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Manual 3 – Decay in ground contact

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www.fwpa.com.au
FWPA Level 4, 10-16 Queen Street,
Melbourne VIC 3000, Australia
T +61 (0)3 9927 3200 F +61 (0)3 9927 3288
E info@fwpa.com.au W www.fwpa.com.au

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MANUAL NO. 3

Decay in Ground Contact

C-H. Wang, R.H. Leicester, and M.N. Nguyen

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This report has been prepared for Forest & Wood Products Australia (FWPA).

Please address all enquiries to:
Urban Systems Program
CSIRO Sustainable Ecosystems
P.O. Box 56, Highett, Victoria 3190

CSIRO

Acknowledgments

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Contents

Executive Summary

- This report presents a service life prediction model for timber installed in-ground and attacked by decay fungi. This model was developed based on the results of three field tests of small clear wood stakes, conducted by the CSIRO Division of Forestry and Forest Products. The first test, conducted between 1968 and 2004 for about 35 years at five sites, consisted of 77 untreated species of heartwood with 10 replicates of each species. The second was a 2.5-year short term test of an untreated species, radia pine sapwood, of 5 replicates at 38 test sites. The third consisted of three treated species installed at three test sites for around 30 years.
- Assuming that the progress of decay follows an idealised bilinear relation over time, the prediction model is characterised by two parameters: the time lag before decay commences, and the decay rate. Because of correlation between them, however, the time lag and decay rate are related by a power-law relation. Estimation of the progress of decay takes into account the effects of natural durability of wood, climate condition of a site, preservative treatment, and internal/external maintenance applications.
- To assist in reliability-based planning and design, probability models for decay depth are developed. Study of the small clear-stake test data shows that decay depth may be modelled by a two-point Weibull distribution. A probabilistic procedure based on a first-order approximation is developed and a durability factor is proposed for reliability assessment of timber poles. The variability contributed by the natural durability of wood, climate parameters, and modelling errors are taken into account.
- Accuracy of the model prediction is gauged by comparing the computed decay depths with those measured from real structures collected from Wedding Bells (Coffs Harbour) of New South Wales, Brisbane, and Melbourne. The equations used for decay depth and service life computation in an engineering design code, a design guide, and a timber service life prediction software package, TimberLife, are given.

1. PREDICTION MODEL

This section summarises the developed prediction model for timber above-ground under attack of decay fungi. The data used for model development and the details of development are described in later sections.

1.1 Notations and Definitions

For simplicity, the following notations are used throughout this report:

r	: decay rate
lag	: decay time lag during which decay does not progress
un	: untreated timber
tr	: treated timber
heart	: outer heartwood
core	: core wood (also referred to as centre wood or inner heartwood)
sap	: sapwood
stake	: small clear test stake
pole	: timber pole

Using these, the following notations are defined:

$r_{\text{un,heart,stake}}$	: decay rate of untreated outer heartwood of clear stake
$lag_{\text{un,heart,stake}}$	: decay time lag of untreated outer heartwood of clear stake
$r_{\text{un,sap,stake}}$	: decay rate of untreated sapwood of clear stake
$lag_{\text{un,sap,stake}}$	: decay time lag of untreated sapwood of clear stake
$r_{\text{un,core,stake}}$	: decay rate of untreated core wood of clear stake
$lag_{\text{un,core,stake}}$	: decay time lag of untreated core wood of clear stake
$r_{\text{tr,sap,stake}}$	: decay rate of treated sapwood of clear stake
$lag_{\text{tr,sap,stake}}$	: decay time lag of treated sapwood of clear stake
$r_{\text{un,heart,pole}}$	: decay rate of untreated outer heartwood of timber pole
$lag_{\text{un,heart,pole}}$	: decay time lag of untreated outer heartwood of timber pole
$r_{\text{un,sap,pole}}$	: decay rate of untreated sapwood of timber pole
$lag_{\text{un,sap,pole}}$	: decay time lag of untreated sapwood of timber pole

$r_{\text{un,core,pole}}$: decay rate of untreated core wood of timber pole

$lag_{\text{un,core,pole}}$: decay time lag of untreated core wood of timber pole

$r_{\text{tr,sap,pole}}$: decay rate of treated sapwood of timber pole

$lag_{\text{tr,sap,pole}}$: decay time lag of treated sapwood of timber pole

In some cases, the timber of durability class 4 is referred to and denoted by the subscript ‘dc4’, as follows,

$r_{\text{un,heart,stake,dc4}}$: decay rate of untreated outer heartwood of durability class 4 clear stake

$lag_{\text{un,heart,stake,dc4}}$: decay time lage of untreated outer heartwood of durability class 4 clear stake

This section presents the basic in-ground decay model for small clear stakes of timber that is in contact with soil directly. Figure 1.1 summarises the relative decay rate of different types of wood taken from a timber log. For convenience, the heartwood will be deemed to comprise two portions, inner heartwood and outer heartwood. In this report, the inner heartwood will be denoted as ‘core wood’. It is assumed that the radius of core wood and the thickness of outer heartwood are equal.

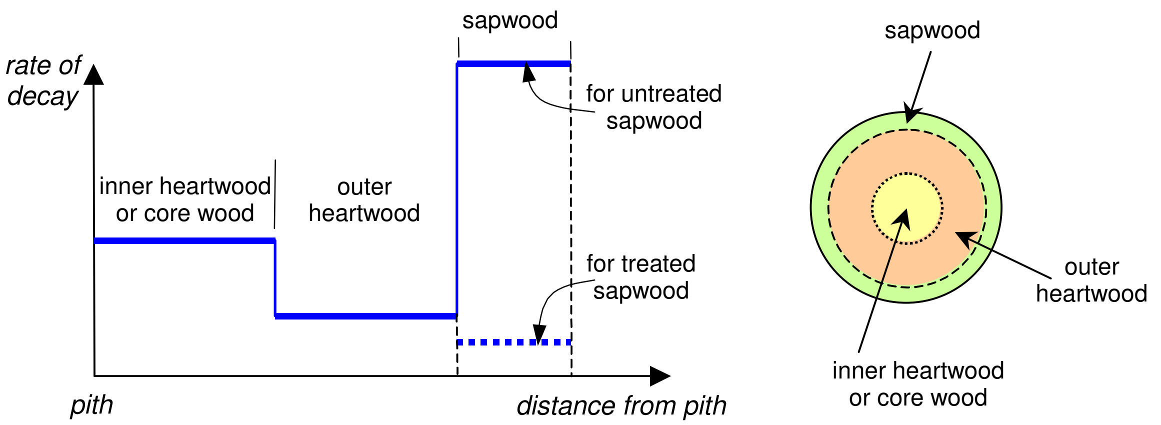


Figure 1.1 Schematic illustration of relative decay rates of different types of wood.

1.2 Model Assumptions

A basic assumption for this model is that progress of decay depth with time t in a timber element follows an idealised bilinear relationship characterised by a decay lag, t_{lag} (years), and a decay rate, r (mm/year). A schematic illustration of this relationship is shown in Figure 1.2. Thus for given d_0, t_{lag}, and r, the decay depth after t years of installation, d_t (mm), is expressed as follows:

$$d_t = \begin{cases} ct^2 & \text{if } t \le t_{d_0}; \\ (t - t_{lag})r & \text{if } t > t_{d_0}. \end{cases} \tag{1.1}$$

in which

$$t_{d_0} = t_{lag} + \frac{d_0}{r} \tag{1.2}$$

$$c = \frac{d_0}{t_{d_0}^2} \tag{1.3}$$

The value of d_0 in Eq. (1.2) could be determined by experimental evidence or expert opinion. If none is available, $d_0 = 5$ mm is recommended.

The expression for decay rate *r* is described in the next subsection.

The decay lag and decay rate are correlated; therefore, given a decay rate *r* determined as described in the previous subsection, the decay lag, t_{lag} (years), is given by

$$t_{lag} = 5.5r^{-0.95} \tag{1.4}$$

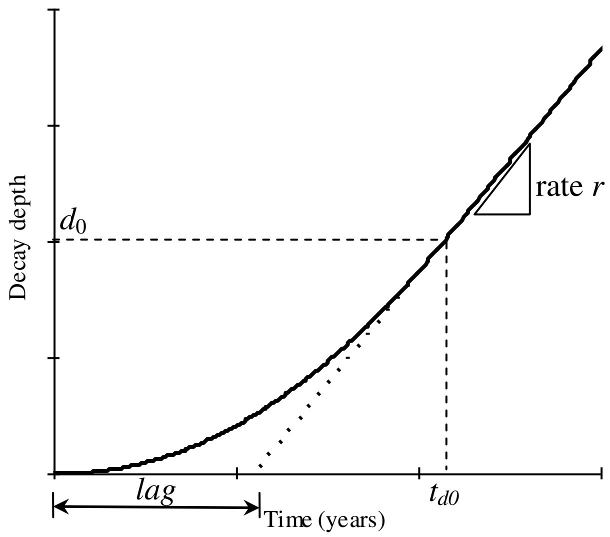


Figure 1.2 Idealised progress of decay depth with time.

1.3 Decay Rate for Untreated Wood Stakes

Decay rate *r* is assumed to be the product of multipliers that take into account the effects of material, construction, and environmental factors as follows:

$$r_{un,stake} = k_{wood} k_{climate} \tag{1.5}$$

where k_{wood} = wood parameter and $k_{climate}$ = climate parameter.

1.4 Values of k_{wood}

First classify species into durability classes 1, 2, 3, and 4 according to Table 1.1.

Table 1.1 Natural durability classification for decay of timber in ground contact

Trade Name	Botanical Name	Wood Type*	Durability Class
Ash, alpine	Eucalyptus delegatensis	E	4
Ash, Crow's	Flindersia australis	H	1
Ash, mountain	Eucalyptus regnans	E	4
Ash, silvertop	Eucalyptus sieberi	E	3
Balau (selangan batu)	Shorea spp.	H	2
Bangkirai	Shorea laevis	H	2
Beech, myrtle	Nothofagus cunninghamii	H	4
Belian (ulin)	Eusideroxylon zwageri	H	1
Blackbutt	Eucalyptus pilularis	E	2
Blackbutt, New England	Eucalyptus andrewsii	E	2
Blackbutt, WA	Eucalyptus patens	E	2
Blackwood	Acacia melanoxylon	H	4
Bloodwood, red	Corymbia gummifera	E	1
Bloodwood, white	Corymbia trachyphloia	E	1
Bollywood	Litsea reticulata	H	4
Box, brush	Lophostemon confertus	H	3
Box, grey	Eucalyptus moluccana	E	1
Box, grey, coast	Eucalyptus bosistoana	E	1
Box, long-leaved	Eucalyptus goniocalyx	E	3
Box, red	Eucalyptus polyanthemos	E	1
Box, steel	Eucalyptus rummeryi	E	1
Box, swamp	Lophostemon suaveolens	H	2
Box, yellow	Eucalyptus melliodora	E	1
Box,white	Eucalyptus albens	E	1
Brigalow	Acacia harpophylla	H	1
Brownbarrel	Eucalyptus fastigata	E	4
Bullich	Eucalyptus megacarpa	E	3
Calantas (kalantas)	Toona calantas	H	2
Candlebark	Eucalyptus rubida	E	4
Cedar, red, western	Thuja plicata	S	3
Cypress	Callitris glaucophylla	S	2
Fir, Douglas (Oregon)	Pseudotsuga menziesii	S	4
Gum, blue, southern	Eucalyptus globulus	E	3
Gum, blue, Sydney	Eucalyptus saligna	E	3
Gum, grey	Eucalyptus propinqua	E	1
Gum, grey, mountain	Eucalyptus cypellocarpa	E	3
Gum, Maiden's	Eucalyptus maidenii	E	3
Gum, manna	Eucalyptus viminalis	E	4
Gum, mountain	Eucalyptus dalrympleana	H	4
Gum, red, forest	Eucalyptus tereticornis	E	1
Gum, red, river	Eucalyptus camaldulensis	E	2
Gum, rose	Eucalyptus grandis	E	3

Gum, salmon	Eucalyptus salmonophloia	E	2
Gum, scribbly	Eucalyptus haemastoma	E	3
Gum, shining	Eucalyptus nitens	H	4
Gum, spotted	Corymbia maculata, incl. corymbia citriodora	E	2
Gum, sugar	Eucalyptus cladocalyx	E	1
Gum, yellow	Eucalyptus leucoxylon	E	2
Hardwood, Johnstone River	Backhousia bancroftii	H	3
Hemlock, Western	Tsuga heterophylla	S	4
Ironbark, grey	Eucalyptus paniculata	E	1
Ironbark, red	Eucalyptus sideroxylon	E	1
Ironbark, red (broad-leaved)	Eucalyptus fibrosa	E	1
Ironbark, red (narrow-leaved)	Eucalyptus crebra	H	1
Ironwood, Cooktown	Erythrophloeum chlorostachys	H	1
Jam, raspberry	Acacia acuminata	H	1
Jarrah	Eucalyptus marginata	E	2
Kapur	Dryobalanops spp.	H	3
Karri	Eucalyptus diversicolor	E	3
Keruing	Dipterocarpus spp.	H	3
Kwila (merbau)	Intsia bijuga	H	3
Mahogany, Philippine, red, dark	Shorea spp.	H	3
Mahogany, Philippine, red, light	Shorea, Pentacme, Parashorea spp.	H	4
Mahogany, red	Eucalyptus resinifera	E	2
Mahogany, white	Eucalyptus acmenoides	E	1
Mahogany, white	Eucalyptus umbra	E	1
Mahogany, southern	Eucalyptus botryoides	E	3
Mallet, brown	Eucalyptus astringens	E	2
Marri	Corymbia calophylla	E	3
Meranti, red, dark	Shorea spp.	H	4
Meranti, red, light	Shorea spp.	H	4
Mersawa	Anisoptera spp.	H	4
Messmate	Eucalyptus obliqua	E	3
Messmate, Gympie	Eucalyptus cloeziana	E	1
Oak, bull	Allocasuarina luehmannii	H	1
Oak, white, American	Quercus alba	H	4
Peppermint, black	Eucalyptus amygdalina	E	4
Peppermint, broad-leaved	Eucalyptus dives	E	3
Peppermint, narrow-leaved	Eucalyptus radiata	E	4
Peppermint, river	Eucalyptus elata	E	4
Pine, black	Prumnopitys amara	S	4
Pine, Caribbean	Pinus caribaea	S	4
Pine, celery-top	Phyllocladus aspleniifolius	S	4
Pine, hoop	Araucaria cunninghamii	S	4
Pine, Huon	Lagarostrobos franklinii	S	3

Pine, kauri	Agathis robusta	S	4
Pine, King William	Athrotaxis selaginoides	S	3
Pine, radiata	Pinus radiata	S	4
Pine, slash	Pinus elliottii	S	4
Ramin	Gonystylus spp.	H	4
Redwood	Sequoia sempervirens	S	2
Rosewood, New Guinea	Pterocarpus indicus	H	3
Satinay	Syncarpia hillii	H	2
Stringybark, Blackdown	Eucalyptus sphaerocarpa	E	2
Stringybark, brown	Eucalyptus baxteri	E	3
Stringybark, red	Eucalyptus macrorhyncha	E	3
Stringybark, white	Eucalyptus eugenioides	E	3
Stringybark, yellow	Eucalyptus muelleriana	E	3
Tallowwood	Eucalyptus microcorys	E	1
Taun	Pometia spp.	H	3
Teak, Burmese	Tectona grandis	H	2
Tingle, red	Eucalyptus jacksonii	E	4
Tingle, yellow	Eucalyptus guilfoylei	E	2
Tuart	Eucalyptus gomphocephala	E	1
Turpentine	Syncarpia glomulifera	H	1
Wandoo	Eucalyptus wandoo	E	1
Woolybutt	Eucalyptus longifolia	E	1
Yate	Eucalyptus cornuta	E	2
Yertchuk	Eucalyptus consideniana	E	2

1.4.1 Wood Parameter for Heartwood

$$k_{wood,heart} = \begin{cases} 0.23 & \text{for class 1;} \\ 0.48 & \text{for class 2;} \\ 0.76 & \text{for class 3;} \\ 1.36 & \text{for class 4.} \end{cases} \tag{1.6}$$

1.4.2 Wood Parameter for Sapwood

$$k_{wood,sap} = \begin{cases} 2.72 & \text{for hardwood;} \\ 5.44 & \text{for softwood.} \end{cases} \tag{1.7}$$

1.4.3 Wood Parameter for Corewood

$$k_{wood,core} = 2k_{wood,heart} \tag{1.8}$$

1.5 Values of $k_{climate}$

The climate parameter $k_{climate}$ could be used to produce an in-ground decay hazard map for Australia that delineates the continent of Australia according to the relative vulnerability of locations to fungal decay due to the climatic variation. A hazard map that divides the continent into four hazard zones is shown in Figure 1.3.

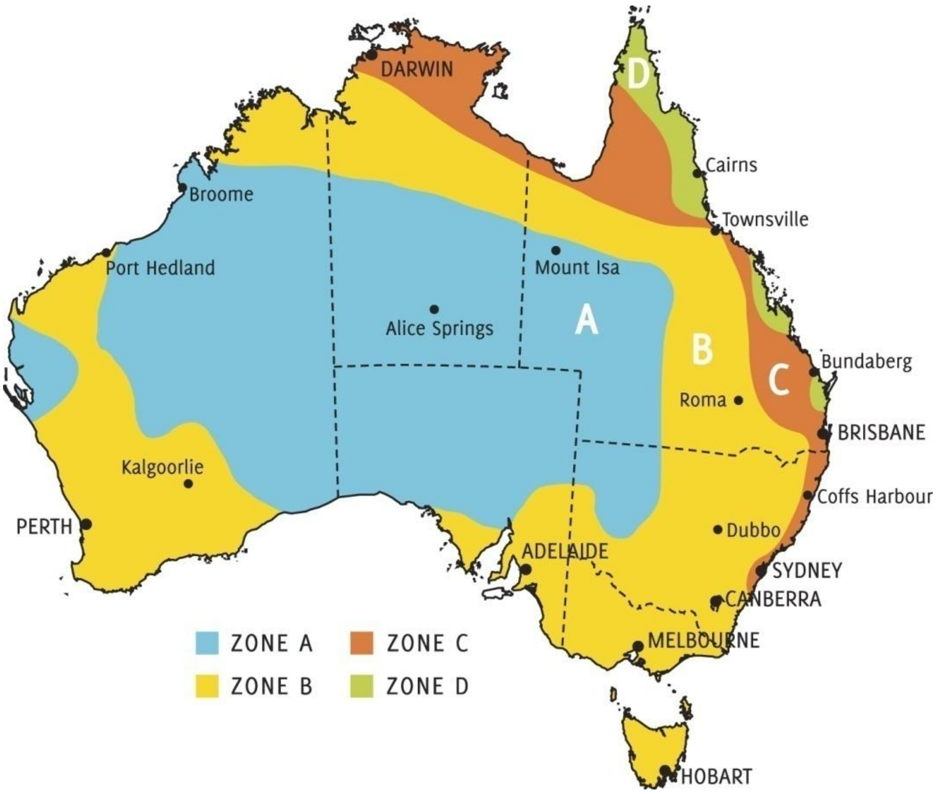


Figure 1.3 A hazard map of Australia for timber in-ground under attack of decay fungi (Zone D is the most hazardous).

Table 1.2 Representative climate parameter values for the hazard zones

In-ground Decay Hazard Zone	Representative $k_{climate}$	Boundary $k_{climate}$
A	0.5	
		1.0
B	1.5	
		2.0
C	2.5	
		2.5
D	3.0	

1.6 Decay Rate for Treated Wood Stakes

First obtain the decay rate for untreated wood stakes according to Eq. (1.5) and the parameters given in Sections 1.4 and 1.5. It is assumed that in a treated timber log, the sapwood is the only type of wood treated with preservative, whilst the heartwood remains untreated.

