International Biodeterioration & Biodegradation xxx (2013) 1–6

Contents lists available at ScienceDirect

International Biodeterioration & Biodegradation

journal homepage: www.elsevier.com/locate/ibiod

# Effectiveness of on-site remediation treatments for framing timber

Tripti Singh [a, *], Dave Page [a], Adrian Bennett [b]

[a] Scion, Private Bag 3020, Rotorua, New Zealand
[b] Ministry of Business Innovation and Employment, Wellington, New Zealand

ARTICLE INFO

*Article history:*
Received 26 March 2013
Received in revised form
16 August 2013
Accepted 5 September 2013
Available online xxx

*Keywords:*
Boron
Copper naphthenate
Leaky building
Remedial treatment
Wood biodeterioration

ABSTRACT

Weathertightness failures in New Zealand buildings due to the combined effects of cladding choices, design and construction faults and the use of untreated framing timber has led to the so called 'leaky building syndrome'. The latest estimated cost of the leaky building crisis in New Zealand is about NZ$11 billion.

This research was conducted to provide a better understanding of the options of using in-situ preservative treatments for controlling incipient and early decay in framing timber which is still structurally sound when remediating leaky buildings.

The research approach involved taking untreated radiata pine sapwood, pre-infecting it with common brown rot fungi either *Oligoporus placenta* or *Gloeophyllum sepiarium*, applying a brush-on timber treatment of either boron-glycol or copper naphthenate to one or more sides, and then maintaining the samples at elevated moisture conditions. After specific durations, the samples were examined and tested to determine the effectiveness of the treatments in slowing down or preventing decay from progressing using measurement of stiffness (express as modulus of elasticity) and decay (expressed as an index of condition).

Assessment confirmed that the performances of both preservatives improved as more sides of timber were treated. However, there were significant differences in efficacy of both preservatives. Boron applied to three or four side appears to have been effective in preventing decay from progressing. Copper naphthenate at the concentration used has not been successful in preventing decay, regardless of the number of faces treated.

The treatment retention in samples treated with boron on three or four sides was about 0.4% (BAE w/w) and 0.65% (BAE w/w) respectively. This is close to or above the cross-sectional retention required by New Zealand H1.2 (interior framing) specification.



## 1. Introduction

Weathertightness failures (Murphy, 2001) in New Zealand buildings resulting in decay of timber framing have caused great concern (Hunn et al., 2002; Cooney, 2009). Most timber used for house framing in New Zealand is radiata pine. Up until 1992, the framing timber was always treated with boron. From the early 1990s, along with boron, a range of alternative timber framing treatment options became available including solvent based preservatives such as copper naphthenate, tri-n butyltin oxide and others (NZS 3640, 2003). Due to changes in the building code, from 1995 to April 2004, homes were often built with untreated kiln-dried radiata pine. Problems with the decay of untreated, kiln-dried radiata pine house framing when water penetrated the exterior cladding (leaky buildings) became prominent in the late 1990's (Hardie, 1997; Hunn et al., 2002). While building regulations requiring the preservative treatment of radiata pine framing were re-introduced in 2003, a large number of deteriorating buildings constructed in the previous decade continued to require extensive repairs (Groufsky, 2008). This generally includes re-cladding and replacement of unsound framing. Where framing appeared to be still sound, it was allowed to dry out and some type of brush-on remedial treatment was applied before new cladding was installed. The efficacy of these brush-on treatments in this type of situation had not been widely tested and there were many situations within buildings where the in-situ application of preservative could only reach one or two surfaces of the components (Cooney, 2009). There was also some uncertainty about the identification of "incipient decay" (Winandy and Morrell, 1993) and whether apparently sound timber adjacent to decaying timber could be

* Corresponding author. Tel.: +64 7 343 5329; fax: +64 7 343 5507.
*E-mail address:* tripti.singh@scionresearch.com (T. Singh).

0964-8305/$ – see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.ibiod.2013.09.003

**Table 1**
Sample treatment and exposure groups.

| Group code | | Exposure type | Number of samples/group | Pre-decay period (weeks) | Number of edges treated | Number of faces treated |
|---|---|---|---|---|---|---|
| Copper naphthenate treated | Boron treated | | | | | |
| C61H | B61H | HMC | 20 | 8 | 1 | – |
| C62H | B62H | HMC | 20 | 8 | 2 | – |
| C63H | B63H | HMC | 20 | 8 | 2 | 1 |
| C64H | B64H | HMC | 20 | 8 | 2 | 2 |
| C31H | B31H | HMC | 20 | 4 | 1 | – |
| C32H | B32H | HMC | 20 | 4 | 2 | – |
| C33H | B33H | HMC | 20 | 4 | 2 | 1 |
| C34H | B34H | HMC | 20 | 4 | 2 | 2 |
| C62L | B62L | LMC | 10 | 12 | 2 | – |
| C64L | B64L | LMC | 10 | 12 | 2 | 2 |
| C32L | B32L | LMC | 10 | 7 | 2 | – |
| C34L | B34L | LMC | 10 | 7 | 2 | 2 |
| | B3H | HMC | 20 | 4 | H1.2 treated | |
| | B3L | LMC | 10 | 7 | H1.2 treated | |
| U3H (untreated) | | HMC | 20 | 4 | – | – |
| U3L (untreated) | | LMC | 10 | 7 | – | – |
| UMH (untreated) | | HMC | 20 | Nil | – | – |
| UML (untreated) | | LMC | 10 | Nil | – | – |

