarnary; CCA = Copper-chrome arsenate; TBT = Tributyl tin naphthenate.

Decay ratings after ten years are summarised in Table 2. These show that the ground proximity test has produced the most extensive decay compared to other test methods. The flat panel test was the next most severe overall (Table S3, Supplementary Material). Ground-level decking, and double-layer

tests gave similar results, although the untreated bearer end of the decking was generally slightly more severe than in the double layer samples, while decay at the treated bearer end was slightly less.

Table 2. Decay Ratings after 10 years exposure at Whakarewarewa, Rotorua.

Treatment	Decking Ground Level	Decking 1 m Above Ground	Ground Proximity	Double Layer	Flat Panel
Water	1.6	2.9	0	3.7	1.9
HFK	4.0	2.9	0.4	5.6	0
ACQ (1/4) *	8.0	9.7	1.6	7.5	6.6
CCA (1/4) *	8.9	9.1	4.8	9.1	8.2
Azoles (1/4) *	7.3	8.7	1.5	7.7	7.3
TBT (1/4) *	7.7	8.8	0.4	7.1	8.3
Spotted Gum	8.8	9.9	7.1	8.5	9.9

* Preservative retentions were one quarter of that required in New Zealand for treatment to the H3 specification.

Decay scores in 2017 were predicted from a mixed-effects regression (conditional on treatment as a random effect; $R^2 = 0.68$, $RMSE = 2.08$, Figure S1). The model showed a statistically significant overall relationship between decay scores in 2011 and 2017 (Coefficient = 0.14 ± 0.07 , d.f. = 345.7, $t = 2.038$, $p = 0.042$). Fixed effects of test type showed that flat panel and ground proximity test had significantly lower scores in 2017 than other tests (d.f. = 342.2, $t = 3.313$, $p = 0.001$ and d.f. = 342.1, $t = 12.890$, $p < 0.001$, respectively).

The conditions produced by the various types of exposure were quite different. Ground level decking tests and flat panel tests are standard above-ground testing methods used in the assessment of wood preservatives in the Australasian Wood Preservation Committee's protocols [26]. The ground proximity test originally produced damp, close-to-ground contact conditions on the underside of the samples, but relatively dry conditions on the upper-side, except during rainy periods (Figure 1). The samples had originally been protected by shade cloth, but this had largely gone by the ten-year assessment, which allowed wind-blown debris to collect on the upper surface and in the gaps between samples. Samples were on-concrete paving slabs with weed-mat underneath, as per the original installation (Figure 5).



Figure 5. Ground proximity test after 10 years exposure. The samples were originally covered with shade cloth but this was damaged and debris from mowing the surrounding grass supported vegetation growth between and on samples. Most of the samples, including preservative-treated, ones were in poor condition.

In the double layer test, the shade cloth cover was still largely intact. Samples were all very wet and slimy, close to saturated, although the upper side of the top layer was relatively dry (Figure 6). The close contact between samples and the surrounding timber/shade cloth protection prevented surfaces from drying rapidly after rain.



Figure 6. Double layer test after 10 years exposure. The upturned samples 3rd–7th from left, upper row) are copper-chrome arsenate (CCA)-treated (between two arrows), all others are untreated controls. The upper surface of the second layer opposite in the lower row is the same treatment. Note that there is very little decay in the CCA treated samples but there is severe decay in all of the untreated samples (examples of visible decay are indicated by asterisk * symbol).

In the ground level decking test, samples remained damp on the underside, particularly at the bearers in all but prolonged dry periods. In the one metre decking, the samples were free to dry on all surfaces except where the ends were in contact with the bearers. The untreated bearers were gradually infected with decay fungi, which then began to spread into the end of the samples in contact with them. At the time of assessment, the samples in both decking tests were relatively dry, although the underside of the ground level decking was damp. There were some decay patches in the untreated decking bearer, but it was still intact.

On the flat panel exposure rack, the lower end of the samples was supported on an “L”-shaped untreated batten. In this type of test, samples are free to dry after wetting by rain, except at the bottom end where they are in contact with the support batten. This was severely decayed in places and the decay activity in the support batten appeared to have carried over into many of the samples.

4. Discussion

At the four-year assessment, the Rotorua ground proximity test was giving useful results, but in the decking, double-layer and flat-panel tests there was very little decay in preservative-treated and spotted gum samples. Severe decay had developed in many of the untreated and HFK-treated pine samples in the double-layer test and there was significant decay in in a few samples of ground level decking. Otherwise, even the untreated pine samples contained little decay. This trend is somewhat similar to the previous studies [17,30] where the rate of decay is low in many commonly used H3 test methods.

When resistance to decay was compared between preservatives, CCA was similar to spotted gum and better than any of the newer preservatives. There was little difference between ACQ, Azoles and TBT. In the original four-year assessment of all test sites [22], the relative order of failure for outdoor exposure was water, HFK, TBT, ACQ, Azoles CCA and spotted gum. This was similar for the ground proximity test at Rotorua except that the ACQ samples were better than the Azole samples.