To facilitate computation, the retention a preservative is converted into a CCA equivalent. For creosote retention, C_{creosote} (in %kg/kg), its CCA equivalent, $C_{\text{CCA-equiv}}$ (in %kg/kg), is

$$C_{\text{CCA-equiv}} = \begin{cases} 0.07C_{\text{creosote}} & \text{for softwoods;} \\ 0.01C_{\text{creosote}} & \text{for hardwoods;} \end{cases} \tag{1.9}$$

If retention is given in kg/m^3, the conversion between %kg/kg and kg/m^3 may be done by (David Gardner, 2001)

$$\text{kg/kg}(\%) = \begin{cases} \dfrac{0.36\times\ \text{kg/m}^3}{D}\times 100 & \text{for CCA treatment,} \\ \dfrac{\text{kg/m}^3}{D}\times 100 & \text{for creosote treatment.} \end{cases} \tag{1.10}$$

in which D is the air-dry density of timber (kg/m^3).

The decay rate of treated sapwood, $r_{\text{tr,sap,stake}}$, is determined by

$$r_{\text{tr,sap,stake}} = \frac{r_{\text{un,sap,stake}}}{1 + B\times C_{CCA-equiv}} \tag{1.11}$$

where $r_{\text{un,sap,stake}}$ is the decay rate of untreated sapwood from Eqs. (1.5) and (1.7); B is given by

$$B = \begin{cases} 45 & \text{for softwoods,} \\ 12 & \text{for hardwoods.} \end{cases} \tag{1.12}$$

1.7 Effects of Maintenance Treatments

If some sort of maintenance action is undertaken then the effect of such action is to add a further time lag to the progress of the decay, as illustrated in Figure 1.4.2. Values of the extra lag are listed in Table 1.4.2. The extra lag value shown is for one application only.

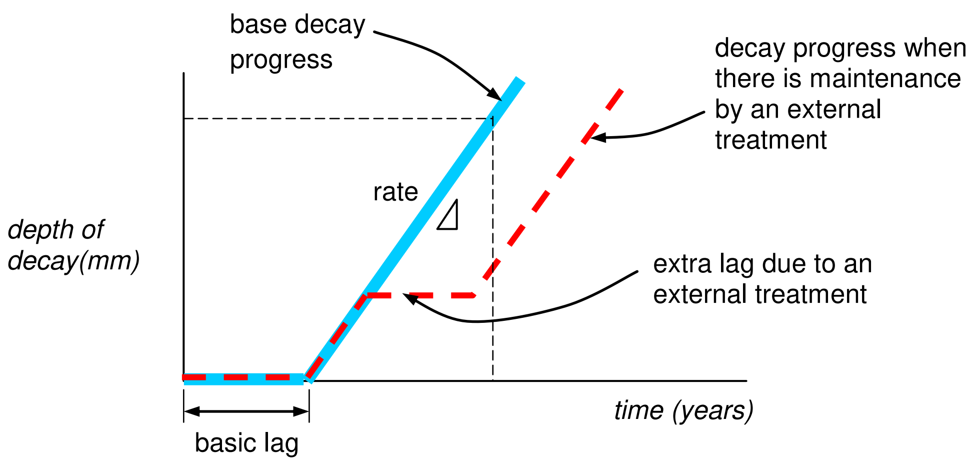


Figure 1.4 Schematic illustration of progress of decay of timber with external treatments.

Table 1.3 Effect of maintenance procedures

Maintenance procedure	*Extra lag for each application of the maintenance procedure (yrs)*	
	Perimeter decay	Centre decay
External diffusing chemical barriers: • Wolman CFB bandage • Osmoplastic 1 • Osmoplastic 2	5	0
External non-diffusing chemical barriers: • Creosote • Copper naphthenate	2	0
External physical barriers: • Concrete collar • Tar-enamel • Denso 600 • Denso Super-wrap	0	0
Insertion of internal diffusing chemicals	0	5

1.8 Attack Patterns for Round Poles

Decay in a timber pole can initiate both from the perimeter progressing inwards and from the pith zone progressing outwards, as illustrated in Figure 4.5.1. It is observed also that both the lag time and decay rate of treated perimeter sapwood as well as corewood of a timber pole are different from that observed from small stake tests.

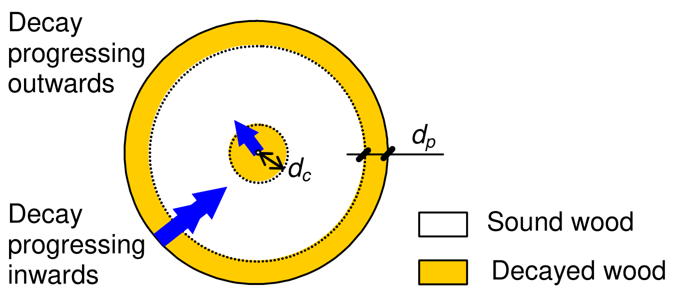


Figure 1.5 Decay patterns of round poles.

Model parameters for decay progressing inwards

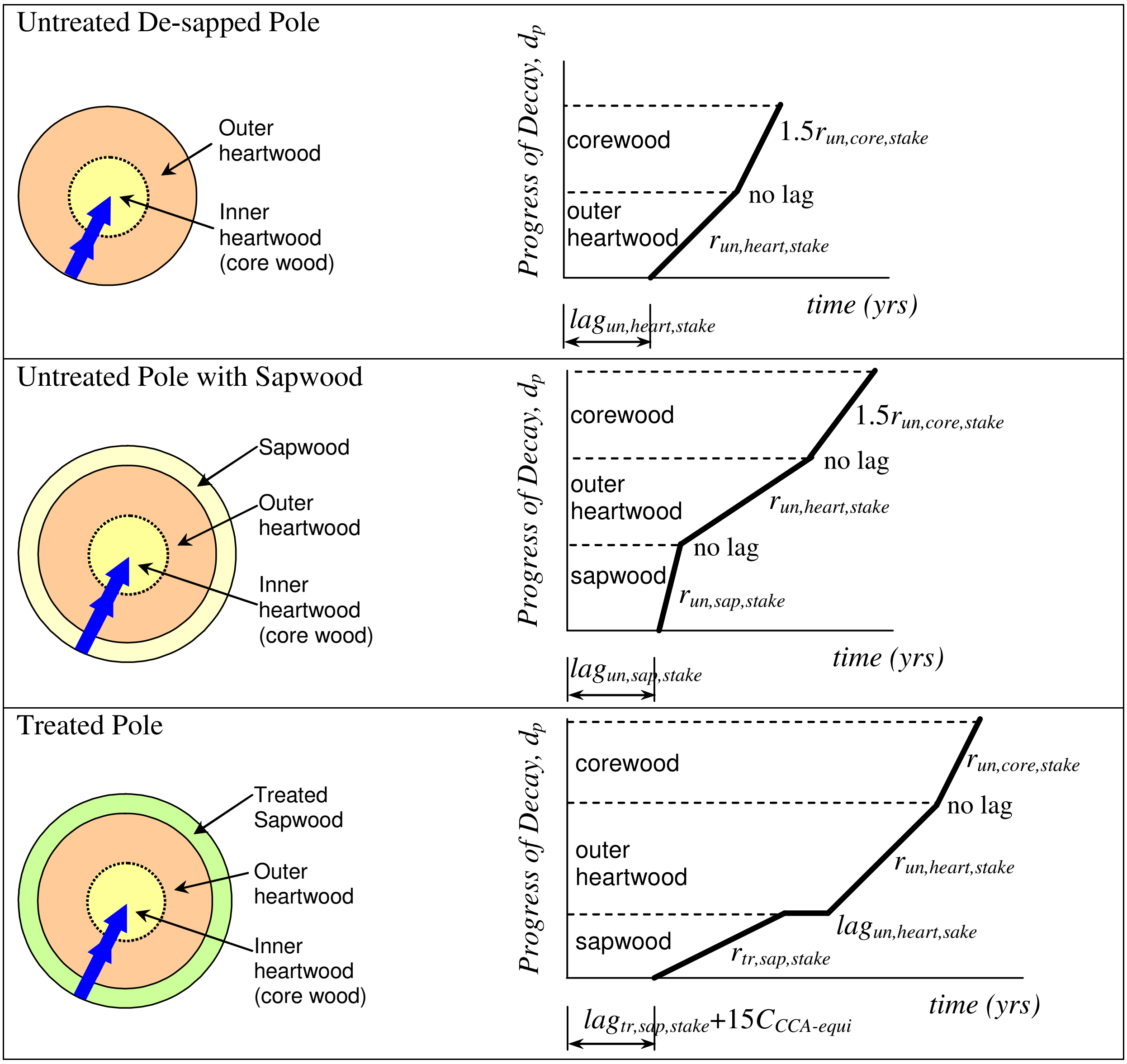


Figure 1.6 Decay of poles progressing inwards

Model parameters for Decay Progressing Outwards

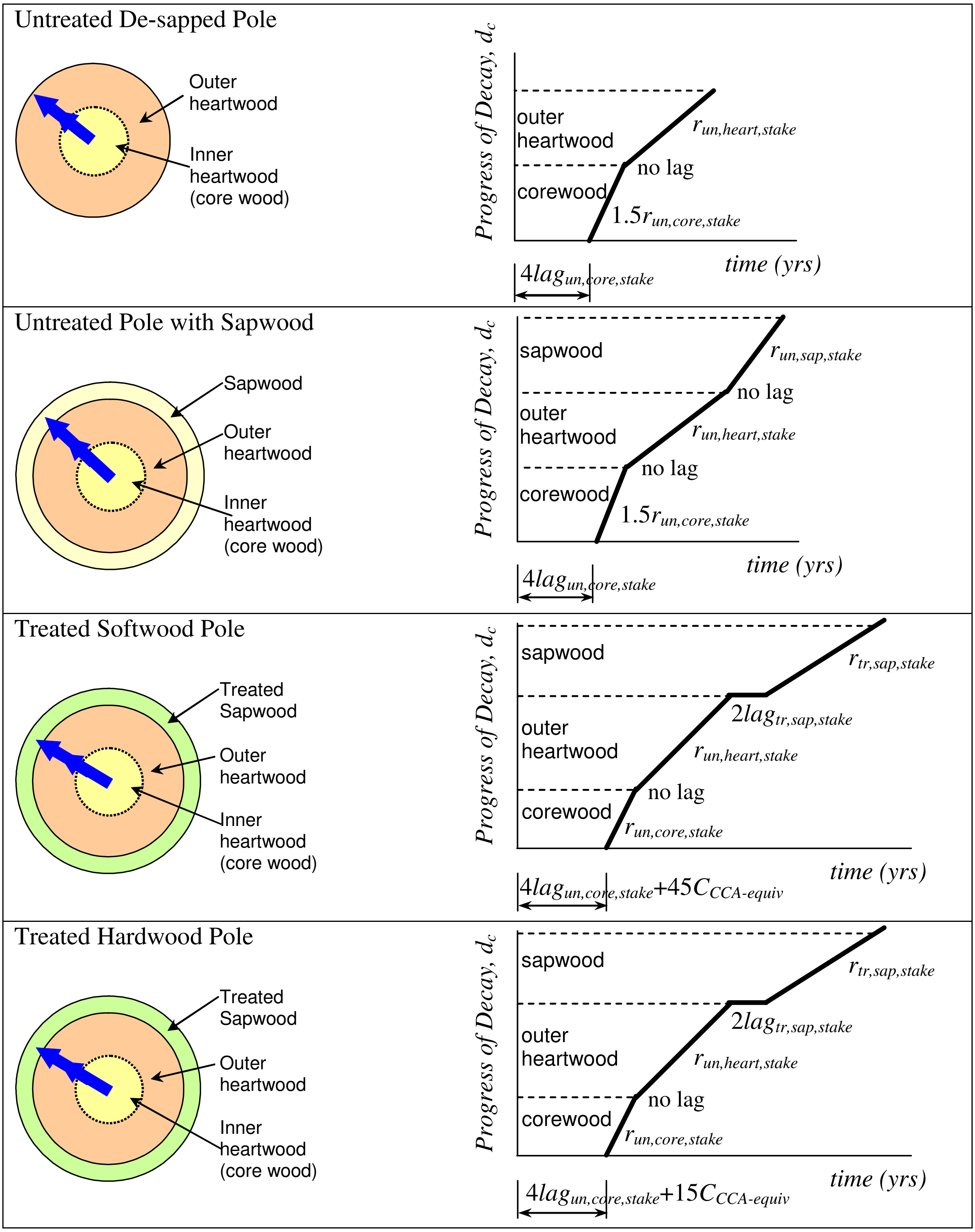
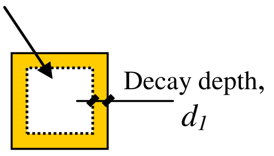
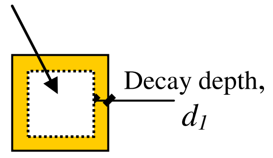
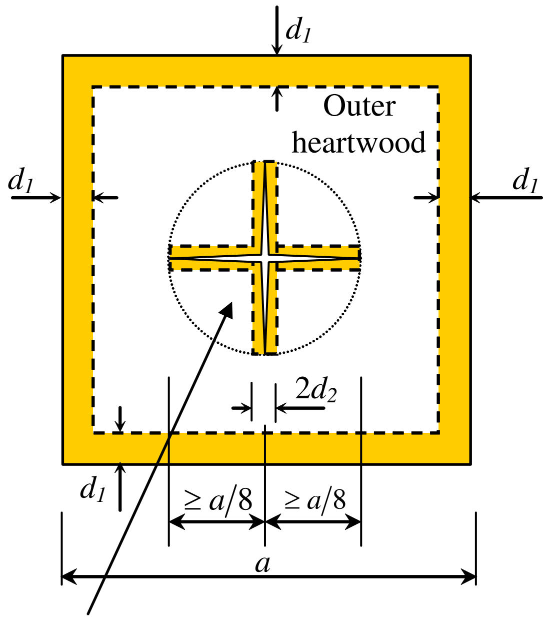
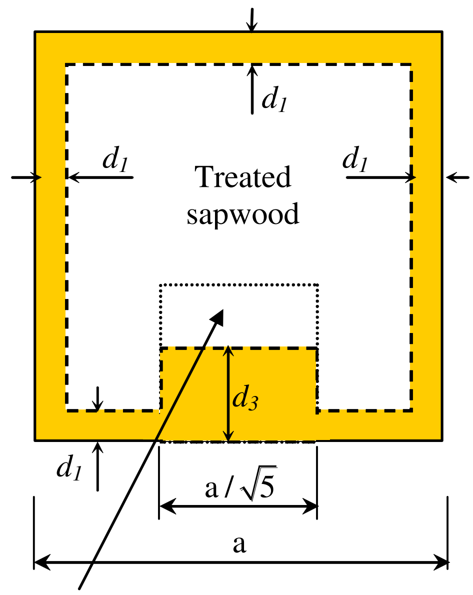


Figure 1.7 Decay of poles progressing outwards

1.9 Attack Patterns for Square Posts

Table 1.4 Cross-sections of square posts and decay paterns

	UNTREATED HARDWOOD	**TREATED SOFTWOOD**
Small size 100x100 150x150	Outer heartwood 	Treated sapwood 
Large size 200x200 250x250	 Corewood	 Outer heartwood (20% of total section area)

2. SOURCE DATA FOR STAKES

2.1 In-ground Decay of Small Clear Stakes of Timber

The decay models presented in the following are based on the set of data collected from small clear stake tests, real timber pole field tests, and samples taken from demolished real structures such as fences and houses. The models are to be modified when more data become available.

The locations of the test sites used are shown in Figure 2.1. An example of measured data is shown in Figure 2.2. The measured data was fitted to a bilinear function as shown in Figure 2.3. Similar plots of all the measured data are given in Appendix B.

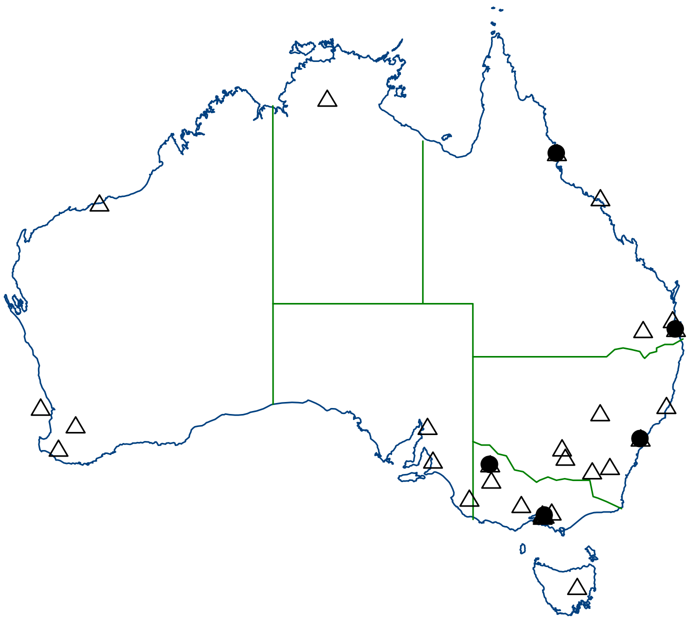


Figure 2.1 Test locations of in-ground stakes

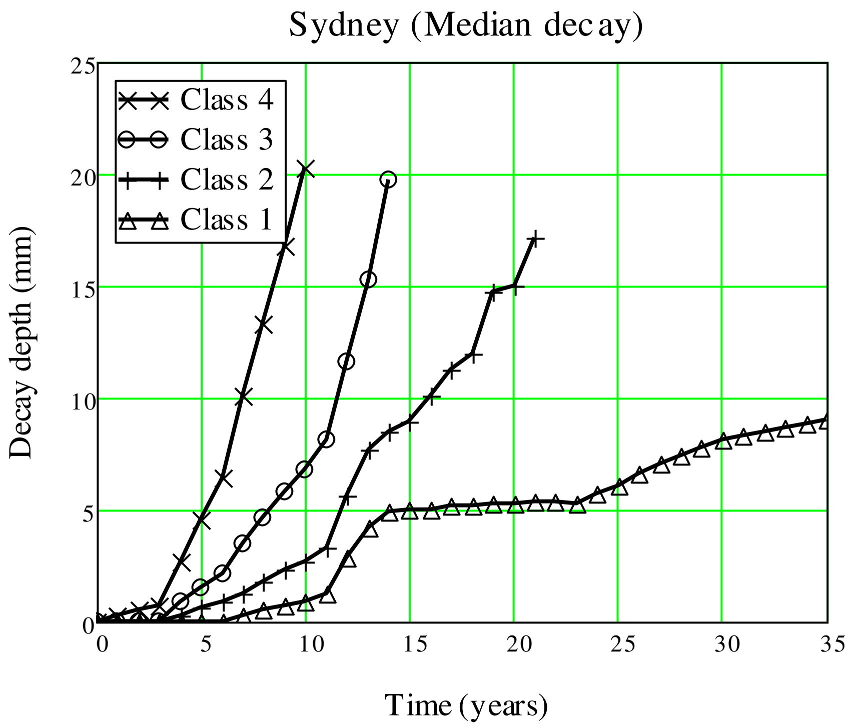


Figure 2.2 Measured stake data from the Sydney test site (Each point represents the median decay depth of wood of one durability class. The decay depth of a stake at a given year is determined by linear interpolation of the observed decay depths assessed every 2 to 3 years)

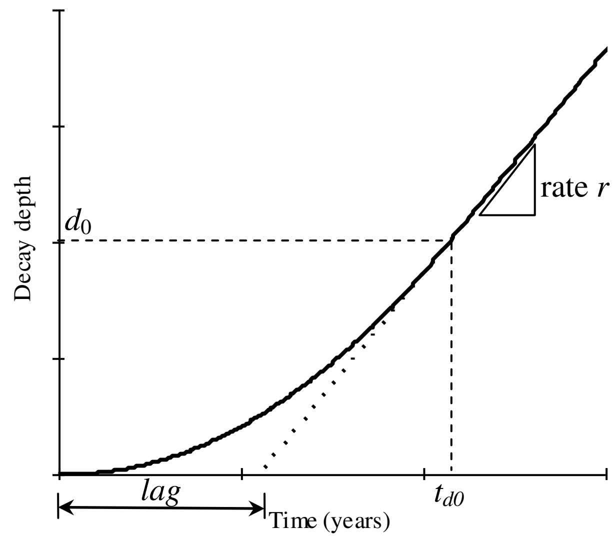


Figure 2.3 Idealised progress of decay depth with time.