successfully protected by brush-on remedial treatments. The possibility that minor decay in timber could be stopped by brush-on treatments was also questioned.

A number of commonly used timber remedial treatment preservatives are readily available (Newbill and Morrell, 1993; Ridout, 2000; Wilkes and Page, 2004). Two of the commonly used products include a copper naphthenate concentrate that is diluted with a light organic solvent such as kerosene or white spirits (Morrell et al., 1996; Richardson, 1997) and the other one is a boron/glycol solution (Edlund et al., 1983; Vinden et al., 1990). Zinc naphthenate concentrate is also being used for non-commercial applications but is regarded as a less effective fungicide than copper naphthenate (Wilkes and Page, 2004).

This research was conducted to determine:

- Whether copper naphthenate or boron brush-on treatments would be effective in controlling decay on framing that already contained incipient or lightly established decay.
- The number of surfaces of a partially degraded component that needed to be coated to control decay.
- The extent of decay that could be present in a component before it was significantly weakened.

## 2. Materials and method

### 2.1. Timber samples

Radiata pine sapwood framing (SG 8), kiln dried and planer gauged to 90 mm × 45 mm, was cut into 950 mm long samples. Samples were sealed at both ends with epoxy paint (Altex Altrabuild 536). A set of samples that had been commercially treated with boron to the H1.2 specification were also included. The samples were all weighed and their moisture content was determined by oven drying biscuits cut from the samples. An oven-dry weight was calculated for each sample using this moisture content data. All samples were soaked in water for 80 min to achieve a moisture content above 30%.

### 2.2. Fungal pre-infection

Two brown rot fungi commonly found causing decay of untreated *Pinus radiata* D. Don, in leaky buildings in New Zealand was selected; *Oligoporus placenta* (Fries 1865) and *Gloeophyllum sepiarium* (Wulf.: Fr.) Karst.

Small 35 mm square blocks of radiata pine sapwood that had been pre-infected with selected brown rot decay fungi (Hedley et al., 2009), either *O. placenta* to be exposed in wetter high moisture content (HMC) conditions (>30% MC) or *G. sepiarium* for samples that were to be exposed in drier, low moisture content (LMC) conditions (25–27% MC), were attached near the centre of each sample on one edge. The samples were stacked in sealed plastic tanks with 20 mm thick plastic fillets separating the layers. In each tank there was a small amount of water in the bottom and a wet foam plastic blanket in the top to maintain high humidity. The tanks were kept in a laboratory where the ambient temperature was 15–20° C. The intention was to pre-decay samples for two periods, the first just sufficient to produce "incipient decay" in the samples, the second to produce more established decay. Half of the HMC samples were left in the pre-decay tanks for four weeks, the remainder for eight weeks. The *G. sepiarium* decay blocks were slower to develop on the LMC samples and half of these samples were in the tanks for seven weeks, the remainder for twelve weeks. The commercially treated samples were kept in the tanks for four weeks, (HMC exposure samples) or seven weeks (LMC exposure samples).

### 2.3. Sample assessment before remedial treatment

At the end of the decay exposure period (as mentioned above), once the samples had reached the required degree of decay, they were removed from the tanks, reweighed, assessed mycelium spread and decay using the American Standards rating systems based on AWPA Standard E7-1993 (AWPA, 1999) shown below.

*Decay Ratings*

10 = No decay.
T = Trace, discolouration or softening, not positively identified as decay.
9 = First stages of decay or damage up to 3% of cross-section.
8 = Lightly established decay, 3–10% of cross-section.
7 = Well established decay, 10–30% of cross section.
6 = Deep established decay, 30–50% of cross section.
4 = Severe decay, nearing failure, more than 50% of the cross section.
0 = Failed.