Between the four- and ten-year assessments decay had obviously progressed in all test types. Brown rot fungi prevailed, although there was obvious white rot decay in the spotted gum samples in the ground proximity, ground-level decking and double layer tests. Soft rot decay was also evident in the same tests, particularly in the Azoles-treated samples. In terms of resistance to decay, fungi across all test methods, spotted gum and CCA-treated groups were significantly most resistant ($p \leq 0.05$) but there was little difference overall between the other three preservatives.

The loss of part of the shade cloth cover over the ground proximity test allowed windblown and other debris, such as grass clippings, to collect on the surface and in the spaces between samples over the six years from the four to ten-year assessments. This supported some vegetation growth and would have increased the decay hazard. This problem also occurs with the existing ground level decking test method, where debris collects on samples, and on the bearers between samples vegetation often grows up between samples also. This also occurs to some extent in exterior building structures such as decks. In accelerated tests, the protection of the samples with shade cloth reduces the decay hazard likely to develop during the service life of normal exterior components. In this test, loss of the shade cloth cover, while resulting in the decay hazard increasing more than if the shade cover had remained in place, was not considered to negate the results from the ground proximity test. Furthermore, the ground proximity test gave meaningful results after four years and it would not be necessary to carry the tests for ten years.

Decay in the flat panel test had progressed considerably over the six years and the average decay rating was worse than for the two decking tests and the double layer test. The resistance to decay order was also quite different to the trends shown in the ground proximity tests. While spotted gum was still the most resistant to decay, CCA and TBT had similar ratings, and Azoles were more resistant than ACQ. This increased decay in the copper-based preservative treated samples may have been associated with the 30-year old CCA-treated support frames. As would be expected after 30 years, the frame structures contained some decay. The untreated lower support battens for the flat panel samples were attached directly to the frames and while there was some decay in these after four years, it was generally only associated with untreated and HFK-treated radiata pine controls. After 10 years, there were areas of severe decay, and the bottom end of samples in these areas contained moderate-severe decay even though conditions were relatively dry. The decay fungi active in the old support frames may have some tolerance to copper [31] and have more readily infected test samples treated with copper-based preservatives [32]. This is similar in some respects to results from the four-year test results at Innisfail, where flat panel samples on old exposure frames were more significantly decayed than those on new frames [22].

The very high moisture content in the double-layer test, even when climatic conditions were very dry, clearly reduced the activity of some decay fungi. Only a few of the control and HFK-treated samples had completely failed after ten years. Resistance to decay in the CCA-treated samples was better than the spotted gum because a small amount of soft rot and some white rot had developed on the spotted gum samples. While the other three preservative-treated groups showed similar resistance to decay, Azoles were slightly better than ACQ, which was better than TBT.

The moisture content differences between the two types of decking tests probably explains why the decay ratings in the ground-level decking were slightly more severe than those for the elevated decking. If results at the untreated bearer are compared to the ground level decking, the order was CCA, spotted gum, ACQ, TBT and Azoles, and this was unchanged at the treated bearer. For the elevated decking test, the order was spotted gum, ACQ, CCA, TBT and azoles, but at the treated bearer end, both TBT and azoles were free from visible decay and better than either CCA or ACQ. There was so little decay in the treated samples in this test after ten years that it was of little value in determining the most effective preservative formulations.

In this series of tests, the samples were treated to 25% of the H3 retention requirement in an attempt to reduce the time required to produce meaningful results. While this indicates that using a lower preservative retention may speed up determinations as to whether a chemical is suitable as a

preservative, tests should include material treated at the predicted required retention to confirm that it will meet the expected minimum life of the commodities it is likely to be used for.

Ground-level decking is currently the most popular method used in New Zealand for above-ground testing of preservatives. It is relatively simple to set up and maintain but often takes ten years or more to produce meaningful results. The ground proximity test provided faster results than the ground level decking and the ranking of the various preservatives was similar. It is relatively simple to set up and should be able to provide meaningful results within 5 years.

5. Conclusions

The review of five accelerated test methods after ten years field exposure confirmed the trend and relative decay rate that was observed at four-year exposure assessment. The use of a mixed effect regression model for prediction showed an overall relationship between the decay rating scores of four and ten years assessments.

Results after ten years confirm that the ground proximity test gives the most useful results in the least time for the test methods assessed. However, climatic conditions are known to influence rates of decay and the ratings order may differ between the Rotorua, New Zealand and other test sites, which have different climatic conditions. Test sites with different environmental conditions may favour other tests, hence collaborative research on various test sites around the world is desirable.

Supplementary Materials: The following are available online at <http://www.mdpi.com/1999-4907/11/5/559/s1>, Figure S1: Decay scores in 2017 were predicted from a mixed-effects regression (conditional on treatment as a random effect; $R^2 = 0.68$, RMSE = 2.08), Table S1: Summary of Statistical Analysis.

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