2.2 Stake Test Data

2.2.1 In-Ground Stake Test No. 1

An in-ground Natural Durability Field Test of Australian Timbers was undertaken for 35 years by the CSIRO Division of Forestry and Forest Products with untreated, heartwwod timber. They provide a measure of the rate of decay across the grain of the wood.

The dimensions of the test specimens are shown in Figure 2.4. The list of species tested is given in Table 2.1. The list of test sites used is given in Table 2.2. There were roughly 10 replicates of each of the 77 species tested at each test site.

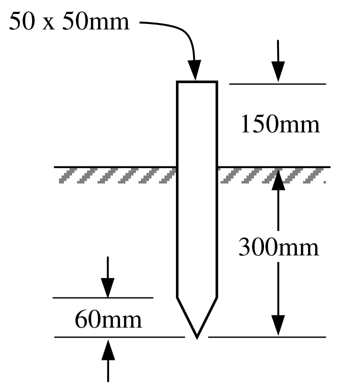


Figure 2.4 Specimen dimensions for square stakes used in in-ground stake tests Nos 1 and 3

Table 2.1 Species tested for in-ground stake test No. 1

Species No.	Botanical Name	Species No.	Botanical Name
0	Euc. moluccana	39	Euc. sieberi
1	Euc. paniculata	40	Euc. globulus
2	Euc. wandoo	41	Euc. saligna
3	Euc. sideroxylon	42	Lophostemon confertus
4	Lophostemon suaveloens	43	Euc. goniocalyx
5	Euc. microcorys	44	Euc. astringens
6	Euc. bosistoana	45	Euc. amygdalina
7	Euc. cloeziana	46	Euc. diversicolor
8	Euc. melliodora	47	Euc. viminalis
9	Euc. leucoxylon	48	Euc. obliqua
10	Euc. tereticornis	49	Euc. radiata
11	Euc. marginata	50	Euc. grandis
12	Euc. resinifera	51	Euc. elata
13	Euc. camaldulensis	52	Euc. fastigata
14	Euc. cornuta	53	Euc. megacarpa
15	Euc. jacksonii	54	Euc. rubida
16	Euc. salmonophloia	55	Euc. regnans
17	Euc. botryoides	56	Allocasuarina luehmannii
18	Euc. cladocalyx	57	Intsia bijuga
19	Euc. longifolia	58	Pterocarpus indicus
20	Euc. eugenioides	59	Acacia harpoghylla
21	Euc. acmenoides	60	Acacia acuminata
22	Euc. eugenioides	61	Anisoptera thyrifera
23	Euc. consideniana	62	Litsea reticulata
24	Euc. muellerana	64	Nothofagus cumminghamii
25	Euc. guilfoylei	65	Tectona grandis
26	Syncarpia hillii	66	Quercus alba
27	Syncarpia glomulifera	69	Sequoia sempervirens
28	Euc. gomphocephala	70	Thuja plicata
29	Euc. pilularis	71	Pseudotsuga menziesii
30	Euc. haemastoma	72	Pinus radiata
31	Euc. maculata	73	C. columellaris
32	Euc. patens	74	Phyllocladus asplenifolius
33	Euc. dives	75	Prumnopitys amara
34	Euc. capitallata	76	Agathis robusta
35	Euc.calophylla	77	Lagarostrobos franklinii
36	Euc. maidenii	78	Anthrotaxis selaginoides
37	Euc. cypellocarpa	79	Euc. polyanthemos
38	Euc. macrorhyncha		

Table 2.2 Test sites for in-ground stake test No. 1

Site ID	Longitude	Latitude	Site Location
1	142.03	–35.13	Walpeup
2	146.03	–17.52	Innisfail
3	151.05	–33.68	Pennant Hills
4	153.17	–27.47	Brisbane
5	145.33	–38.00	Mulgrave

Table 2.3 Assumed relationship between decay scores and depth of decay for square stakes

Decay Score	Loss of Section (%)	Decay Depth (mm)
8	0	0
7	7.5	1
6	22.5	3
5	37.5	5
4	52.5	8
3	67.5	11
2	82.5	15
1	95.5	20
0	100	25

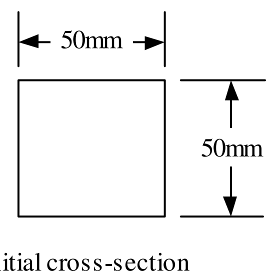


Figure 2.5 Square cross section

2.2.2 *In-Ground Stake Test No. 2*

This section refers to unpublished data by the CSIRO Division of Forestry and Forest Products. The tests were undertaken on a single substrate of wood, namely radiata pine sapwood. The timber was treated only by permethrin, to reduce the susceptibility to attack by insects; it is assumed that permethrin does not have any effect on the decay rate of decay.

The dimensions of the rectangular test specimens used are shown in Figure 2.6. The site locations for the test are listed in Table 2.4. There were 5 replicates at each site. The specimens were evaluated at 1.0, 2.0 and 2.5 years after installation. The information is useful for comparing the effects of climate of various sites on the in-ground decay in the direction transverse to the grain.

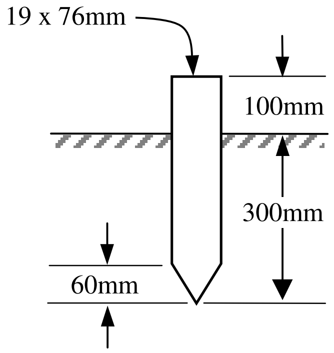


Figure 2.6 Specimen dimensions used in in-ground stake tests No. 2

Table 2.4 Test sites for in-ground stake test No. 2

Site I.D.	Longitude	Latitude	Place	
3	152.60	–31.83	Taree	
4	146.55	–34.75	Narrandra	
5	153.10	–27.47	Brisbane(Salisbury	QLD
6	151.20	–27.53	Dalby(Dunmore)	QLD
7	148.65	–20.08	Rockhampton(Mackay)	QLD
8	146.03	–17.52	Innisfail	QLD
9	151.05	–33.68	Pennant Hills(Sydney)	NSW
10	148.62	–32.25	Dubbo	NSW
11	146.35	–34.23	Griffith	NSW
12	148.15	–35.53	Batlow(Tumbarumba)	NSW
13	149.22	–35.28	Canberra	ACT
14	145.17	–37.98	Highett(Melbourne)	VIC
15	143.90	–37.43	Creswick	VIC
16	142.10	–36.05	Horsham(Wail)	VIC
17	145.73	–37.87	Powelltown	VIC
18	147.25	–42.08	Hobart	TAS
19	142.03	–35.13	Walpeup	VIC
20	140.78	–37.08	Mount Gambier	SA
21	138.27	–33.03	Wirrabara	SA
22	138.60	–34.93	Adelaide	SA
23	145.30	–38.03	Rowville(Melbourne)	VIC
24	132.27	–14.44	Katherine	NT
25	152.97	–26.97	Beerburrum	QLD
26	115.08	–31.92	Perth(Como)	WA
27	145.18	–38.10	Frankston(Melbourne)	VIC
28	117.18	–32.93	Narrogin	WA
29	116.15	–34.25	Manjimup	WA
30	118.60	–20.37	Port Hedland	WA

Table 2.5 Assumed relationship between decay scores and depth of decay for rectangular stakes

Decay Score	**Loss of Section (%)**	**Decay Depth (mm)**
8	0	0
7	7.5	0.6
6	22.5	1.8
5	37.5	3.0
4	52.5	4.4
3	67.5	5.9
2	82.5	7.4
1	95.5	8.9
0	100	9.5

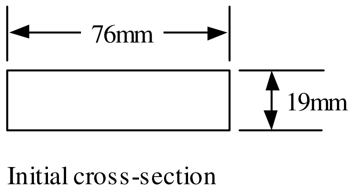


Figure 2.7 *Cross-section of the wood specimens in in-ground stake tests No. 2*

2.2.3 In-Ground Stake Test No. 3

This section refers to unpublished data on treated timber stakes by the CSIRO Division of Forestry and Forest Products. The three substrates used for the stakes and their id numbers were as follows:

- Radiata pine sapwood (id = 1)
- Eucalyptus regnans heartwood (id = 2)
- Eucalyptus regnans sapwood (id = 3)

The treatments used for the timbers are listed in Table 6. Several retention levels were used for each preservative treatment. There were 2-15 replicates for each substrate/treatment/retention specification. The three sites used and their id numbers were as follows:

- Innisfail (id = 1) Long. = 146.00° Lat. = –17.50°
- Pennant Hills (id = 2) Long. = 151.10° Lat. = –33.70°
- Walpeup (id = 3) Long. = 142.00° Lat. = –35.10°

For the Radiata pine sapwood and Eucalyptus regnans heartwood, the specimens were of square cross-sections and placed in the ground as indicated in Figure 2; the relationship between score and depth of decay was assumed to be as shown in Table 3. For the case of Eucalyptus regnans sapwood, the specimens were round sections roughly 70 mm in diameter with 20 mm thickness of treated sapwood; the relationship between score and depth of decay is assumed to be as shown in Table 2.6. The data for the treated regnans heartwood has not been used in this report.

Table 2.6 Assumed relationship between decay scores and depth of decay for round sections

Decay Score	Loss of Sapwood Section (%)	Decay Depth (mm)
8	0	0
7	7.5	1.1
6	22.5	3.4
5	37.5	5.8
4	52.5	8.5
3	67.5	11.5
2	82.5	15.0
1	95.5	18.6
0	100	20.0

The test specimens were assessed about once every three years for a period of 30 years. The data for representative creosote (id = 1) and CCA (id = 23, 24, 25) were used to study the effects of preservative treatment and retention rates used on the resistance to in-ground decay in the direction transverse to the grain of the wood.

Table 2.7 List of preservatives used in in-ground stake test No. 3

I.D.	PRESERVATIVE
1	K55 Creosote
2	British Creosote
3	AWPA
4	Trimbol Creosote (old)
5	Furnace Oil
6	K55 Creosote + Furnace Oil(1:1)
7	K55 Creosote + Furnace Oil(3:1)
8	5% PCP in Furnace Oil
9	2.5% PCP in Furnace Oil
10	K55 Creosote + 2.5% PCP in Furnace Oil
11	5% PCP in Diesel fuel Oil
12	2.5% PCP in Furnace Oil + 0.5% Chlordane
13	2.5% PCP in Furnace Oil + 1% Chlordane
14	2.5% PCP in Furnace Oil + 2% Chlordane
15	2.5% PCP in Furnace Oil + 0.25% Benzenehexachloride
16	2.5% PCP in Furnace Oil + 0.5% Benzenehexachloride
18	2.5% PCP in Furnace Oil + 0.25% Dieldrin
19	2.5% PCP in Furnace Oil + 0. 5% Dieldrin
20	2.5% PCP in Furnace Oil +1% Dieldrin
21	K55 Creosote + Vertical Retort Tar (1:1)
22	Untreated Controls
23	Boliden K33
24	Celdure “A”
25	Tanalith “C”
26	Celcure “Old”
27	Boliden S 25
28	Zn-Cr-As
29	Tanalith “CA”
30	Borio Acid – Neobor
31	Wolman U.B.R.
32	Wolman U.A.R.
33	Wolman U.R.6
35	Patent Diffusion Salt
36	Cu-Cr-B-As (RJ)
37	Copper-Penta (Japanese)
38	B.C.T. Creosote Residue
39	Wolmanit C.B.
40	K55 Curatar Creosote + dehydrated V.R.Tar (1:1)
41	BCT Creosote New Distillate
42	Timbrol New F Creosote
H	Wesemate Treated with Duratar Creosote
K	Karri Treated with Duratar Creosote
D1	10% Celcure “A” Dip Treatments
D2	20% Copper Naphthenate Dip Treatment
D3	Zylamon T Dip Treatments
D4	Zylamon T.R. Dip Treatment
D5	K55 Creosote + 10% Middle Tar Oil
D6	5% PCP in Diesel Oil

3. DATA PROCESSING FOR STAKES

3.1 Data presentation

In this Section it is the intention to compare the measured data with the decay model predictions. In doing this the equations used for the model predictions are those given in Section 1, except that the value of $k_{climate}$ used is not that for a hazard zone, but rather it is the value computed for the test site locations according to the procedure given in Section 3.2. In Appendix B, the test data is plotted again but this time the associated curves are fitted bilinear equations; the decay rate and decay lag given by these equations are used to define (in quantified terms) the trends of the test data.

In this report, data points for untreated timber refer to median values for all data within a durability class on a given site. This will be denoted as Class Data, and also includes sapwood as a Class.

Data points for treated timber refer to median values for a given substrate/treatment/site. These will be denoted as Species Data.

3.2 The Model Equation

The basic equation for the decay rate for the model is

$$r_{un,stake} = k_{wood} k_{climate} \tag{3.1}$$

where k_{wood} = wood parameter and $k_{climate}$ = climate parameter.

the relationship between the decay lag t_{lag} and decay rate r is assumed to be given by

$$t_{lag} = 5.5 r^{-0.95} \tag{3.2}$$

In the following the procedure for computing $k_{climate}$ will first be given, and then the test data will be compared with the model computed according to equations (3.1) and (3.2), using parameters given in Section 1.

3.3 Parameter $k_{climate}$

A model for a climate index was obtained by using information obtained from specimens deployed for the IN-ground Stake Tests Nos 1 and 2. By correlating the climatic parameters with the measured in-ground decay of the small clear stakes, a climate index was derived that was roughly proportional to the observed rates of decay.

In a previous development of the decay prediction model, the climatic parameters considered were only the mean annual rainfall and mean annual temperature. When annual rainfall at a site concentrates in relatively short periods of time in a year, which is a characteristic in parts of Northern Territory and New South Wales, using annual rainfall only is likely to overestimate fungal decay. Subsequently, the number of dry months in a year was included, in addition to rainfall and temperature, to account for this effect. A dry month is defined as the month during which the total rainfall does not exceed 5 mm. As shown in Appendix A, under such conditions there is the opportunity for the outer surface of in-ground timber to dry below the fibre saturation point if the rainfall in a given month is less than 5 mm. The significance of this is that decay essentially stops when the moisture content of timber is below the fibre saturation point.

The climate function considering the effects of mean annual temperature, rainfall and number of dry months to decay, $f(R)$, is proposed as follows,

$$k_{climate} = f\left(R_{mean}\right)^{0.3} g\left(T_{mean}\right)^{0.2} \tag{3.3}$$

in which R_{mean} is the mean annual rainfall, and N_{dm} denotes the number of dry months per year. The function considering the effect of temperature, $g(T_{mean})$, is

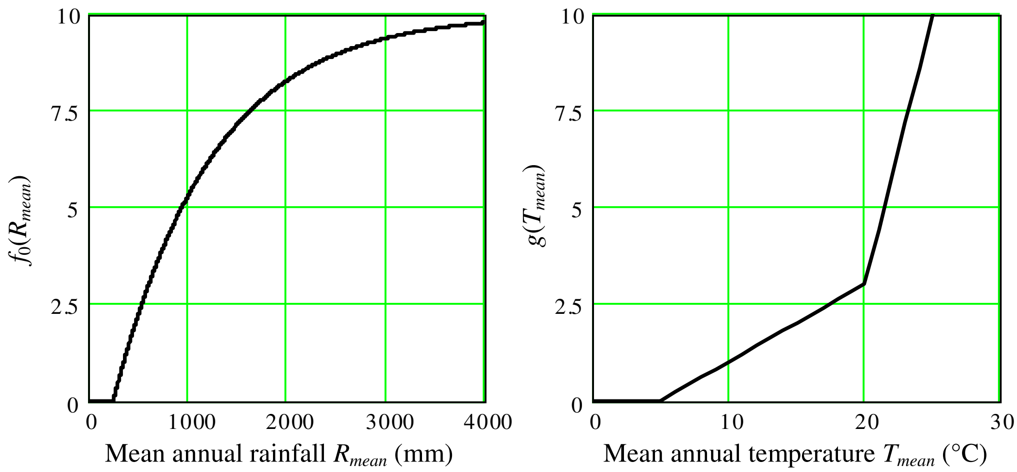
$$f(R_{mean}) = \begin{cases} 0 & \text{if } R_{mean} \le 250 \text{ mm or } N_{dm} > 6, \\ f_0(R_{mean})\left(1 - \dfrac{N_{\mathrm{dm}}}{6}\right) & \text{if } R_{mean} > 250 \text{ mm and } 0 \le N_{dm} \le 6 \end{cases} \tag{3.4}$$

$$g(T_{mean}) = \begin{cases} 0 & \text{if } T_{mean} \le 5^{\circ}\mathrm{C}, \\ -1 + 0.2T_{mean} & \text{if } 5 < T_{mean} \le 20^{\circ}\mathrm{C}, \\ -25 + 1.4T_{mean} & \text{if } T_{mean} > 20^{\circ}\mathrm{C}. \end{cases} \tag{3.5}$$

and

$$f_0(R_{mean}) = 10\left[1 - e^{-0.001(R_{mean}-250)}\right] \tag{3.6}$$

where T_{mean} is the mean annual temperature. The two functions $g(T_{mean})$ and $f_o(R_{mean})$ are shown plotted in Figure 3.1.



(a) Plot of $f_0(R_{mean})$ (b) Plot of $g(T_{mean})$

Figure 3.1 Functions of $f_0(R_{mean})$ and $g(T_{mean})$.

The climate parameter $k_{climate}$ defined by Eq. (3.3) was evaluated at the Bureau of Meteorology weather stations shown in Figure 3.2. Using this data, hazard zones were developed using the boundary values shown in Table 1.2. These hazard zones are plotted in Figure 3.3. On the basis of expert opinion, this map was modified as shown in Figure 3.4.