Please cite this article in press as: Singh, T., et al., Effectiveness of on-site remediation treatments for framing timber, International Biodeterioration & Biodegradation (2013), http://dx.doi.org/10.1016/j.ibiod.2013.09.003

**Table 2**
Preservative application rates and retention.

| Treatment | Copper naphthenate | | Boron | |
|---|---|---|---|---|
| | Application rate (g/m$^2$) | Retention (g/100 g Cu) | Application rate (g/m$^2$) | Retention (g/100 g BAE) |
| **HMC samples** | | | | |
| One edge | 149 | 0.006 ± 0.001[a] | 182 | 0.107 ± 0.019 |
| Two edges | 140 | 0.011 ± 0.003 | 184 | 0.220 ± 0.033 |
| One face, two edges | 188 | 0.028 ± 0.006 | 182 | 0.426 ± 0.046 |
| Four sides | 220 | 0.044 ± 0.011 | 211 | 0.650 ± 0.083 |
| **LMC samples** | | | | |
| Two edges | 168 | 0.013 ± 0.003 | 179 | 0.215 ± 0.015 |
| Four sides | 241 | 0.048 ± 0.002 | 214 | 0.693 ± 0.055 |

[a] Standard deviation.

Decay feeder blocks were removed and external decay mycelium was cleaned off. Samples were then tested for deflection as a plank in a mechanical strength testing machine to assess the stiffness. The machine used for stiffness testing was a custom-built, three point, deflection measuring machine which gradually applies a 872 N load centrally to the sample over a 914 mm span. After stiffness measurement samples were placed in filleted stacks in the laboratory. Large fans were used to blow air through the stacks until the sample moisture content was below 20%.

### 2.4. Preservative treatment of samples

After two weeks of drying, two coats of remedial treatment products were applied by brush, either 50/50 copper naphthenate and kerosene (1.2% Cu w/v) or a boric acid/borax mixture in monoethylene glycol (20% Boric Acid Equivalent).

The sample infected with *O. placenta*, the treatment was applied to either one edge, two edges, two edges and a face or four sides. For samples infected with *G. sepiarium*, the treatment was applied to either two edges or four sides.

### 2.5. Sample exposure and assessment

After the preservative treatment, the samples were re-wetted and placed in tanks approximately 1 m long, 0.8 m wide and 0.8 m deep with a tight fitting lid and a drain in the bottom. Samples infected with *O. placenta*, were kept at 100% relative humidity (RH) and were intermittently wetted to maintain high moisture content (HMC), greater than 30% moisture content. Samples infected with *G. sepiarium* were kept at 95% RH to maintain low moisture content (LMC) samples at 25–27% moisture content. Samples were allocated randomly to the groups shown in Table 1.

Control samples of untreated *P. radiata* that had not been infected with decay fungi were placed in both the LMC and HMC tanks.

The samples were evaluated every two months for the first eighteen months of the study, and after that, at six monthly intervals. For all assessments during the trial, samples were removed from exposure tanks, weighed and measured using the same MOE apparatus as previously. The assessments measured deflection, moisture content, and amount of decay. The surfaces of each sample were tested with a blunt probe to determine the extent of decay based on AWPA Standard E7-1993 (AWPA, 1999). Moisture