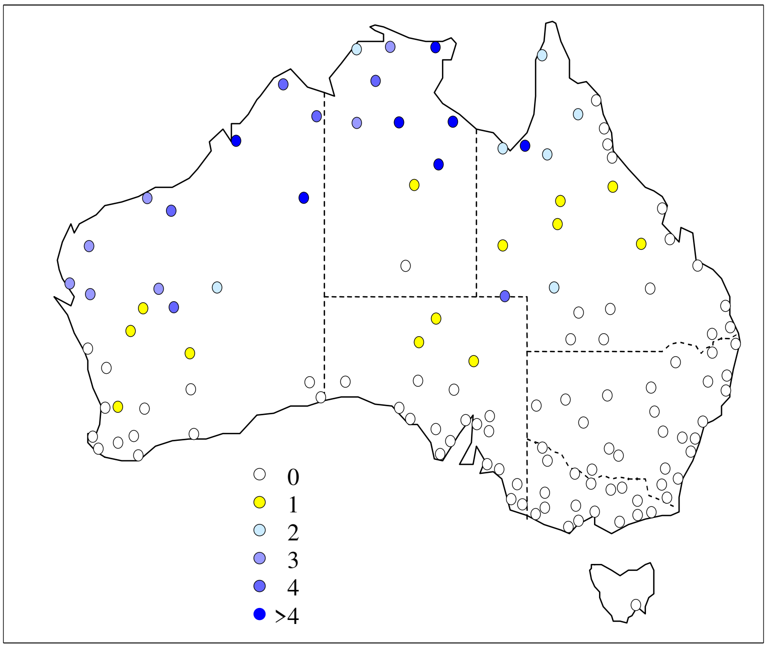


Figure 3.2 *Map showing the location of the weather stations (the Number of months per year in which rainfall < 5mm is indicated by the colour of the circles shown on the map).*

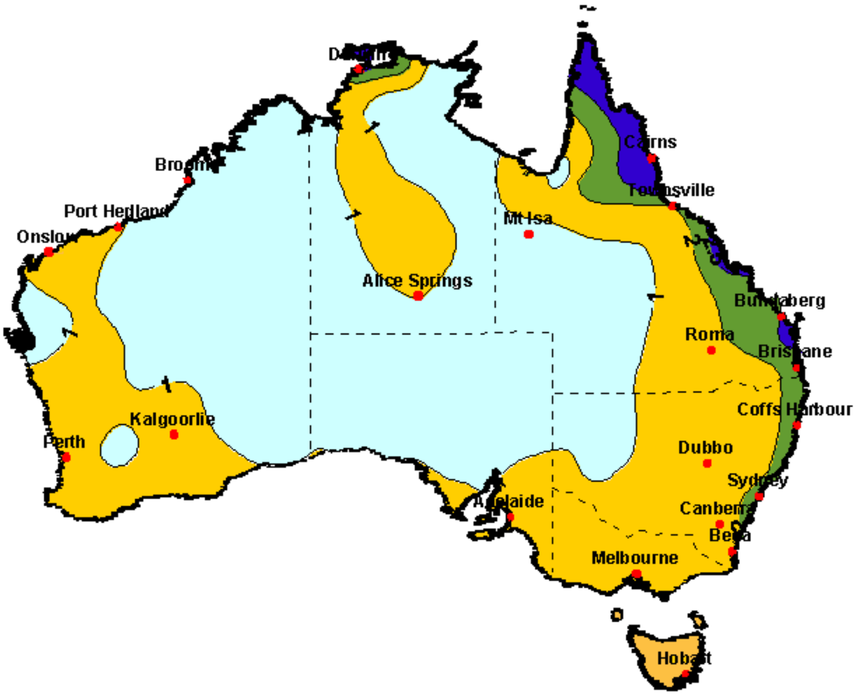


Figure 3.3 Hazard map based on Eq. (3.3)

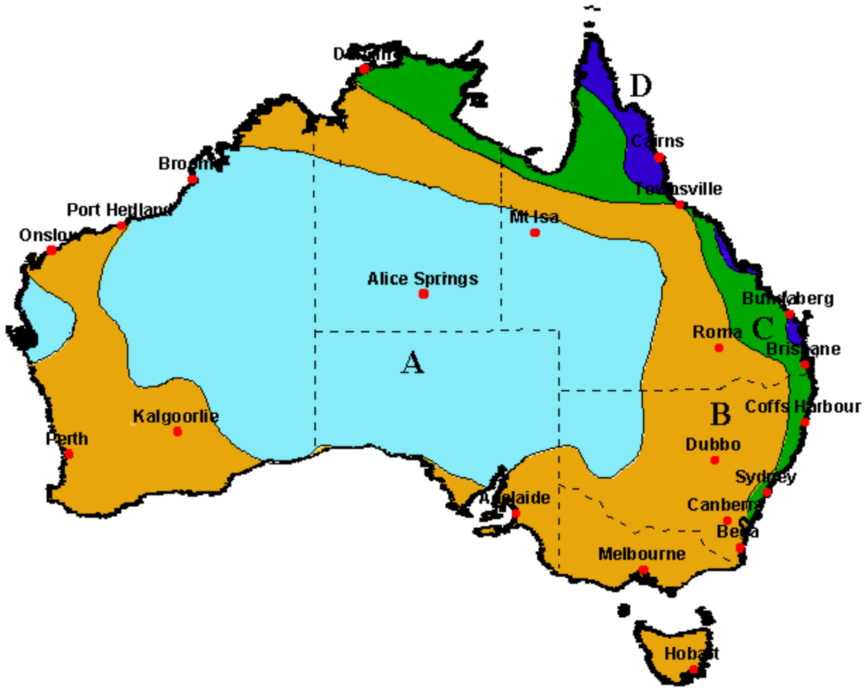


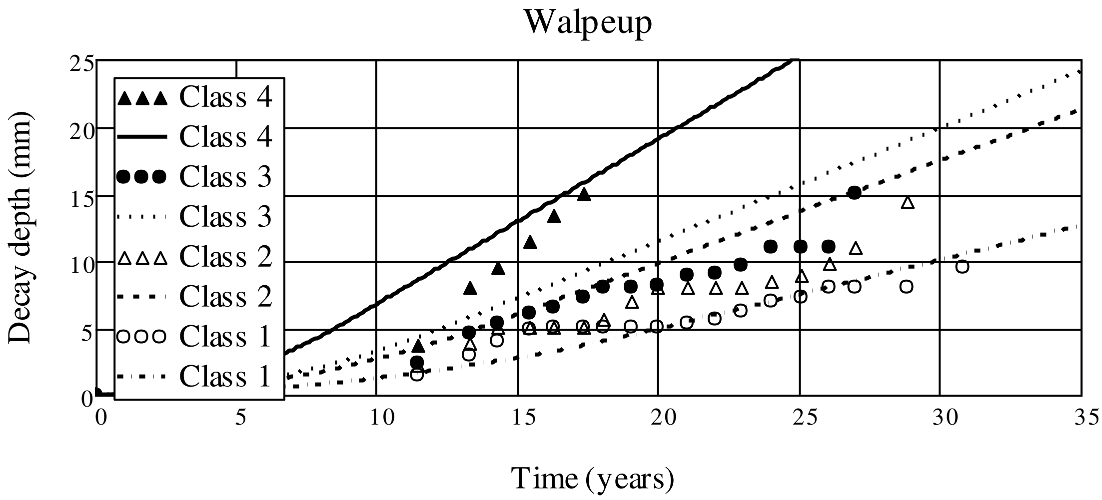
Figure 3.4 Modified hazard map after considering expert opinion (D is the most hazardous)

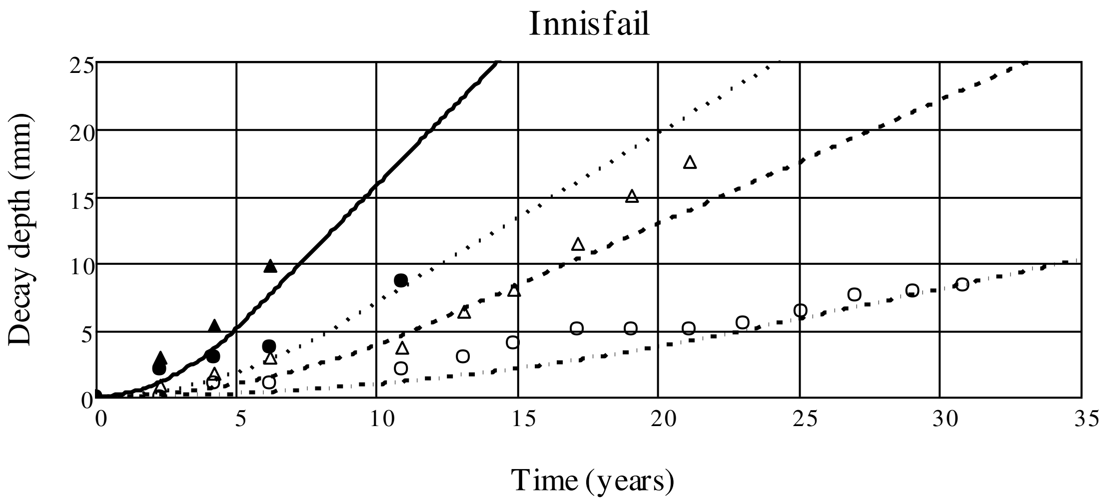
3.4 Untreated wood

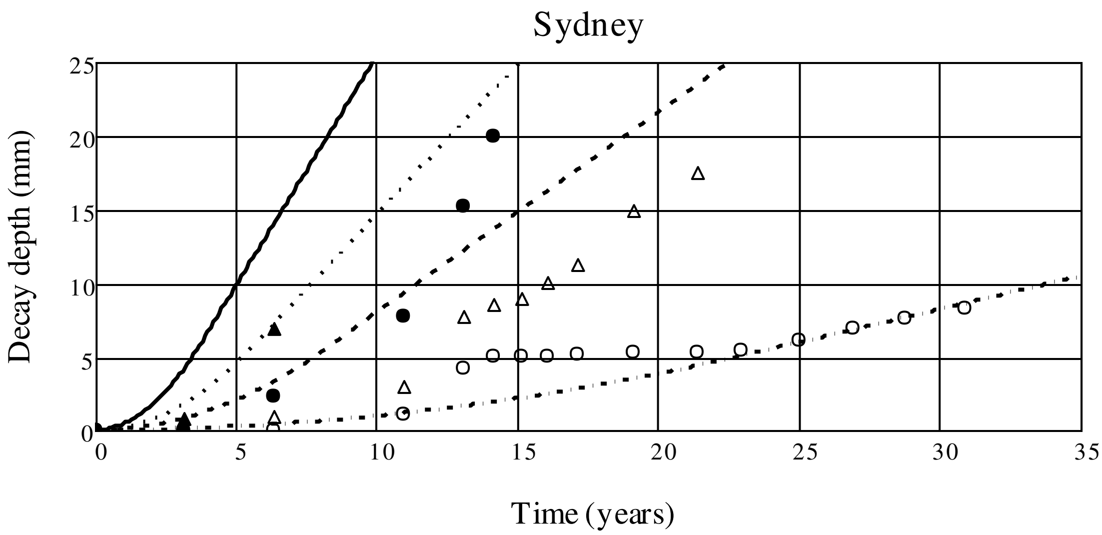
Figure 3.5 shows the measured data points of decay obtained from the untreated stake tests at the five major test sites and the bilinear curves predicted by the model given in Section 1.

Figure 3.6 shows a comparison between measured and predicted decay rates, in terms of durability Class Data.

Figure 3.7 shows a comparison between measured and predicted correlation between the decay rate and decay lag, again in terms of durability Class Data.


Walpeup
Class 4
Class 4
Class 3
Class 3
Class 2
Class 2
Class 1
Class 1
Decay depth (mm)
0
5
10
15
20
25
0
5
10
15
20
25
30
35
Time (years)


Innisfail
Decay depth (mm)
0
5
10
15
20
25
0
5
10
15
20
25
30
35
Time (years)


Sydney
Decay depth (mm)
0
5
10
15
20
25
0
5
10
15
20
25
30
35
Time (years)

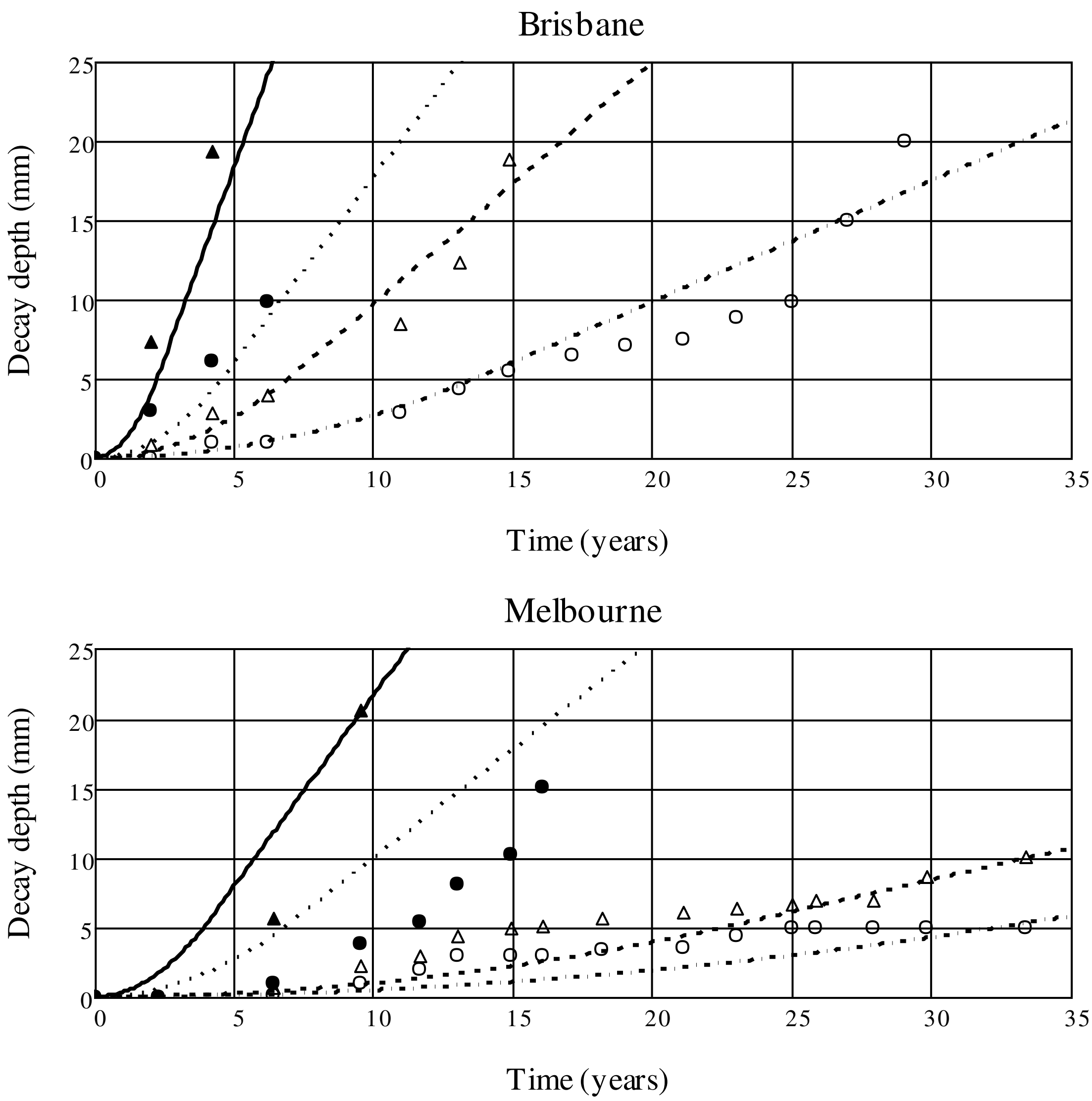


Figure 3.5 Measured decay for untreated timber (Class Data) and model predictions.

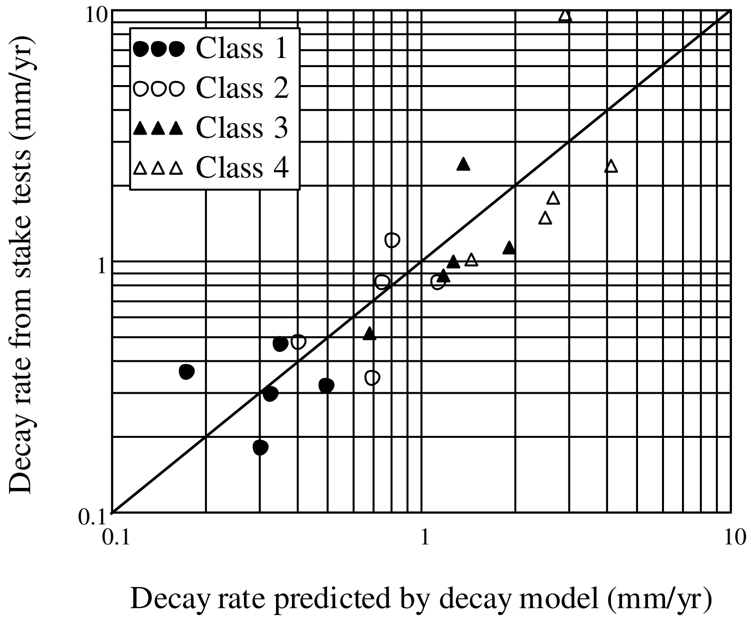
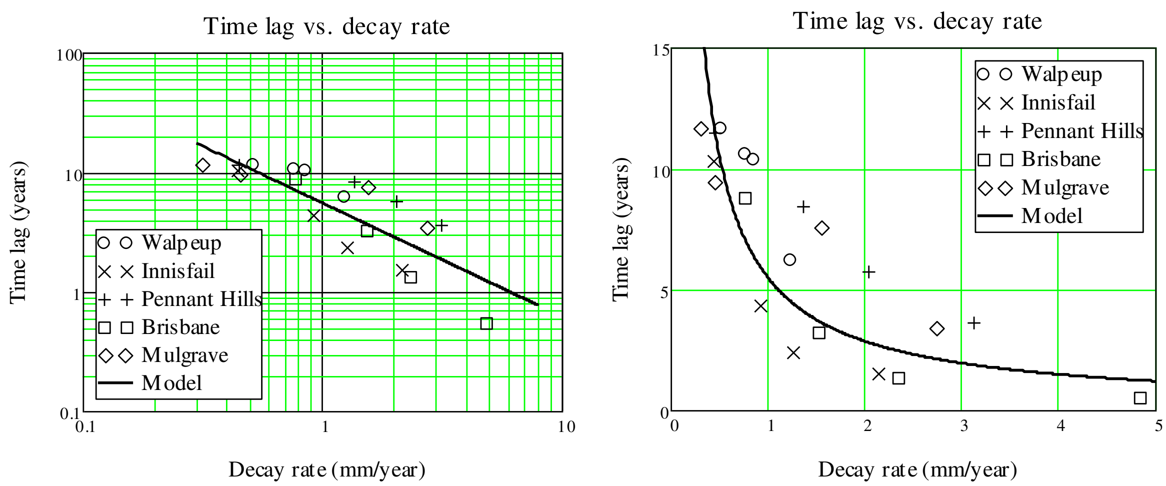


Figure 3.6 Comparison between predicted and measured decay rates of wood stakes (each point denotes the median value for a single durability class of timber at a particular test site)



(a) logarithmic scale (b) linear scale

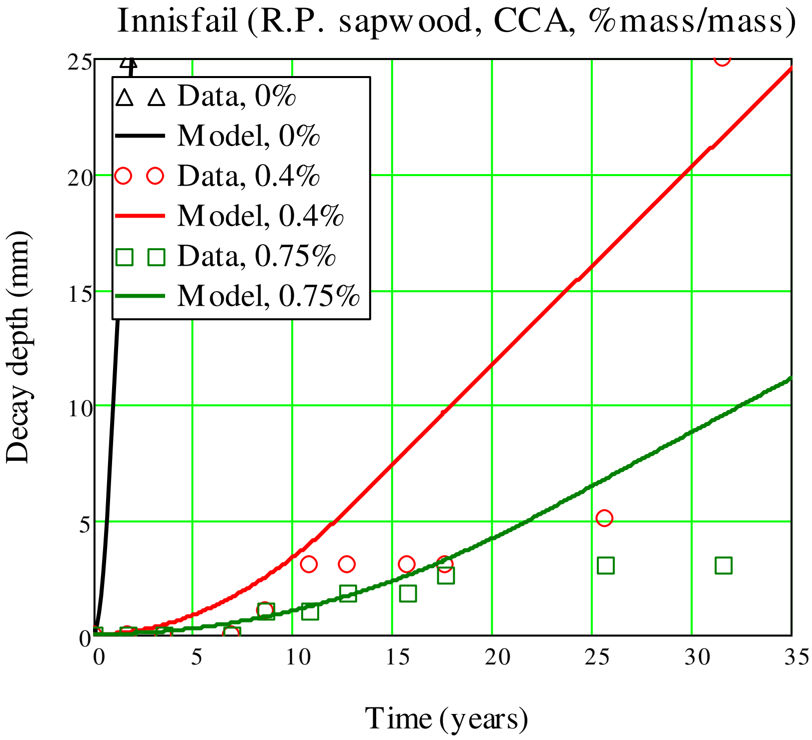
Figure 3.7 Decay lag and decay rate from stake test for untreated wood. (Each point represents the median decay rate–lag pair observed at one site for untreated stakes of one durability class)

3.5 Treated wood

Figure 3.8 shows the measured data points of decay obtained from the untreated stake tests at the five major test sites and the bilinear curves predicted by the model given in Section 1.