**Table 3**
Annual mycelium spread, index of condition and deflection.

| Group code | Mycelium spread rating | | | Index of condition[a] | | | Deflection (mm) | | |
|---|---|---|---|---|---|---|---|---|---|
| | 56-wk | 108-wk | 159-wk | 56-wk | 108-wk | 159-wk | 56-wk | 108-wk | 159-wk |
| **High moisture content groups (159 weeks)** | | | | | | | | | |
| C61H | 3.4 | 4.2 | 5.3 | 7.6 | 6.5(1)[c] | 4.5(3) | 2.36 | 3.04 | 3.92 |
| C62H | 3.6 | 4.2 | 5.4 | 7.8 | 6.5(1) | 4.3(3) | 2.46 | 2.94 | 4.26 |
| C63H | 3.1 | 3.2 | 4.3 | 8.0 | 7.6 | 6.1(2) | 2.16 | 2.31 | 3.07 |
| C64H | 1.1 | 1.9 | 2.4 | 8.0 | 7.8 | 7.6 | 2.16 | 2.22 | 2.30 |
| B61H | 3.6 | 4.1 | 4.7 | 7.3 | 6.5 | 5.6 | 2.31 | 2.92 | 3.25 |
| B62H | 1.5 | 1.5 | 1.7 | 8.0 | 8.0 | 8.3 | 2.38 | 2.40 | 2.44 |
| B63H | 1.2 | 1.1 | 1.1 | 8.3 | 8.2 | 8.6 | 2.13 | 2.16 | 2.20 |
| B64H | 1.0 | 1.0 | 1.0 | 8.2 | 8.1 | 8.5 | 2.19 | 2.24 | 2.25 |
| C31H | 3.3 | 4.3 | 5.1 | 7.6 | 6.9 | 4.7(4) | 2.46 | 2.93 | 4.31 |
| C32H | 3.2 | 4.2 | 5.5 | 7.9(1) | 6.3(1) | 3.5(8) | 2.50 | 3.06 | 5.20 |
| C33H | 2.1 | 3.2 | 4.6 | 8.7 | 7.8 | 6.5 | 2.47 | 2.64 | 3.11 |
| C34H | 1.3 | 2.7 | 3.8 | 8.8 | 8.3 | 6.7(2) | 2.29 | 2.46 | 3.15 |
| B31H | 4.1 | 4.5 | 5.0 | 6.9 | 6.0 | 4.6(2) | 2.69 | 3.62 | 4.26 |
| B32H | 1.7 | 1.6 | 1.8 | 9.0 | 8.5 | 8.9 | 2.30 | 2.32 | 2.37 |
| B33H | 1.0 | 1.0 | 1.0 | 9.5 | 9.2 | 9.8 | 2.33 | 2.32 | 2.36 |
| B34H | 1.0 | 1.0 | 1.3 | 9.3 | 8.9 | 9.4 | 2.18 | 2.19 | 2.24 |
| B3H[b] | 1.0 | 1.0 | 1.0 | 10.0 | 10.0 | 10.0 | 3.88 | 3.88 | 3.93 |
| U3H | 3.9 | 4.5 | 5.2 | 7.2 | 5.1(4) | 2.9(10) | 2.66 | 4.11 | 5.76 |
| UMH | 2.7 | 2.4 | 2.9 | 9.4 | 8.5 | 7.7(2) | 2.28 | 2.39 | 3.01 |
| **Low moisture content groups (157 weeks)** | | | | | | | | | |
| C62L | 3.1 | 3.8 | 3.4 | 6.4(1) | 5.4(2) | 4.7(3) | 3.19 | 3.75 | 4.21 |
| C64L | 1.3 | 1.6 | 1.8 | 7.9 | 7.3 | 7.7 | 2.35 | 2.52 | 2.58 |
| B62L | 2.4 | 2.8 | 3.2 | 7.7 | 7.5 | 7.3 | 2.55 | 2.61 | 2.71 |
| B64L | 1.0 | 1.0 | 1.0 | 8.0 | 8.0 | 8.2 | 2.29 | 2.39 | 2.36 |
| C32L | 2.2 | 2.9 | 3.3 | 8.1 | 7.3 | 6.1(1) | 2.22 | 3.15 | 3.29 |
| C34L | 1.0 | 1.1 | 1.0 | 8.2 | 8.0 | 8.1 | 2.08 | 2.21 | 2.18 |
| B32L | 1.1 | 1.6 | 1.7 | 8.3 | 8.1 | 8.3 | 2.09 | 2.18 | 2.18 |
| B34L | 1.0 | 1.0 | 1.0 | 8.2 | 8.4 | 8.4 | 2.30 | 2.39 | 2.36 |
| B3L[b] | 1.1 | 1.0 | 1.0 | 10.0 | 10.0 | 10.0 | 3.73 | 3.84 | 3.83 |
| U3L | 2.5 | 3.4 | 3.9 | 6.3(1) | 5.0(3) | 4.4(3) | 3.37 | 4.21 | 4.18 |
| UML | 1.7 | 1.9 | 2.2 | 9.6 | 8.1(1) | 7.5(1) | 2.25 | 2.99 | 3.02 |

[a] Index of condition is the average decay rating for all of the samples in a group.
[b] This group was framing grade timber, all other groups were clears grade sapwood.
[c] The number of samples in the group that had failed (in parenthesis).

Please cite this article in press as: Singh, T., et al., Effectiveness of on-site remediation treatments for framing timber, International Biodeterioration & Biodegradation (2013), http://dx.doi.org/10.1016/j.ibiod.2013.09.003