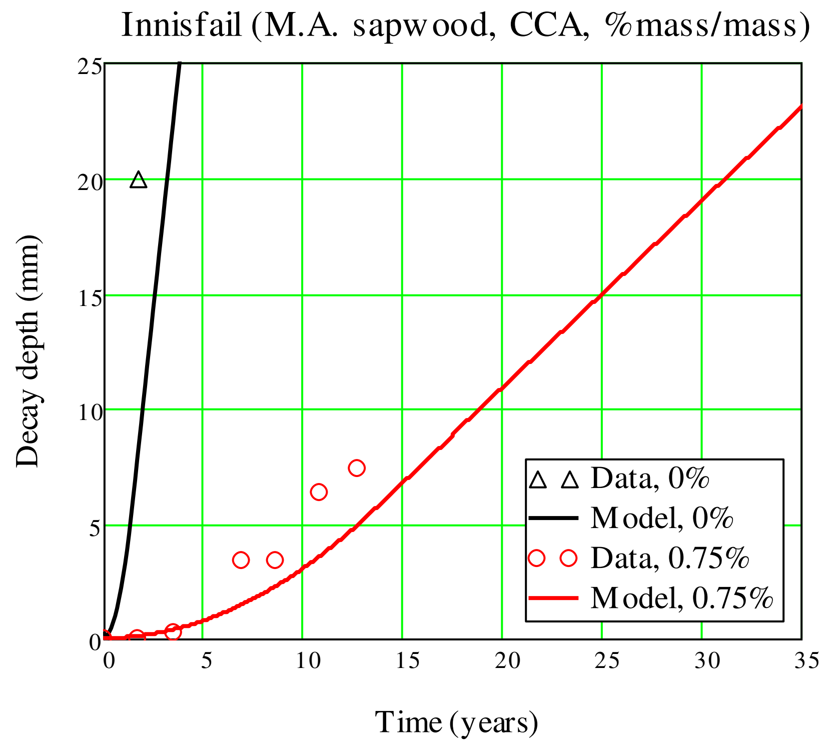
Figures 3.9 and 3.10 shows a comparison between measured and predicted decay rates for treated sapwood, in terms of Species Data.

Figure 3.11 shows a comparison between measured and predicted correlation between the decay rate and decay lag, again in terms of Species Data.



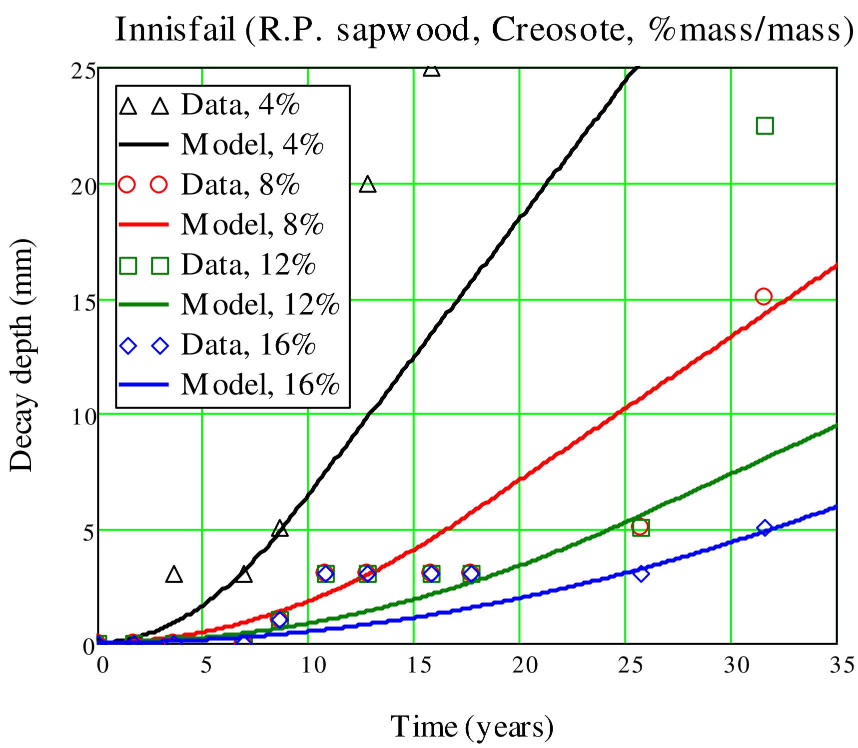
Note: Percentages in the legend are preservative retention in %mass/mass

Decay progress of CCA-treated radiate pine sapwood at Innisfail



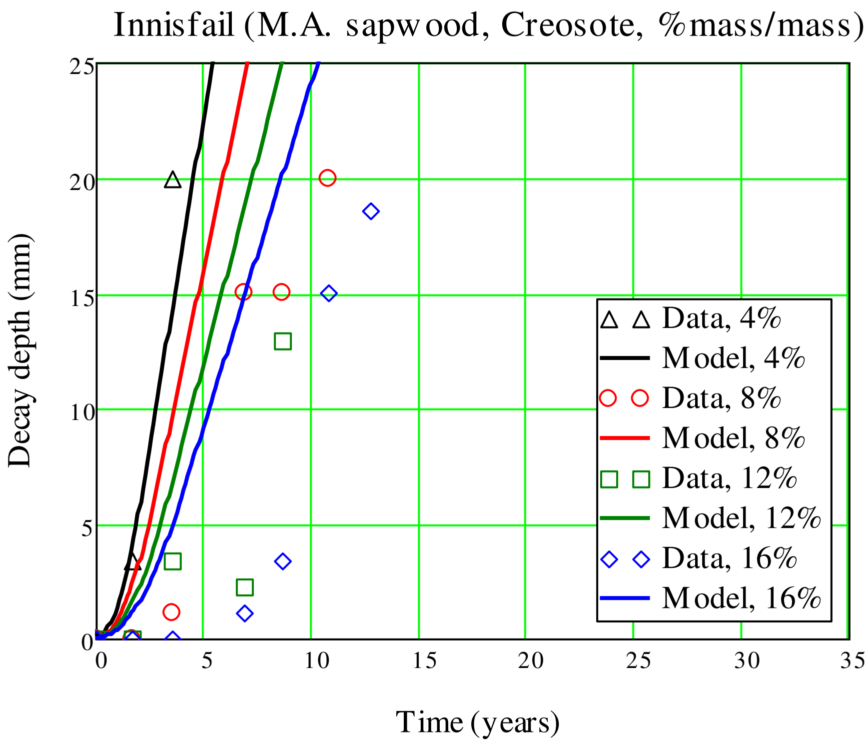
Note: Percentages in the legend are preservative retention in %mass/mass

Decay progress of CCA-treated mountain ash sapwood at Innisfail



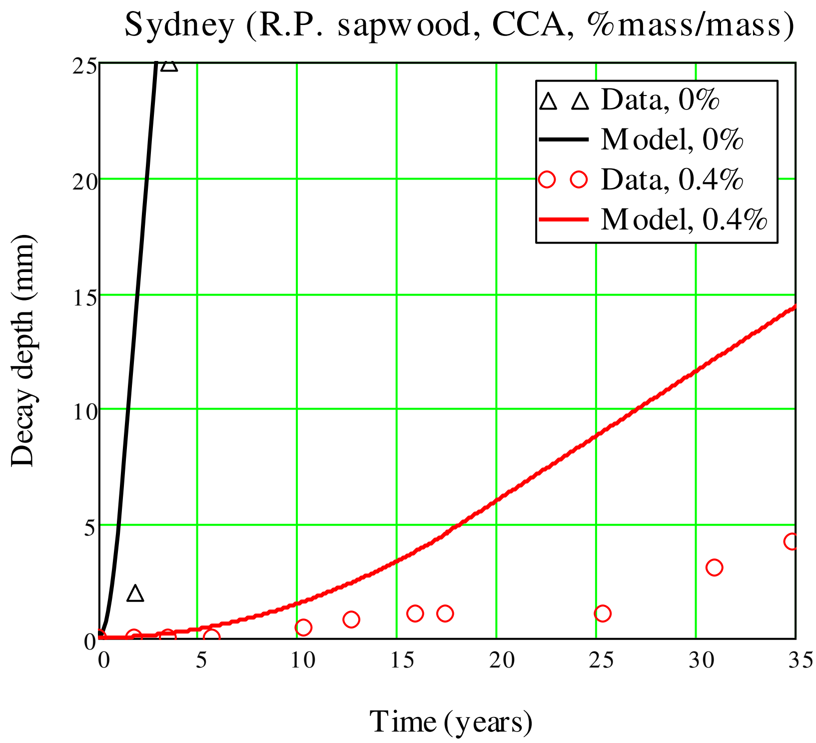
Note: Percentages in the legend are preservative retention in %mass/mass

Decay progress of creosote-treated radiate pine sapwood at Innisfail



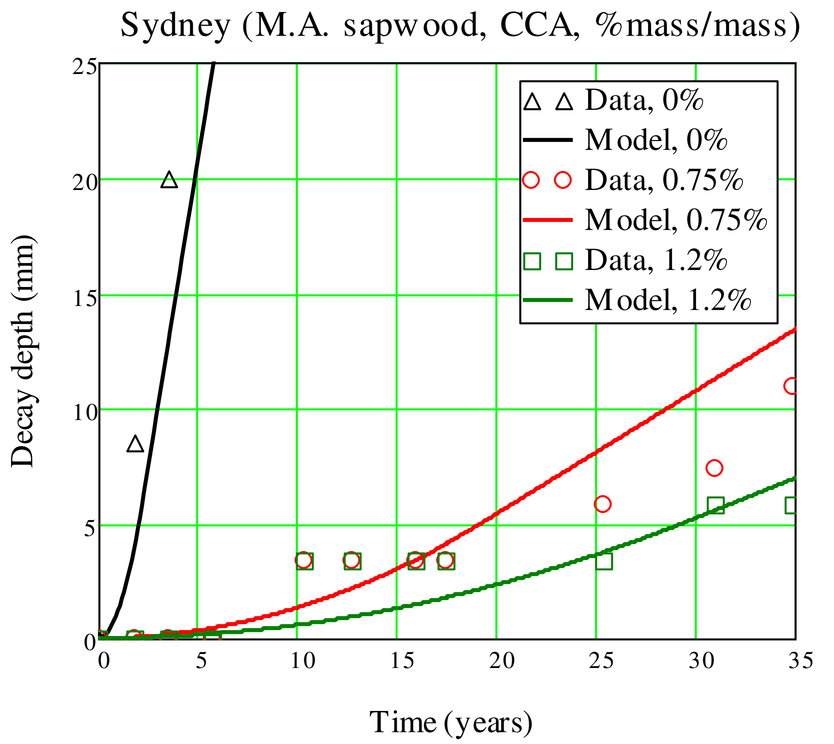
Note: Percentages in the legend are preservative retention in %mass/mass

Decay progress of creosote-treated mountain ash sapwood at Innisfail



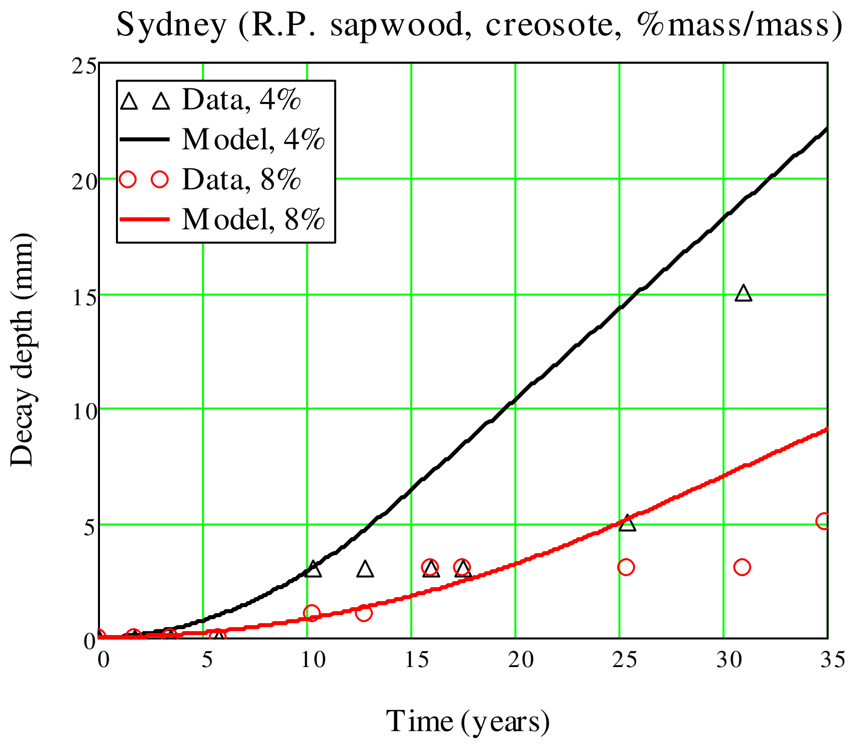
Note: Percentages in the legend are preservative retention in %mass/mass

Decay progress of CCA-treated radiate pine sapwood in Sydney



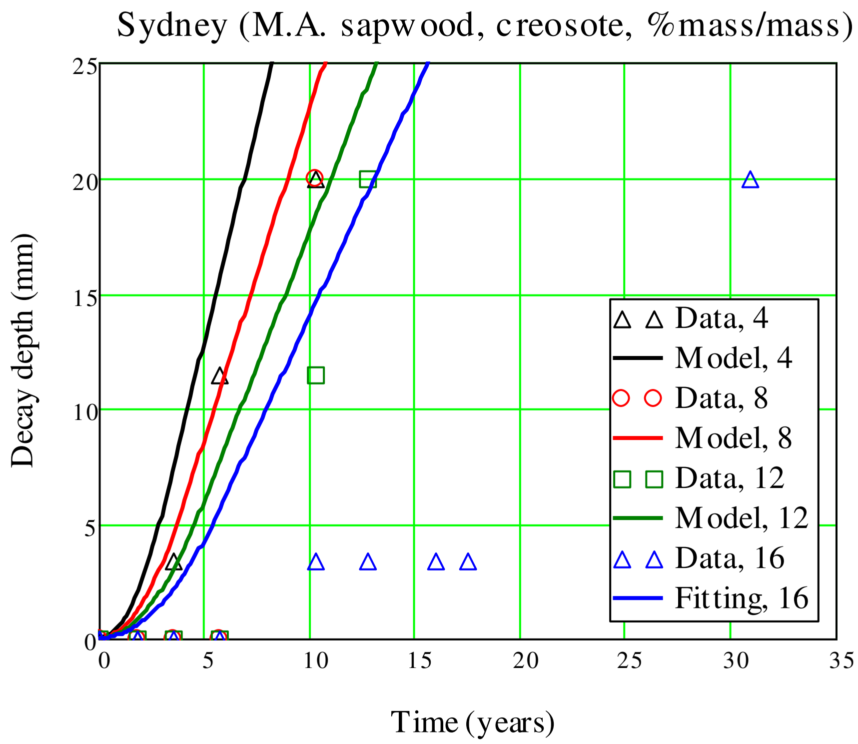
Note: Percentages in the legend are preservative retention in %mass/mass

Decay progress of CCA-treated mountain ash sapwood in Sydney



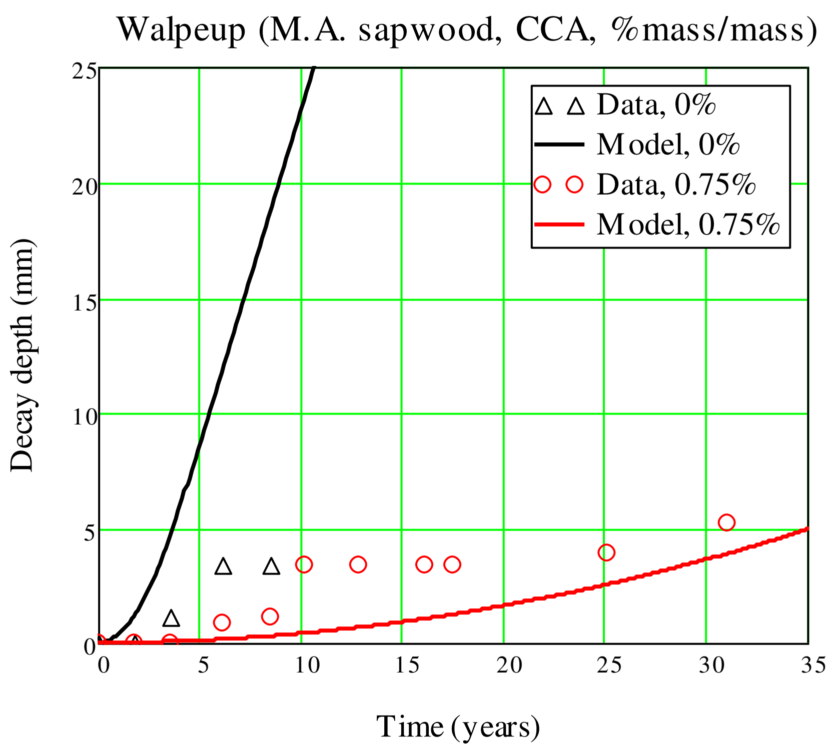
Note: Percentages in the legend are preservative retention in %mass/mass

Decay progress of creosote-treated radiate pine sapwood in Sydney



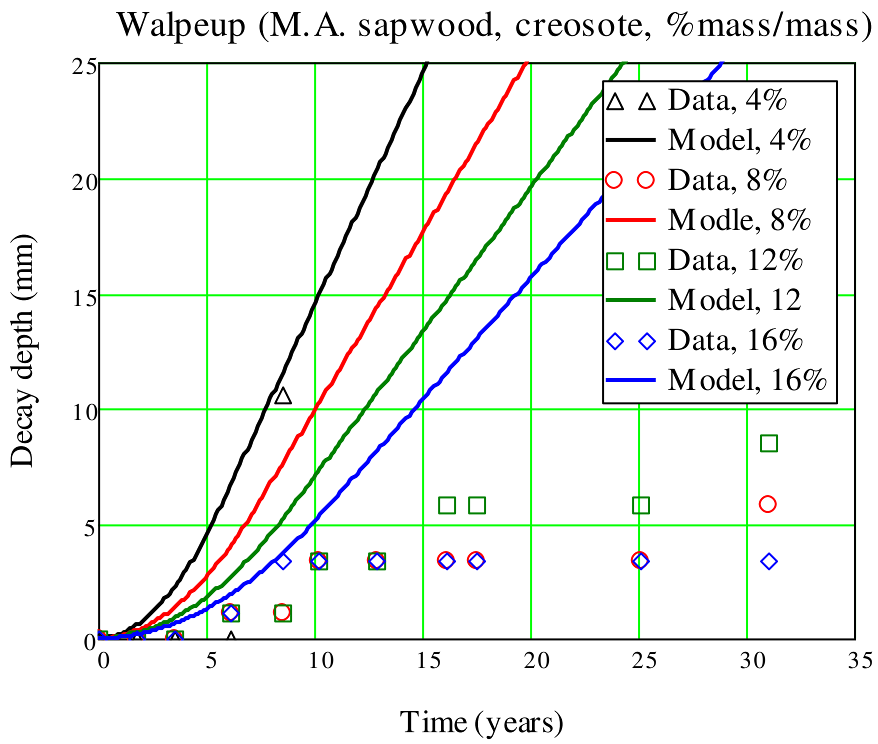
Note: Percentages in the legend are preservative retention in %mass/mass

Decay progress of creosote-treated mountain ash sapwood in Sydney



Note: Percentages in the legend are preservative retention in %mass/mass

Decay progress of CCA-treated mountain ash sapwood at Walpeup



Note: Percentages in the legend are preservative retention in %mass/mass

Decay progress of creosote-treated mountain ash sapwood at Walpeup

Figure 3.8 Progress of decay in timber sapwood treated with CCA and creosote

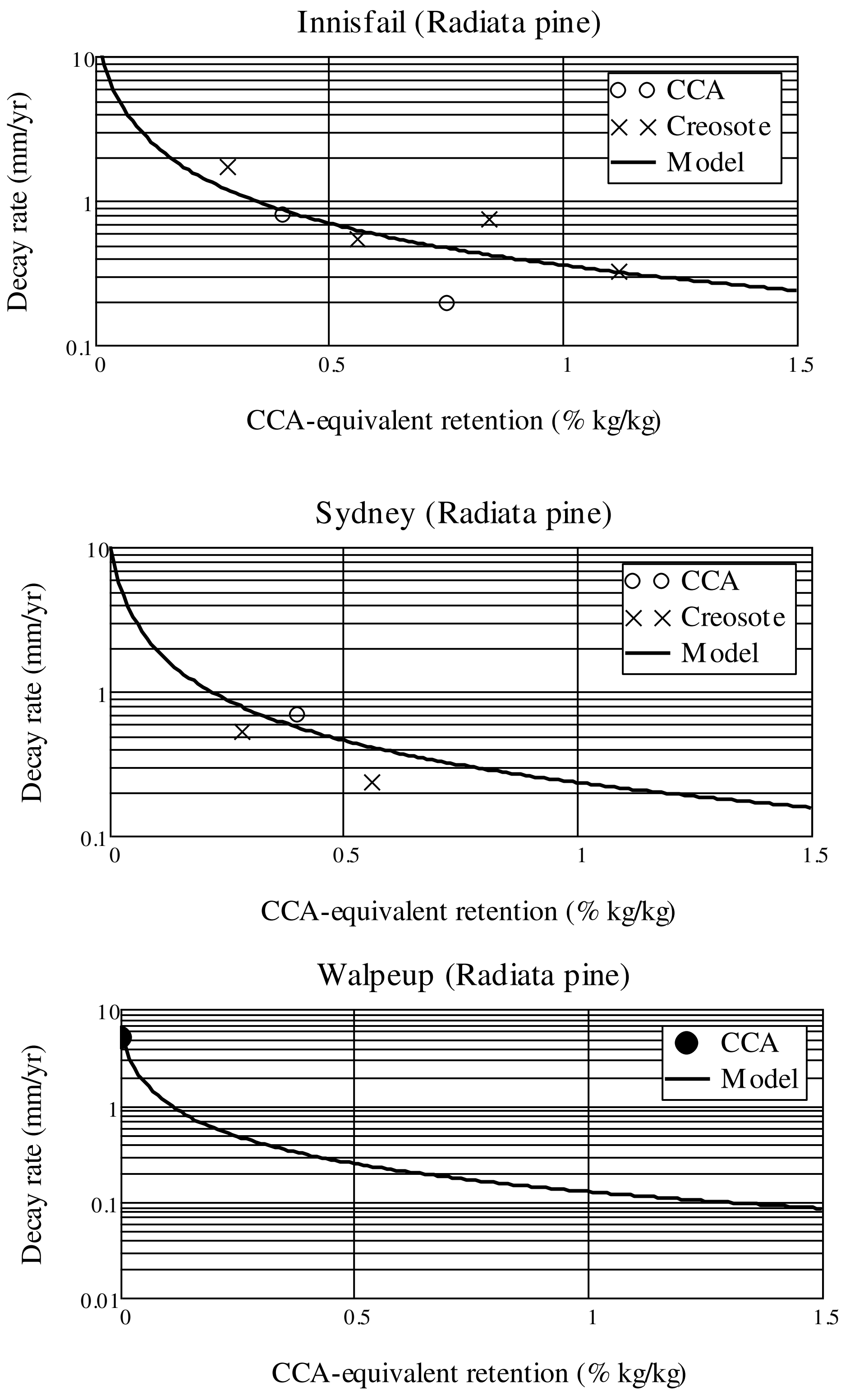


Figure 3.9 *Decay rate versus CCA-equivalent retention in radiata pine (Species Data)*

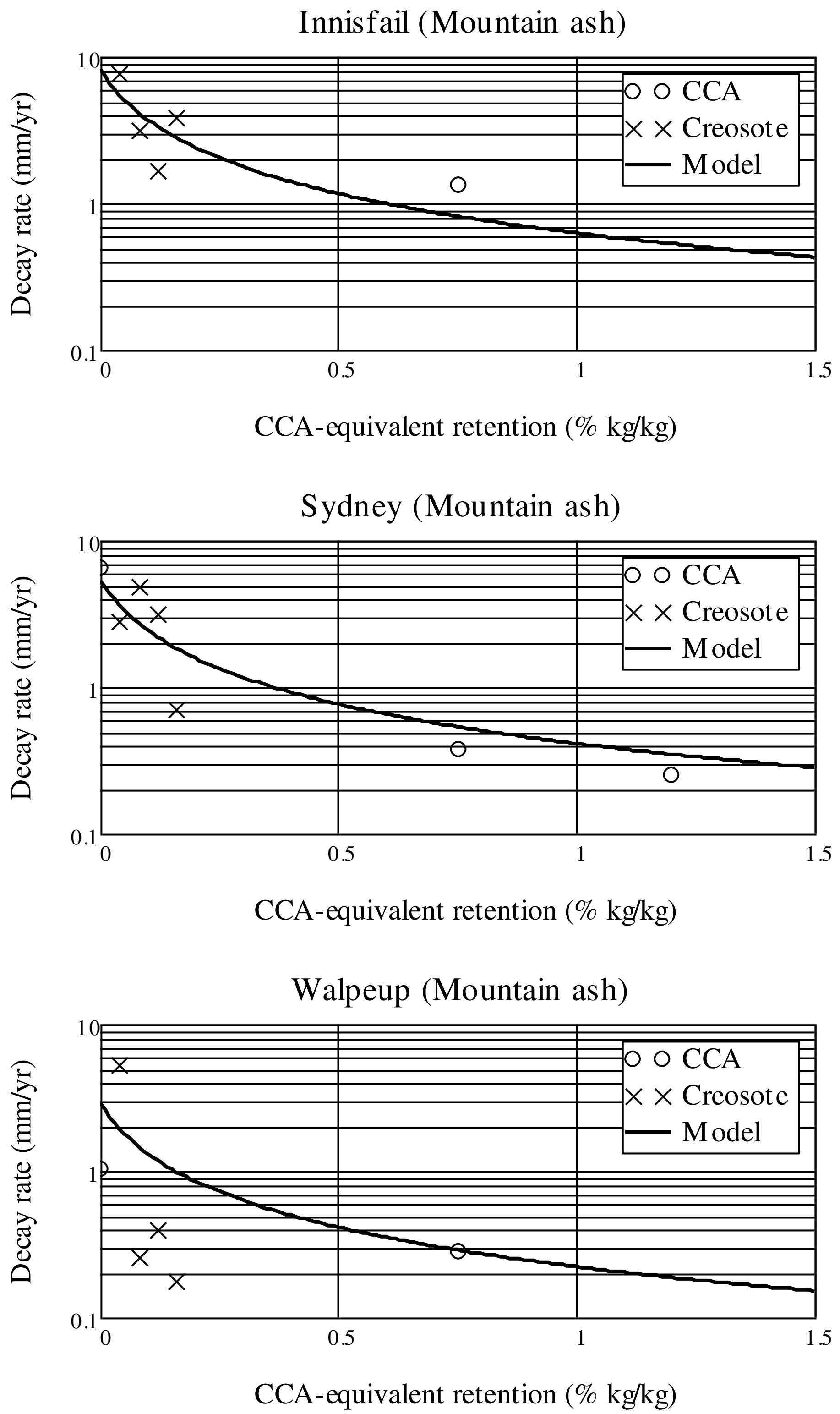
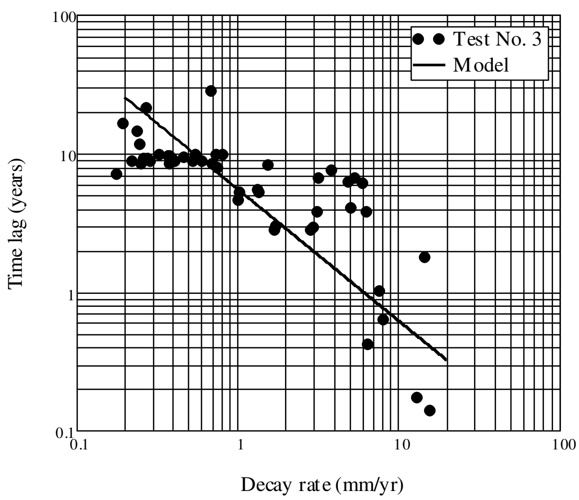
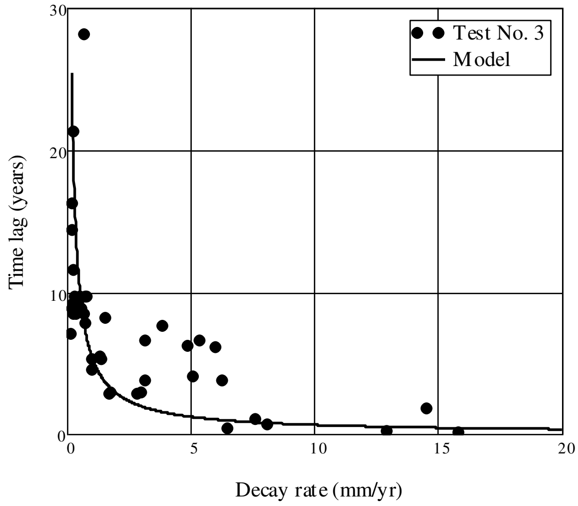


Figure 3.10 *Decay rate versus CCA-equivalent retention in mountain ash(Species Data)*



(a) logarithmic scale



(b) linear scale

Figure 3.11 Correlation between decay lag and decay rate from stake test for treated wood. (Species Data)

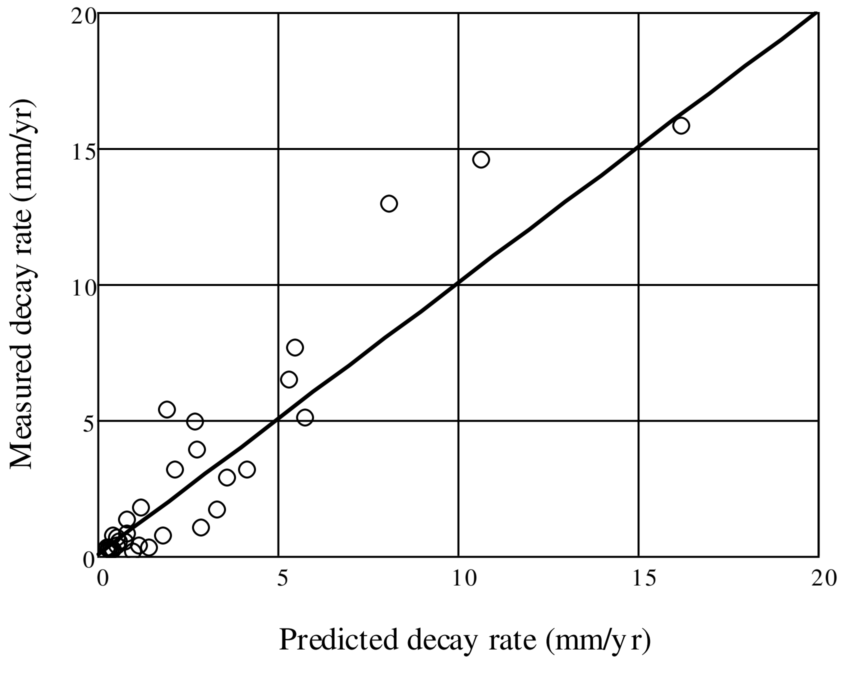


Figure 3.12 *Measured versus predicted decay rate, Species Data(R=0.94)*

Figure 3.12 shows the measured and predicted decay rates of the treated mountain ash and radiata pine sapwoods observed in the stake test for treated wood. The correlation coefficient is 0.94.

4. SOURCE DATA FOR WEDDING BELLS

4.1 Wedding Bells Round Poles

4.1.1 General

The number of specimens that have been assessed and input into the Database for Wedding Bells poles is 74 specimens are in-ground sections (including sections at ground line).

5. DATA PROCESSING FOR WEDDING BELLS

5.1 Strength of Non-decayed Wood

A number of poles from Wedding Bells test site were used to measure the bending strength of non-decayed wood.

Small clear specimens of size of 15×15×300 mm were taken from longitudinal locations A, B, C (or C_1), and D, as shown in Figure 5.1. Figure 5.2 shows the locations where the specimens, numbered 1 (circumference), 2 (internal but just away from circumference decay), and 3 (internal and just away from internal decay), were taken on a cross-section of decayed wood, and Figure 5.3 shows that of non-decayed wood. The test setup is shown in Figure 5.4.

Based on the test results, it was found that no obvious difference in strength (Figure 5.5) and stiffness (Figure 5.6) between wood adjacent to decayed area and that adjacent to no decayed area. The findings are based on a relatively small number of test specimens. Improvement in confidence and accuracy is expected when more tests are carried out in the next stage of the project.

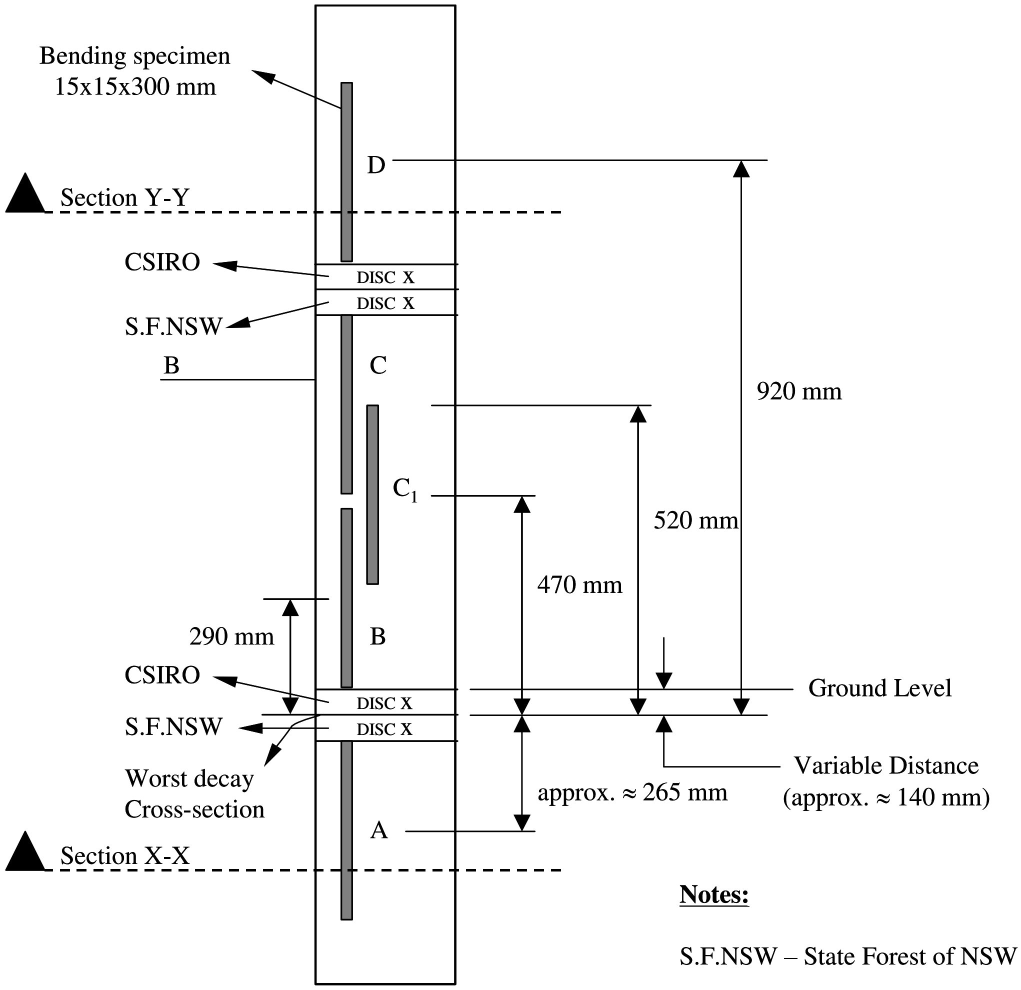
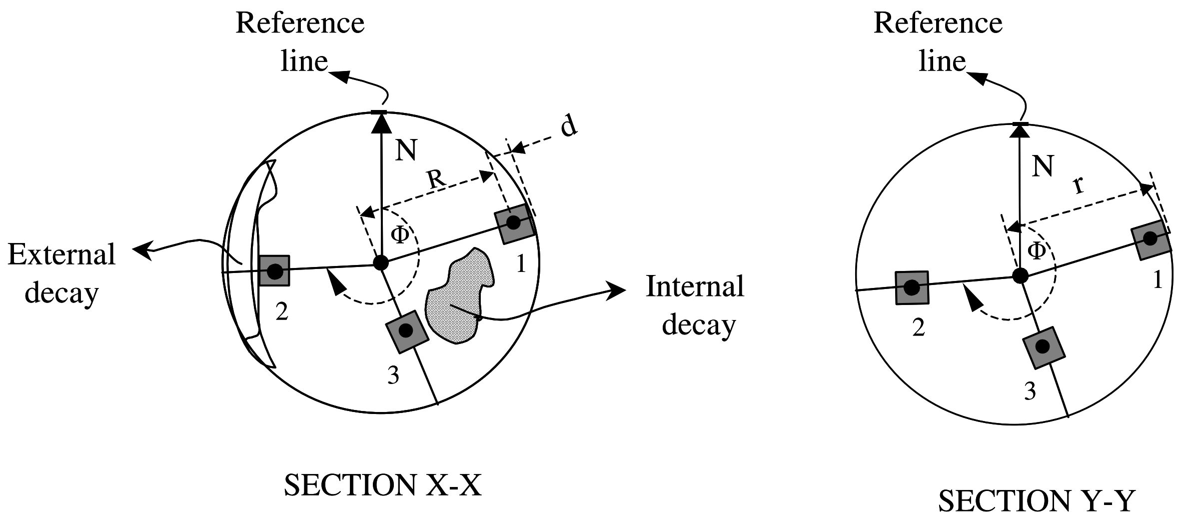


Figure 5.1 *Locations where small clear specimens were taken.*



Notes:

1- Circumference
2- Just in from circumference decay
3- Just in from internal decay
r = R + d

Figure 5.2 Top view of a pole with detected decay or near ground level (see Fig 2.4).

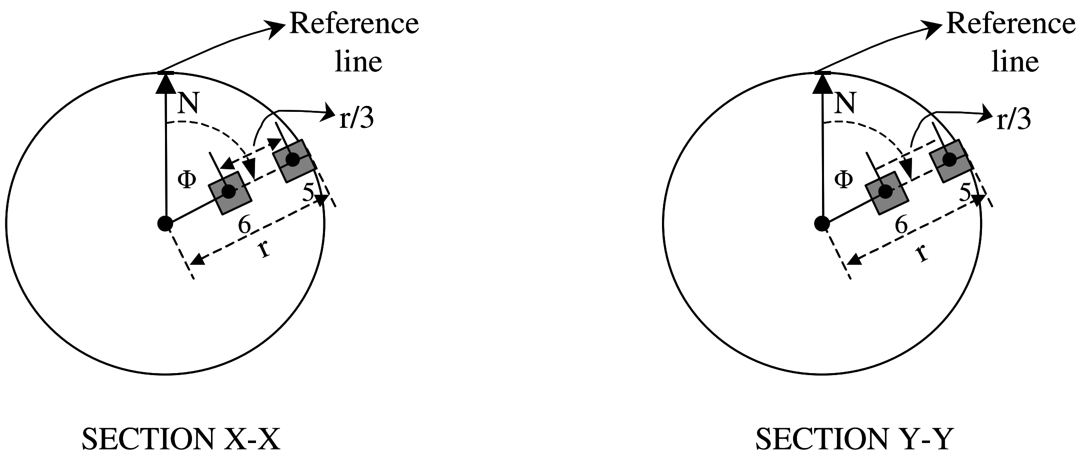


Figure 5.3 ***Top view of a pole with no detected decay or near the ground level (see Fig 2.4).***