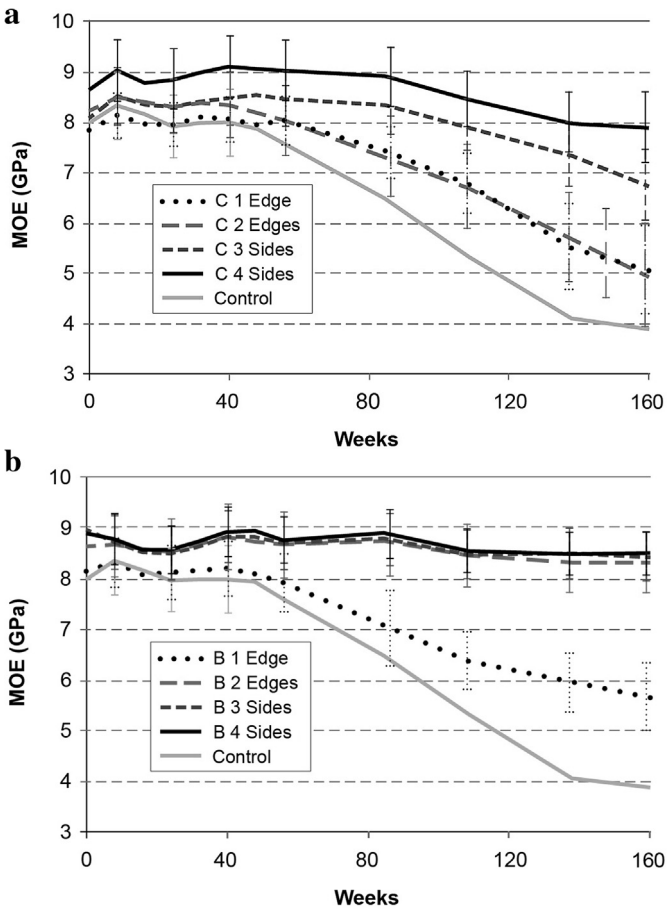


**Fig. 1.** a. The mean modulus of elasticity (MOE) for copper naphthenate treated samples. b. The mean modulus of elasticity (MOE) for boron treated samples.

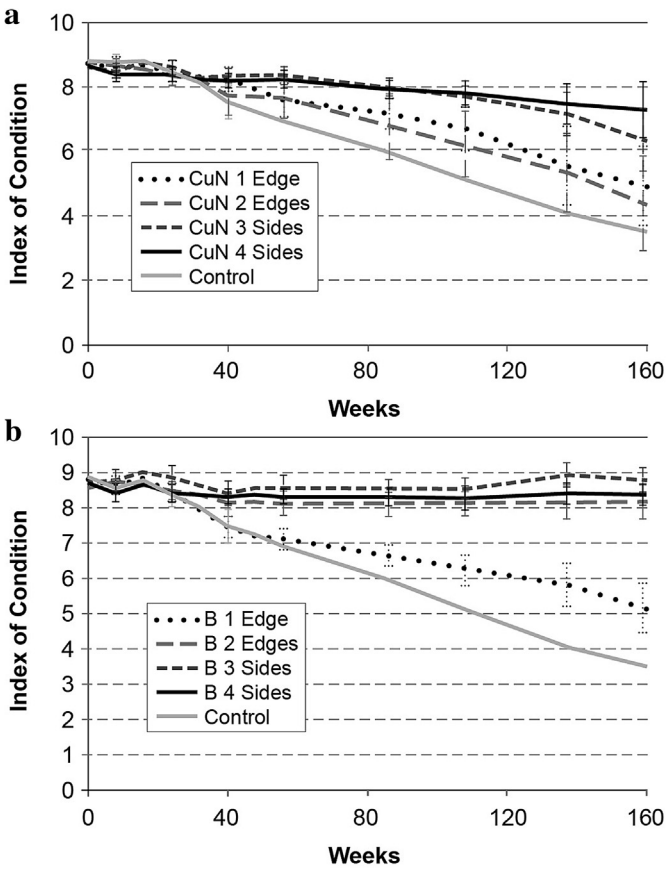


**Fig. 2.** a. The mean index of condition for Copper naphthenate treated. b. The mean index of condition for Boron treated samples.

content calculations were based on changes in sample weight. Deflection as a plank under a constant load was measured. Modulus of Elasticity (MOE) for each sample was calculated using sample cross-section and deflection measurements.

After assessment the samples were returned to their original exposure positions. The HMC samples were sprayed with water as they were re-installed but the LMC samples were protected from wetting.

After the 159-week, final assessment, five samples for each preservative type, that had been treated on various sides, were removed from each of the HMC and the LMC exposure groups randomly. Biscuits were removed from each sample for chemical analysis and for reagent testing to determine the penetration of the preservative and the extent of decay.

For decay analysis, one set of samples from each group was sprayed with methyl orange reagent which turns a pink-red colour where there is an active decay (Ellis, 1961). Samples were matched to analyses of preservative distribution. For copper naphthenate, samples were sprayed with rubeanic acid reagent which turns blue-black in the presence of copper (Cummins, 1966). For boron, samples were sprayed with tumeric reagent which turns red in the presence of boron (Robinson, 1939).

### 2.6. Statistical analysis

A two-way analysis of variance was conducted and least significant difference tests were used to compare differences between the efficacy of two preservatives and also the differences between treating various sides of framing timber for each preservative.

Differences were considered to be significant at $P \leq 0.05$.

## 3. Results

### 3.1. Timber treatment retention levels before exposure

The application of two coats of both preservatives solutions resulted in appreciable uptake of treatment (Table 2). For boron glycol, the average coverage rate was 190 g/m$^3$, whereas for copper naphthenate the average coverage rate for all samples was 180 g/m$^3$.

Preservative uptake data indicated that the preservative retention in all of the copper naphthenate treated samples was well below the minimum of 0.10% (w/w Cu) required by the H3.2 specification in NZS 3640:2003 (Chemical Preservation of Round and Sawn Timber). Preservative retentions in samples treated with boron on three or four sides were generally above the minimum 0.4% BAE requirement of the H1.2 specification (Table 2). The variations in the retention rates were relatively small particularly given the variable nature of timber. The standard deviation for boron glycol retention was in the range of 10–18% of mean. For copper naphthenate, it was higher at 22–28% of mean.