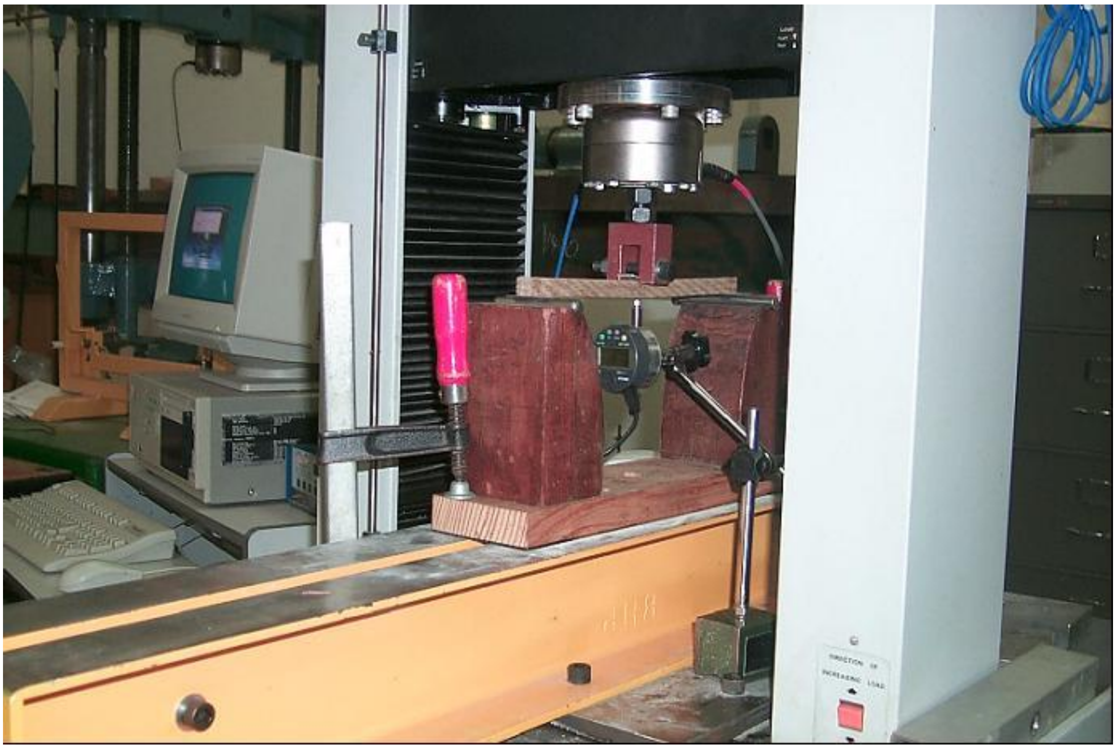


Figure 5.4 ***Strength test setup for non-decayed wood specimens.***

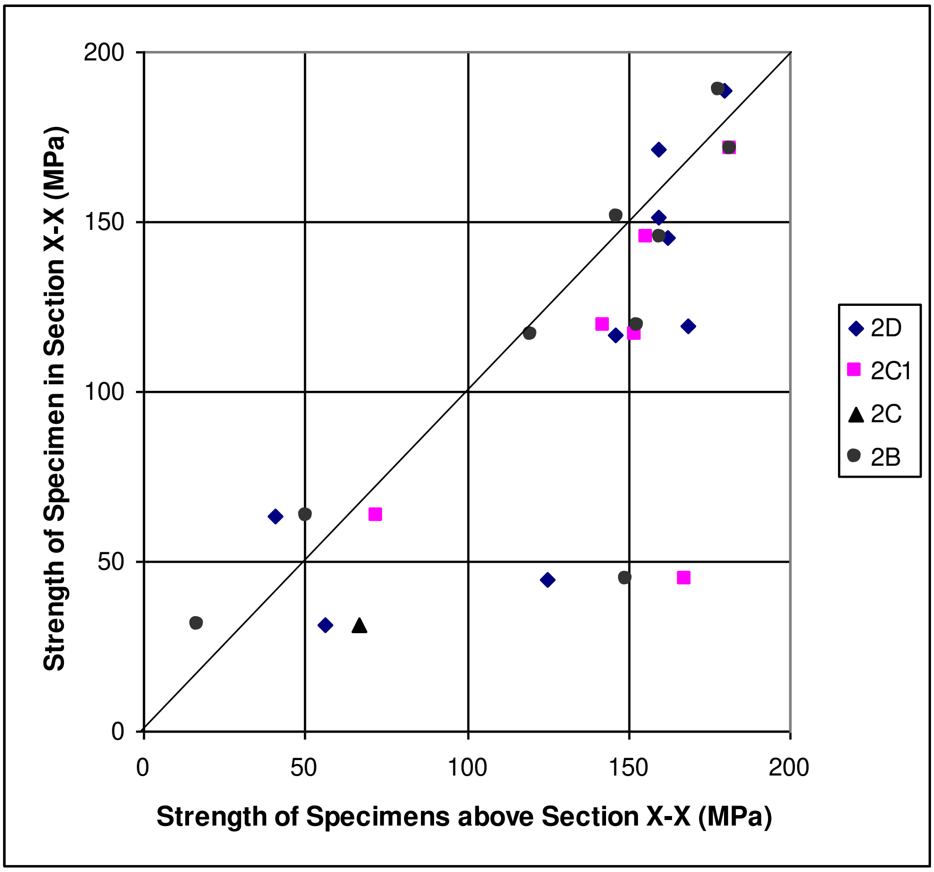


Figure 5.5 ***Comparison of strength between specimen 2-A (at Section X-X) and specimens 2-D, 2-C1, 2-C and 2-B (above Section X-X) for poles with detected decay (Figure 2.5).***

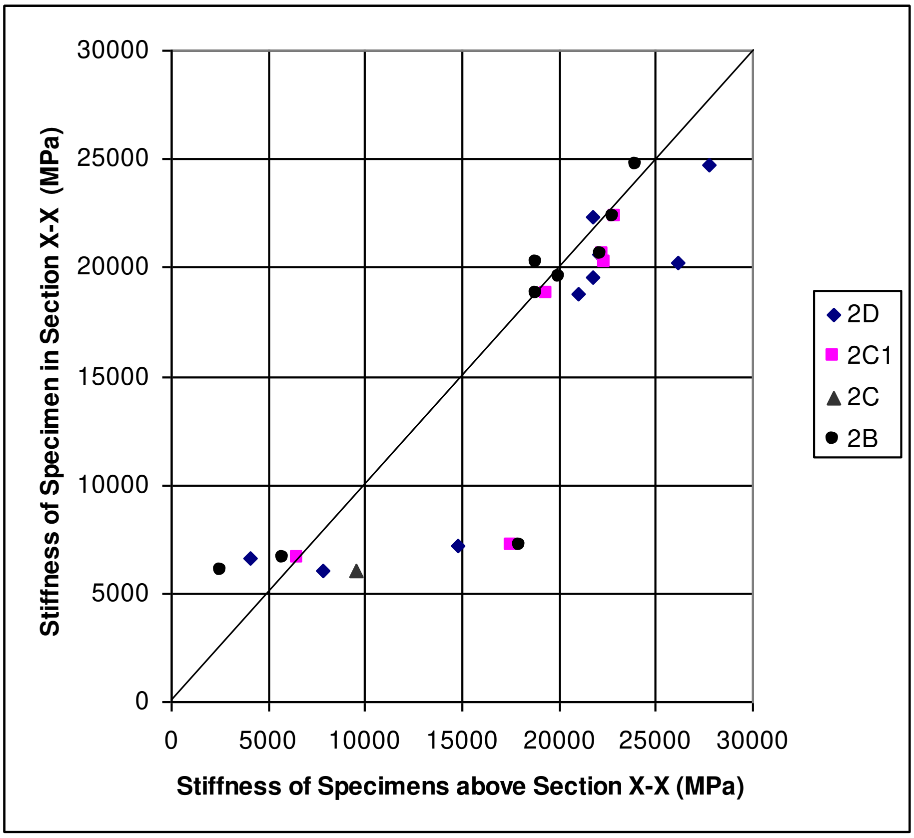


Figure 5.6 ***Comparison of stiffness between specimen 2-A (at Section X-X) and specimens 2-D, 2-C1, 2-C and 2-B (above Section X-X) for poles with detected decay (Figure 2.5).***

5.2 Wedding Bells Round Poles

5.2.1 Comparison of the assessment results with predicted decays

The climate parameter k_{climate} for the Wedding Bells test site (Coffs Harbour, NSW, latitude: –38.39°, longitude: 134.60°) is determined to be 2.134.

Figure 5.7 presents the measured and predicted data. The predicted decays computed using the theory equations in Section 1 with a modification depicted in the below Figure 3.1.2. For given t_{lag} and r, the decay depth is computed

Comparative plots of predicted decay versus measured decay using the data from Tables 3.1.2.1 are provided in Figures 3.1.2.1 to 3.1.2.3.

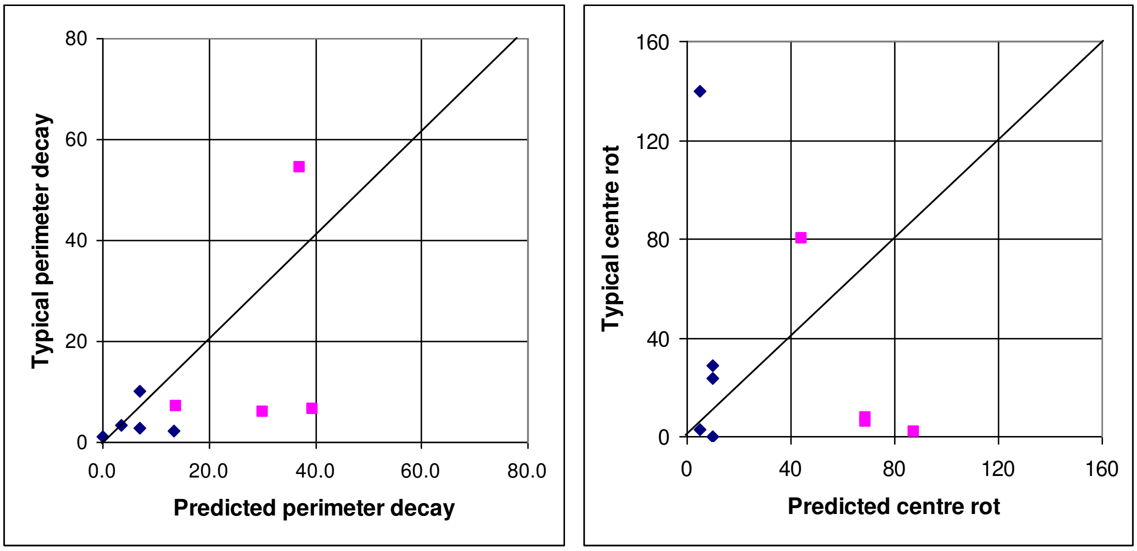
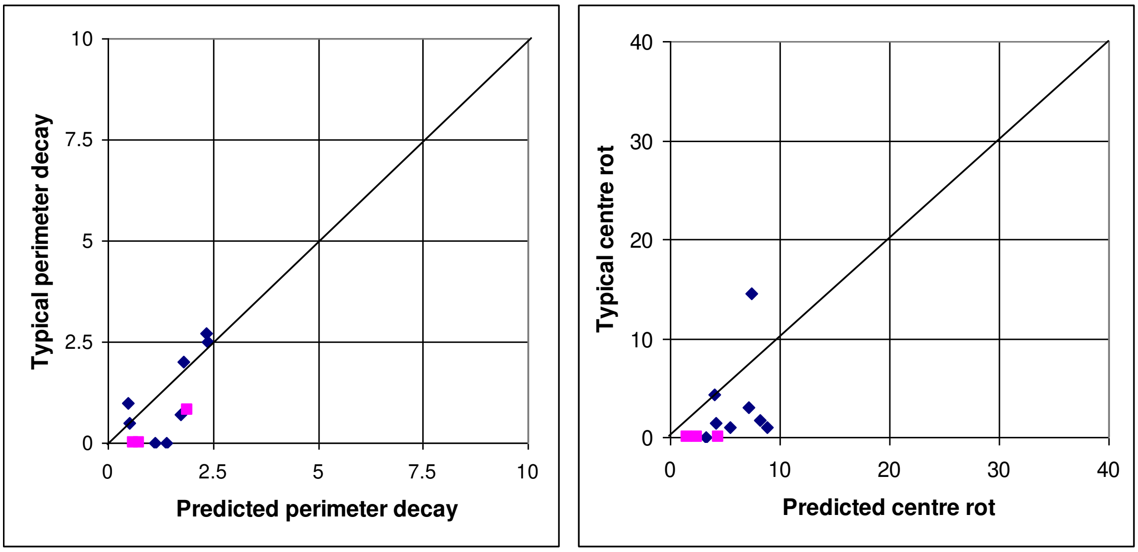


Figure 5.7 Reality check with **typical** decay values of untreated poles of durability class 1



(diamond points) and class 2 (square points). Data are from Table 3.1.2.1.

Figure 3.1.2.2 Reality check with **typical** decay values of CCA-treated poles of durability class 2 (diamond points) and class 4 (square points). Data are from Table 3.1.2.1.

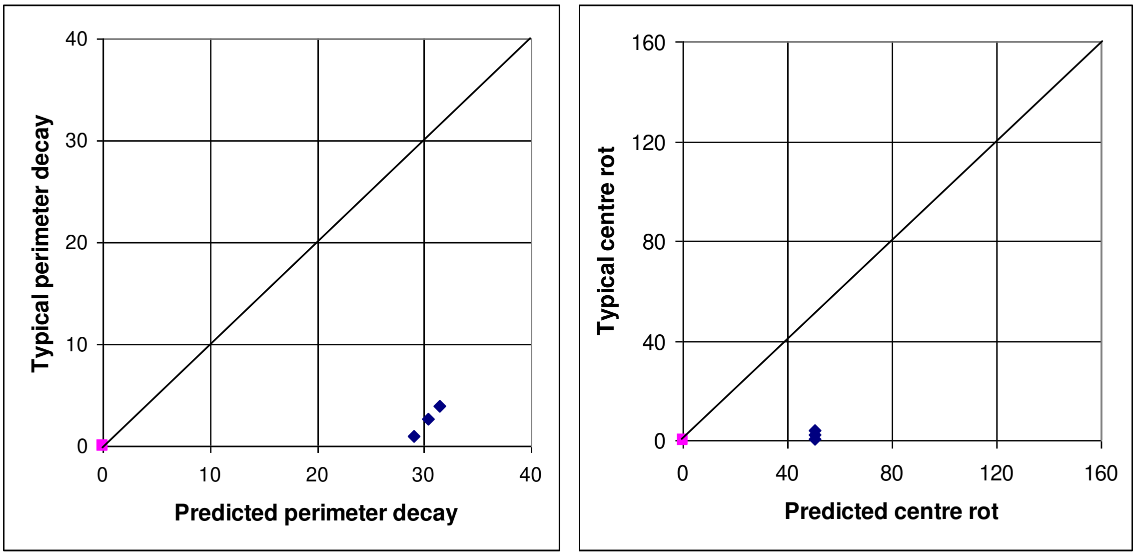


Figure 3.1.2.3 Reality check with **typical** decay values of Creosote-treated poles of durability class 2 (diamond points) and class 4 (square points). Data are from Table 3.1.2.1.

Table 3.1.2.1 Calibration data from Wedding Bells poles and predicted decay.

Group	Duration of service (yrs)	IG decay rating	Preser-vative	Retention (%kg/kg)	Treatment type	Number of treatment	Sapwood thickness (mm)	Peri decay typical	Centre rot typical	Peri decay predicted	Centre rot predicted
1	18	1	none	0	none	0	0	3.5	140.0	3.5	5.17
2	18	1	none	0	diffusing paste	4	0	1.0	3.0	0.0	5.17
3	25	1	none	0	none	0	0	2.8	23.8	7.0	9.93
4	25	1	none	0	physical barrier	1	0	10.2	28.5	7.0	9.93
5	25	1	none	0	non-diffusing paste	4	6	2.3	0.0	17.3	9.93
6	18	2	none	0	physical barrier	1	24	54.5	80.0	37.1	44.55
7	22	2	none	0	physical barrier	2	22	6.5	7.5	39.6	69.13
8	22	2	none	0	diffusing paste	2	23	6.0	6.0	40.4	69.13
9	25	2	none	0	non-diffusing paste	3	0	7.0	2.0	14.0	87.57
10	18	2	CCA	1	physical barrier	3	32	0.0	4.3	1.1	4.08
11	18	2	CCA	0.98	diffusing paste	4	33	0.5	1.5	1.2	4.16
12	22	2	CCA	0.83	none	0	36	2.5	14.5	2.4	7.36
13	22	2	CCA	1.1	physical barrier	3	34	0.0	1.0	1.4	5.49
14	22	2	CCA	1.67	diffusing paste	2	37	1.0	0.0	0.6	3.31
15	25	2	CCA	1.1	none	0	41	2.0	3.0	1.8	7.09
16	25	2	CCA	0.96	physical barrier	1	31	2.7	1.7	2.3	8.21
17	25	2	CCA	0.9	non-diffusing paste	4	27	0.7	1.0	2.6	8.77
18	25	2	Creosote	13	none	0	29	4.0	2.3	31.4	50.39
19	25	2	Creosote	13	physical barrier	1	27	2.7	0.5	30.3	50.39
20	25	2	Creosote	13	non-diffusing paste	3	29	1.0	4.0	31.4	50.39
21	25	4	CCA	1.3	none	0	74	0.0	0.0	0.6	1.56
22	25	4	CCA	0.73	physical barrier	1	82	0.8	0.0	1.9	4.40
23	25	4	CCA	1	non-diffusing paste	5	88	0.0	0.0	1.0	2.51
24	25	4	Creosote	24	none	0	73	0.0	0.0	0.4	0.97

6. REALITY CHECKS WITH IN-SERVICE DATA

6.1 Brisbane round house stumps

6.1.1 General

In-ground decay of a set of 19 round stumps of a Queensland-type house in Kedron, Brisbane was assessed after 53 years in service. The data were grouped into 6 groups. These stumps were of untreated eucalypts and having no maintenance treatment applied during 53 years of service.

6.1.2 Comparison of the assessment results with predicted decays

Table 3.2.2.1 presents the Calibration data (Nguyen et al 2003b) and the predicted decays computed using the theory equations in Section 1. The in-ground climate factor specific for Brisbane is $k_{\text{climate}} = 2.5$.

Comparative plots of predicted decay versus measured decay using the data from Tables 3.2.2.1 are provided in Figure 3.2.2.1.

Table 3.2.2.1 Calibration data from round house stumps in Brisbane and prediction

ID	In-ground decay class	Sap-wood	Repli-cates	Typical perimeter decay	90%tile perimeter decay	Typical centre rot	90%tile centre rot	Predicted perimeter decay	Predicted centre rot
1	1	0	3	5	7.8	51.7	73	25.1	106.22
2	1	5	5	13.2	16.6	71.4	88	34.5	106.22
3	1	0	3	46	50	83.3	106	25.1	106.22
4	1	5	2	51	66.2	90	98	34.5	106.22
5	2	0	2	11	18.2	90	106	58.0	171.67
6	2	20	4	23.5	32.6	108.8	170	79.0	171.67

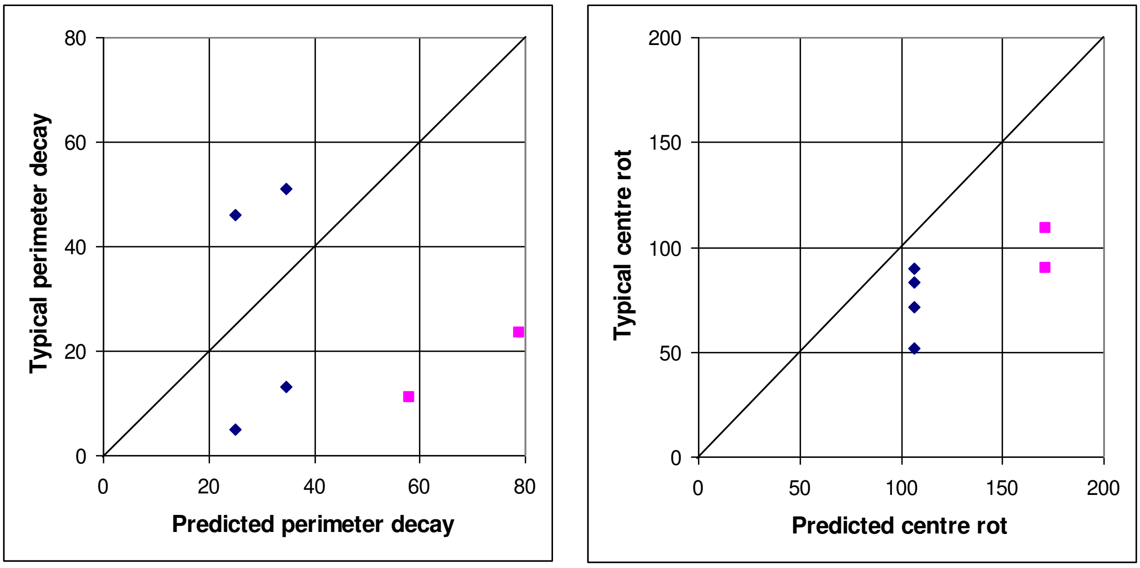


Figure 3.2.2.1. Reality check with **typical** decay values of untreated stumps of durability class 1 (diamond points) and class 2 (square points).