### 3.2. Moisture content

The moisture content of the LMC samples remained relatively constant through the exposure period, generally close to 25%. The average moisture content of the HMC samples generally stayed above 30% throughout the exposure period.

Please cite this article in press as: Singh, T., et al., Effectiveness of on-site remediation treatments for framing timber, International Biodeterioration & Biodegradation (2013), http://dx.doi.org/10.1016/j.ibiod.2013.09.003

### 3.3. Performance of treated samples

Mycelium became established on the untreated surfaces of samples within six months of installation in the exposure stacks. This progressed steadily, particularly on the untreated samples and those treated on only one edge. This indicates that drying of samples after pretreatment infection was not enough to kill the decay. Mycelium development on copper naphthenate treated surfaces in the HMC tanks continued throughout the trial.

By comparison there was no decay mycelium on boron treated surfaces. On the samples where decay mycelium developed on untreated faces of boron treated samples it began to degenerate after two years exposure and was largely inactive by the end of the trial. Decay ratings and deflection data are summarised in Table 3.

As expected, the performances of both preservatives improved as more sides of the timber were treated ($P \leq 0.05$). This is reflected in both the measurement of stiffness (expressed as MOE; Fig. 1a and b) and of decay (expressed as index of condition; Fig. 2a and b). Overall, the boron-glycol treated samples performed significantly better ($P \leq 0.05$) than those treated with copper naphthenate (Figs. 1 and 2).

Over the test period, decay rating changes followed that same pattern as changes in deflection (Table 3). Decay progressed steadily in the samples treated with copper naphthenate on one or two edges (C1 or C2; Fig. 2a) and those treated with boron on one edge (B1; Fig. 2b). There was very little change in the other boron treated groups ($P \leq 0.05$).

Noticeable deflection increases and changes in MOE have generally been restricted to those samples which contained moderate-severe decay (ratings 6 or lower).

### 3.4. Preservative retention and internal decay at final assessment

The analytical results showed that there was no significant loss of copper naphthenate over the exposure period whereas preservative retention in the HMC boron treated samples has been reduced by between 24% and 55% (Appendix, Table 1). The samples in the upper layer of the exposure tank (B64H/4) had the highest loss and samples lower in the tank lost progressively less.

Samples in the LMC stack were not sprayed with water and condensation drippage affected only a few in specific areas of the stack. Boron loss in the analysed samples varied from 27% to 47%.

Figs. 1–3 (in Appendix) shows the spot test results for internal decay and preservative penetration at the final assessment. The distribution of copper in the copper naphthenate treated samples is relatively close to the surface and shows very little evidence of redistribution following treatment. The spot test of boron samples (Appendix, Fig. 2), treated on three sides from HMC show that the preservative has spread through the whole sample cross-section. Virtually no internal decay was observed. Fig. 3 (in Appendix) showed the distribution of boron in LMC samples. Spot test clearly indicates that boron can penetrate the full cross-section even in samples that were below 30% moisture content and provided protection against decay.

## 4. Discussions

The two test brown rot fungi, *O. placenta* and *G. sepiarium* used in this study have most commonly been associated within leaky building in NZ (Stahlhut, 2008). Brown rot basidiomycetes fungi is the most common and destructive type of decay in building around the world (Viitanen and Ritschkoff, 1991; Alfredsen et al., 2005; Schmidt, 2006). Internal pore fungi such as *O. placenta* or *Antrodia xantha* (Schmidt and Moreth, 2003) prefer high moisture content and decay actively on timber with moisture above fibre saturation point (Schmidt, 2007). *G. sepiarium* grows optimally in high temperatures with lower moisture content (Gilbertson, 1981; Eslyn, 1986). Previous research has shown that for the radiata pine, the minimum wood moisture content for decay progression on framing timber inoculated with decay fungi was 24–25% mc (Page et al., 2003). In this study, the targeted moisture content for test framing samples were achieved in both LMC and HMC tanks (Table 3). Given the right substrate for nutrient, decay fungi can grow prolifically on wood at fibre saturation point (approximately 30% moisture content) (Page et al., 2003).

This study simulated typical leaky building scenario where wood remains exposed to a humid and wet environment containing active decay fungi. Regardless of the extreme conditions in this study, brush-on boron treatment on at least two edges and a face was able to control decay. However, copper naphthenate has not been successful in preventing decay, regardless of the number of faces treated. The treatment retention in samples treated with boron on three or four sides was about 0.04% (BAE w/w) and 0.065% (BAE w/w) respectively. This is close to or above the cross-sectional retention required to inhibit fungal growth on framing (H1.2 specification; NZS 3640). The copper retention for samples treated with copper naphthenate on four sides was on average only 44% of the H3.2 requirement (NZS 3640, 2003) and less than would normally be required for decay prevention.

In copper naphthenate treated samples, preservative penetration was generally limited to a 5–10 mm envelope around the outside. Preservative retention and distribution did not change during the exposure period. In samples treated with boron, some preservative was lost during wetting after treatment but the remaining preservative distributed through the sample cross section, including in samples where the moisture content was below 30%. Hence the ability of boron to diffuse in presence of moisture contributed to preventing internal decay. Results of this study are in agreement with previous studies where when boron is not applied in whole cross-sections, it re-distributes by diffusion if sufficient moisture is available (Lloyd et al., 1990; Lebow et al., 2010).

Previous studies have shown that the extensive loss of borates occurs only when timber remains wet throughout its cross-section for a long period (Obanda et al., 2008). The rate of loss is reduced as retention approaches a level that is insufficient to drive the diffusion process and that level is above the toxic limit for decay (Drysdale, 1994; Lloyd, 1995). The current study showed that the periodic wetting helped diffusion into the timber without causing serious loss of boron. Preservative retention data showed the boron is in range of 0.30–0.64% after 3 years exposure. Based on our previous study, this concentration is more than the minimum toxic threshold of boron needed to inhibit brown rot fungi i.e. in the order of 0.15–0.25% boric acid (Hedley et al., 2009). This indicates that the boron diffused into the wood in sufficient amounts to inhibit or even kill incipient or pockets of decay hence prevented decay development over the 3 year period.

In NZ, leaky home crisis will be on-going for some time. While the building standards have been substantially tightened, several thousand homes are still awaiting renovation (Price Waterhouse Coopers, 2009). Any ability to reduce the cost, such as being able to treat timber in place rather than having to remove and replace when not required is beneficial to both building owners and the country in general. A better understanding of the effectiveness of remedial treatment is of considerable significance for leaky building repair. Even a few thousand dollars saved per house would represent tens of millions of dollars saved overall.

## 5. Conclusion

This study showed that the boron glycol mixture applied to three or four sides of 50 mm thick radiata pine framing at a rate that

Please cite this article in press as: Singh, T., et al., Effectiveness of on-site remediation treatments for framing timber, International Biodeterioration & Biodegradation (2013), http://dx.doi.org/10.1016/j.ibiod.2013.09.003

achieves 0.4% BAE retention will protect against decay development. Copper naphthenate in kerosene at the applied retention slowed brown rot decay development but did not prevent it. The application of higher strength Copper naphthenate solution may have reduced decay spread on the surface but limited penetration is unlikely to prevent internal decay development.

## Acknowledgements

We would like to thank the Ministry of Business Innovation and Employment, Wellington, New Zealand for funding this project. Assistance of Jackie van der Waals and Ian Simpson is greatly appreciated in setting up and assessing at various stages of the trial. The authors would like to greatly acknowledge late Dr. Mick Hedley for initiating this project. His encouragement and intellectual support is greatly missed.

## Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.ibiod.2013.09.003.

## References

Alfredsen, G., Solheim, H., Jenssen, K.M., 2005. Evaluation of Decay Fungi in Norwegian Buildings. IRG/WP 05–10562. International Research Group on Wood Protection, Stockholm, Sweden.
AWPA, 1999. E7–93 Standard Method for Evaluating Wood Preservatives by Field Tests with Stakes. American Wood-Preservers' Association Book of Standards. American Wood Preservers Association, Birmingham, Alabama.
Cooney, R., 2009. Timber Preservation and Remediation of Leaky Houses. Department of Building and Housing, Wellington.
Cummins, H.N.O., 1966. Spot Test for Wood Preservatives; Testing of Cu with Rubenic Acid. New Zealand Forest Services, FRI Leaflet. Forest Research Institute, Rotorua, New Zealand, p. 14.
Drysdale, J.A., 1994. Boron Treatment for Preservation of Wood – a Review of Efficacy Data for Fungi and Termites. IRG/WP 94-30037. International Research Group on Wood Preservation, Stockholm, Sweden.
Edlund, M.L., Henningson, B., Kaarik, A., Dicker, P.E., 1983. A Chemical and Mycological Evaluation of Fused Borate Rods and a Boron/glycol Solution for Remedial Treatment of Window Joinery. IRG/WP 94-30037. International Research Group on Wood Preservation, Stockholm, Sweden.
Ellis, B.C., 1961. Methods for Chemical Analysis of Decayed Wood. Forest Product Laboratory, Report No. 2177. USDA Forest Service, Madison Wisconsin.
Eslyn, W.E., 1986. Utility pole decay. Part 4: growth-Temperature relations and decay capabilities of eleven major utility pole decay fungi. Holzforschung 40, 69–77.
Gilbertson, R.L., 1981. North American wood-rotting fungi that cause brown rots. Mycotaxon 12, 372–416.
Groufsky, G., 2008. Progress addressing weathertightness. Build 103, 47–48.
Hardie, G., 1997. Untreated *Pinus radiata* for structural use. Build 39, 18–20.
Hunn, D., Bond, I., Kernohan, D., August 2002. Report of the Overview Group on the Weathertigntness of Buildings to the Building Industry Authority. Building Industry Authority, Wellington.
Hedley, M.E., Page, D., van der Waals, J., September 2009. Application of borocol 200RH (Framesaver) to control decay on pre-decayed model frame units. Scion Wood Process. Newsl, 1–3.
Lebow, S., Lebow, P., Halverson, S., 2010. Penetration of boron from topically applied borates solutions. For. Prod. J. 60, 13–22.
Lloyd, J.D., 1995. Leaching of boron wood preservatives – a reappraisal. In: Proceedings British Wood Preserving and Damp Proofing Association Annual Convention. British Wood Preserving and Damp Proofing Association, Derby, U.K.
Lloyd, J.D., Dickinson, D.J., Murphy, R.J., 1990. The Probable Mechanisms of Action of Boric Acid and Borates as Wood Preservatives. IRG/WP/1450. International Research Group on Wood Preservation, Stockholm, Sweden.
Morrell, J.J., Love, C., Freitag, C., 1996. Integrated remedial protection of wood in bridges. In: National Conference on Wood Transportation Structure. Department of Agriculture, Forest Services, Forest Product Laboratory, Madison, USA, pp. 445–457.
Murphy, C., 2001. Cladding defects study. Build 66, 8.
Newbill, M.A., Morrell, J.J., 1993. Ability of over-the-counter preservatives to protect Western wood species from fungal attack. For. Prod. J. 43, 35–40.
Obanda, D.N., Shupe, T.F., Barnes, H.M., 2008. Reducing leaching of boron-based wood preservatives – a review of research. Bioresour. Technol. 99, 7312–7322.
Page, D., Hedley, M., Patterson, B., van der Waals, J., 2003. The Effect of Wood Moisture Content and Timber Treatment on Initiation and Development of Decay in Radiata Pine Framing. Confidential client report. Forest Research, Rotroua, New Zealand.
Price Waterhouse Coopers, 2009. Weathertightness Estimating –s the Cost. Department of Building and Housing, Wellington, New Zealand.
Ridout, B., 2000. Timber Decay in Buildings. Spon Press, Taylor and Francis Group, London.
Richardson, H.W., 1997. Handbook of Copper Compounds and Applications. Marcel Dekker, New York.
Robinson, K.L., 1939. A method of determination of small quantities of boron in plant material. Analyst 64, 324–328.
Schmidt, O., 2007. Indoor wood-decay basidiomycetes: damage, causal fungi, physiology, identification and characterization, prevention and control. Mycol. Progr. 6, 261–279.
Schmidt, O., 2006. Wood and Tree Fungi: Biology, Damage, Protection, and Use. Springer Verlag, Berlin Heidelberg, p. 334.
Schmidt, O., Moreth, U., 2003. Molecular identity of species and isolates of internal pore fungi *Antrodia* spp. and *Oligoporus placenta*. Holzforschung 57, 120–126.
Stahlhut, D., 2008. Decay Fungi from New Zealand Leaky Buildings: Isolation, Identification and Preservative Resistance (PhD thesis). The University of Waikato, New Zealand.
NZS 3640, New Zealand Standard, 2003. Chemical Preservation of Round and Sawn Timber. (Wellington). Reprinted incorporating Amendments 1, 2, 3, 4, and 5: 21 December 2012. Standards, New Zealand, Wellington, New Zealand.
Viitanen, H., Ritschkoff, A.C., 1991. Brown Rot Decay in Wooden Constructions. EFfect of Temperature, Humidity and Moisture. Swedish University of Agricultural Sciences, Uppsals, p. 57. Sweden Document No. 222.
Vinden, P., Drysdale, J., Spence, M., 1990. Thickened Boron Treatment. IRG/WP 90-3632. International Research Group on Wood Preservation, Stockholm, Sweden.
Wilkes, O., Page, D., 2004. Stop the Rot: Stabilisation of Historic Timber Structures, Interim Guidelines. Published by Department of Conservation, Wellington, New Zealand.
Winandy, J.E., Morrell, J.J., 1993. Relationship between incipient decay, strength and chemical-composition of Douglas-fir heartwood. Wood Fiber Sci. 25, 278–288.

Please cite this article in press as: Singh, T., et al., Effectiveness of on-site remediation treatments for framing timber, International Biodeterioration & Biodegradation (2013), http://dx.doi.org/10.1016/j.ibiod.2013.09.003