Data are from Table 3.2.2.1.

6.2 Melbourne Rectangular Fence Posts

6.2.1 General

In-ground decay totally 192 fence posts of 8 fences in Melbourne was assessed. These posts were not untreated timber and no maintenance treatment applied when in service.

6.2.2 Comparison of the assessment results with predicted decays

Table 3.3.2.1 presents the Calibration data and the predicted decays computed using the theory equations in Section 1. The in-ground climate factor specific for Melbourne is $k_{climate} = 1.67$.

Comparative plots of predicted decay versus measured decay using the data from Tables 3.3.2.1 is provided in Figures 3.3.2.1.

Table 3.3.2.1 Calibration data from fence posts in Melbourne and prediction

Location (VIC)	Timber Species	In-ground decay class	Service Age (yrs)	Repli-cates	Typical (Average) (mm)	90 %-tile value (mm)	Predicted decay (mm)
Beaconsfield	RRG	2	13	24	18.9	34.9	4.98
Bentleigh E.	RRG	2	19	24	9.2	11.4	9.79
Chelsea Heights	GG	1	28	24	***50.8***	***64.0***	5.51
Glen Waverley	RRG	2	30	24	***27.4***	***59.4***	18.61
Mooroolbark	RRG	2	33	24	39.0	60.0	21.01
Mt Waverley	RRG	2	35	24	19.0	39.7	22.62
Doncaster E.	RRG	2	36	24	***21.6***	***60.0***	23.42
Blackburn S.	RRG	2	37	24	***40.5***	***58.0***	24.22

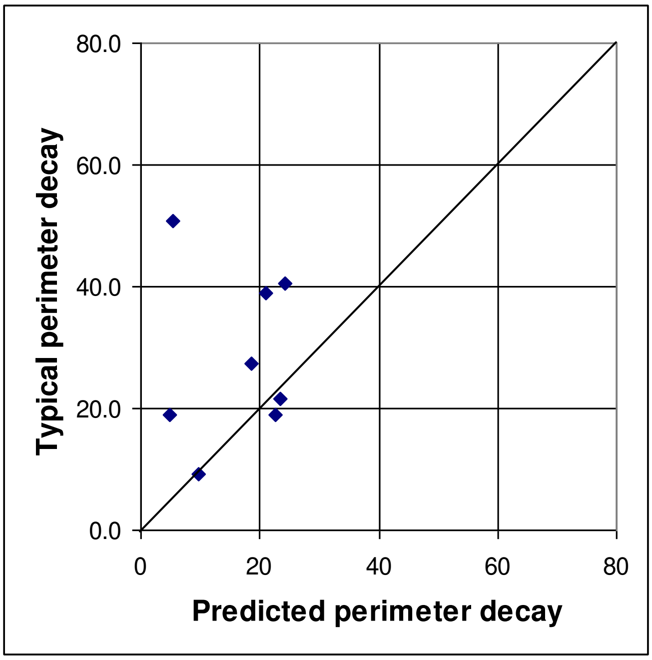


Figure 3.3.2.1. Reality check with fence posts in Melbourne.

Data are from Table 3.3.2.1.

6.3 Melbourne Rectangular House Stumps

6.3.1 General

In-ground decay 19 house stumps a house in Melbourne was assessed. The details of the data and the processing were presented in CMIT-2003-044 (Nguyen et al 2003b). These stumps were of untreated timber and having no maintenance treatment applied.

6.3.2 Comparison of the assessment results with predicted decays

Table 3.4.2.1 presents the Calibration data (Nguyen et al 2003b) and the predicted decays computed using the theory equations in Section 1. The in-ground climate factor specific for Melbourne is $k_{\text{climate}} = 1.67$.

Comparative plots of predicted decay versus measured decay using the data from Tables 3.4.2.1 is provided in Figures 3.4.2.1.

Table 3.4.2.1 Calibration data from 'Barnacle' house stumps in Melbourne and prediction

Species	IG Class	Exterior/ Interior*	Replicates	Age	Typical value	90%tile value	Predicted decay
Gum, red river	2	Int	9	43	9.31	14.75	29.03
Gum, red river	2	Ext	10	43	22.50	46.38	29.03

(*) 'Ext' stumps were located at outer perimeter of the house; 'Int' stumps were located inside.

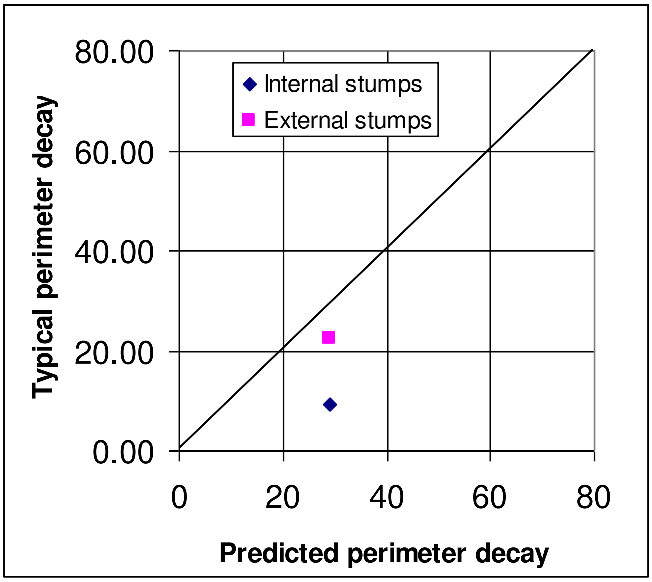


Figure 3.4.2.1. Reality check with 'Barnacle' house stumps in Melbourne. Data are from Table 3.4.2.1.

7. RELIABILITY ANALYSIS

7.1 Variability of Decay of Stakes

The data from the field tests was processed to obtain an estimate of the uncertainties associated with the use of the model. To do this, two-parameter Weibull distributions were fitted to the data. From this it was found that the uncertainties associated with k_{wood}, denoted by a coefficient of variation (COV), V_{wood}, was about 0.45, 0.55, 0.75, and 0.90 for timber of durability classes 1, 2, 3, and 4, respectively (Table 7.1). The years at which the COVs were estimated are given in Table 7.2. Table 7.3 gives the measured and the predicted decay rate of untreated heartwood for the five untreated wood test sites. Similarly the uncertainty associated with $k_{climate}$, denoted by a COV, $V_{climate}$, was found to have a value of about 0.55. The uncertainty associated with $k_{climate}$ is illustrated by the scatter of the data shown in Figure 7.1.

Table 7.1 Coefficient of variation for k_{wood} measured at the untreated stake wood test sites

Durability Class	Computed COV					Average
	Walpeup	Innisfail	Sydney	Brisbane	Mulgrave	
1	0.429	0.429	0.49	0.479	0.391	0.444
2	0.387	0.55	0.557	0.656	0.547	0.539
3	0.575	0.803	1.011	0.826	0.588	0.761
4	0.551	0.784	1.238	0.907	1.126	0.921

Table 7.2 Years after specimen installation at which the COV were estimated

Durability Class	Year of Evaluation for COV					Average
	Walpeup	Innisfail	Sydney	Brisbane	Mulgrave	
1	30.817	30.816	35.3	25.019	33.4	31.07
2	26.984	17.089	17.092	13.036	29.844	20.809
3	22.962	6.186	10.922	6.189	14.922	12.236
4	16.247	6.186	6.299	1.995	6.4	7.425

Table 7.3 Measured vs. predicted decay rates of untreated heartwoods

Durability Class	Test Site	Measure decay rate (mm/yr)	Predicted decay rate (mm/yr)
1	Walpuep, VIC	0.483	0.245
	Innisfail, QLD	0.442	0.691
	Sydney, NSW	0.406	0.454
	Brisbane, QLD	0.608	0.491
	Mulgrave, VIC	0.305	0.382
2	Walpuep, VIC	0.605	0.511
	Innisfail, QLD	0.989	1.443
	Sydney, NSW	0.984	0.949
	Brisbane, QLD	1.376	1.027
	Mulgrave, VIC	0.468	0.799
3	Walpuep, VIC	0.656	0.81
	Innisfail, QLD	1.507	2.287
	Sydney, NSW	1.22	1.504
	Brisbane, QLD	2.525	1.628
	Mulgrave, VIC	1.06	1.266
4	Walpuep, VIC	1.162	1.433
	Innisfail, QLD	2.51	4.046
	Sydney, NSW	2.012	2.661
	Brisbane, QLD	6.71	2.88
	Mulgrave, VIC	1.768	2.24

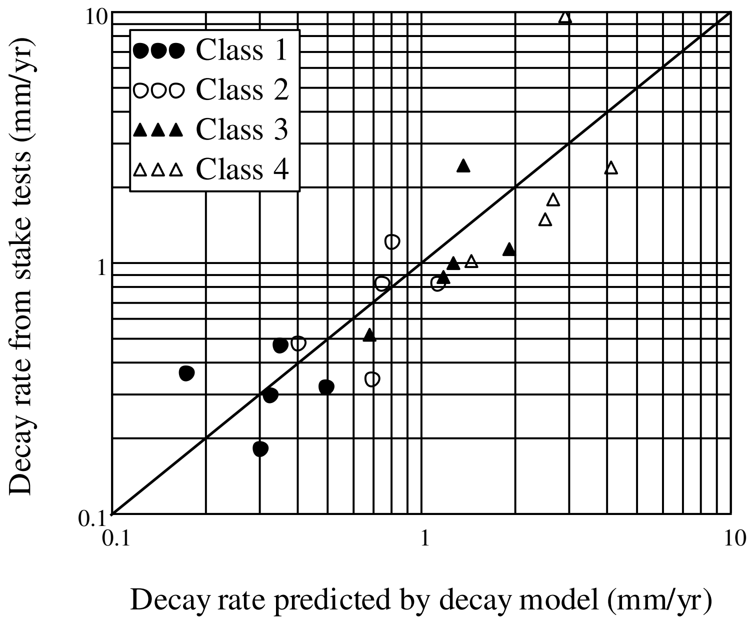
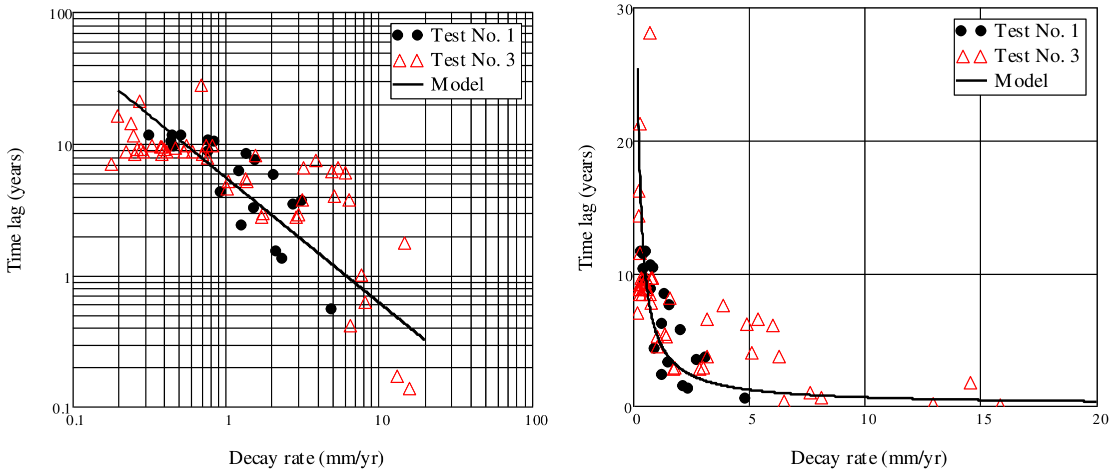


Figure 7.1 Comparison between predicted and measured decay rates of wood stakes (each plotted point denotes the median value for a single durability class of timber on a particular test site)



(a) logarithmic scale (b) linear scale

Figure 7.2 Decay lag and decay rate from stake test Nos. 1 and 3.

7.2 Mean Pole Strength

At time zero, the bending strength of a round pole, R_0, is given by

$$R_0 = \frac{\pi}{32} D^3 f_{ult} \tag{7.1}$$

where *D* is the initial diameter (mm) and f_{ult} is the ultimate fiber strength of undecayed wood (MPa). If attack by decay fungi occurs, then in accordance with the above assumption, after time *t* the bending strength, denoted by R_t, becomes

$$R_t = \frac{\pi}{32}\left(D - 2d_t\right)^3 f_{ult} \tag{7.2}$$

where d_t is the decay depth (mm) at time *t*.

Considering that the decay depth d_t is a random variable, the bending strength at time *t* is also a random variable. The mean strength at time *t*, denoted by $R_{mean,t}$, may be estimated by a first-order approximation as follows,

$$R_{mean,t} \simeq \frac{\pi}{32}\left(D - 2\bar{d}_t\right)^3 f_{ult} \tag{7.3}$$

where $\bar{d}_t$ is an estimate of the mean decay depth at time *t*.

7.3 Variability of Pole Strength

The variance of strength at time *t*, denoted by $\sigma_{R,t}^2$, is given by a first-order approximation,

$$\sigma_{R,t}^2 \simeq \left(V_d \bar{d}_t\right)^2 \left(\left.\frac{\partial R_t}{\partial d_t}\right|_{d_t=\bar{d}_t}\right)^2 = \left[\frac{3\pi}{16} f_{ult} V_d \bar{d}_t \left(D - 2\bar{d}_t\right)^2\right]^2 \tag{7.4}$$

where $\bar{d}_t$ is an estimate of mean value of decay depth at time t, and V_d denotes the uncertainty of decay due to timber properties. The uncertainty parameter V_d will be taken to be a COV defined by

$$V_d = \sqrt{V_{wood}^2 + V_{climate}^2 + V_{model}^2} \tag{7.5}$$

where V_{wood} and $V_{climate}$ have been defined in Section 0, and V_{model} allows for uncertainties in the model for the decay rate of stakes, assumptions on the attack pattern, and errors arising from the assumption of applying stake data to poles. Although there is no direct information on V_{model}, some idea of its magnitude can be obtained from an examination of uncertainties measured in structural modelling. For this project a value of $V_{model} = 0.5$ is chosen. Thus Eq. (7.5) leads to the value of V_d for in-ground poles to be 0.85, 0.9, 1.1, and 1.2 for timber of durability classes 1, 2, 3, and 4 of timber, respectively.

The uncertainty in pole strength arising directly from the uncertainty in the estimate of the depth of decay will be denoted by the coefficient of variation $V_{dur,t}$ and is given by

$$V_{dur,t} = \frac{\sigma_{R,t}}{R_{mean,t}} = \frac{6 V_d \bar{d}_t}{D - 2\bar{d}_t} \tag{7.6}$$

In addition to uncertainty arising from the decay depth $V_{dur,t}$ given in Eq. (7.6), the initial strength is also uncertain. The initial COV of the bending strength, $V_{R,0}$, may be combined approximately with $V_{dur,t}$ to give the estimate of the uncertainty of strength at time t, denoted by $V_{R,t}$, as follows,

$$V_{R,t}^2 = V_{R,0}^2 + V_{dur,t}^2 \tag{7.7}$$

7.4 Reliability-Based Durability Factor

Using the approximation discussed by Ravindra and Galambos (1978), the acceptable design strength R_{design} can be approximated by

$$R_{design} = k_{com} R_{mean} \exp\left(-0.6\beta V_R\right) \tag{7.8}$$

where

k_{com} = an arbitrary factor applied to both load and strength specifications
R_{mean} = mean value of R
V_R = COV of R
β = safety index

A durability factor k_D will be defined by

$$k_D = \frac{R_{design,t}}{R_{design,0}} \tag{7.9}$$

where

$R_{design,0}$ = initial design strength
$R_{design,t}$ = design strength at time t

Then from Eq. (7.8) we obtain

$$R_{design,0} = k_{com} R_{mean,0} \exp\left(-0.6\beta V_{R,0}\right) \tag{7.10}$$

$$R_{design,t} = k_{com} R_{mean,t} \exp\left(-0.6\beta V_{R,t}\right) \tag{7.11}$$

where

$R_{mean,0}$ = initial value of strength
$R_{mean,t}$ = mean value of strength at time t
$V_{R,0}$ = initial COV of strength
$V_{R,t}$ = COV of strength at time t

Hence, substituting Eqs. (7.10) and (7.11) into (7.9) leads to

$$k_D = \left(1 - \frac{2\bar{d}_t}{D}\right)^3 \exp\left[-0.6\beta\left(V_{R,t} - V_{R,0}\right)\right] \tag{7.12}$$

where $V_{R,t}$ is obtained from Eq. (7.7).

8. EQUATIONS FOR USE IN DESIGN GUIDE AND TIMBERLIFE

The following assumptions were made in computing the service lives of timber poles and posts in the design guide:

- The corewood diameter is 1/3 of the overall
- For treated softwood, the CCA penetration area is 80% of the cross-section
- For treated hardwood, the CCA penetration is 15 mm for decay classes 1 & 2, 20 mm for classes 3 & 4
- The allowable residual strength is 0.7 of the original

8.1 Decay Rate for Untreated Wood Stakes

Decay rate r is assumed to be the product of multipliers that take into account the effects of material, construction, and environmental factors as follows:

$$r_{un,stake} = k_{wood} k_{climate} \tag{8.1}$$

where k_{wood} = wood parameter and $k_{climate}$ = climate parameter.

8.1.1 Wood Parameter for Heartwood

$$k_{wood,heart} = \begin{cases} 0.23 & \text{for class 1;} \\ 0.48 & \text{for class 2;} \\ 0.76 & \text{for class 3;} \\ 1.36 & \text{for class 4.} \end{cases} \tag{8.2}$$

8.1.2 Wood Parameter for Sapwood

$$k_{wood,sap} = \begin{cases} 2.72 & \text{for hardwood;} \\ 5.44 & \text{for softwood.} \end{cases} \tag{8.3}$$

8.1.3 Wood Parameter for Corewood

$$k_{wood,core} = 2k_{wood,heart} \tag{8.4}$$

8.1.4 Decay Rate for Treated Wood Stakes

It is assumed that in a treated timber log, the sapwood is the only type of wood treated with preservative, whilst the heartwood remains untreated.

To facilitate computation, the retention a preservative is converted into a CCA equivalent. For creosote retention, C_{creosote} (in %kg/kg), its CCA equivalent, $C_{\text{CCA-equiv}}$ (in %kg/kg), is

$$C_{\text{CCA-equiv}} = \begin{cases} 0.07C_{\text{creosote}} & \text{for softwoods;} \\ 0.01C_{\text{creosote}} & \text{for hardwoods;} \end{cases} \tag{8.5}$$

If retention is given in kg/m^3, the conversion between %kg/kg and kg/m^3 may be done by (David Gardner, 2001)

$$\text{kg/kg}(\%) = \begin{cases} \dfrac{0.36 \times \text{ kg/m}^3}{D} \times 100 & \text{for CCA treatment,} \\ \dfrac{\text{kg/m}^3}{D} \times 100 & \text{for creosote treatment.} \end{cases} \tag{8.6}$$

in which D is the air-dry density of timber (kg/m^3).

The decay rate of treated sapwood, $r_{\text{tr,sap,stake}}$, is determined by

$$r_{\text{tr,sap,stake}} = \frac{r_{\text{un,sap,stake}}}{1 + B \times C_{CCA-equiv}} \tag{8.7}$$

where $r_{\text{un,sap,stake}}$ is the decay rate of untreated sapwood from Eqs. (1.5) and (1.7); B is given by

$$B = \begin{cases} 45 & \text{for softwoods,} \\ 12 & \text{for hardwoods.} \end{cases} \tag{8.8}$$

8.2 Climate Parameter

The climate parameter values used for the design guide service life computation is shown in Table 8.1

Table 8.1 Climate parameter values used for service life computation

Hazard Zone	$k_{climate}$
A	0.5
B	1.5
C	2.5
D	3.0

8.3 Decay Lag

The decay lag and decay rate are correlated; therefore, given a decay rate r determined as described in the previous subsection, the decay lag, t_{lag} (years), is given by

$$t_{lag} = 5.5r^{-0.95} \tag{8.9}$$

8.4 Decay Progress and Parameters of Round Poles

8.4.1 Decay Patterns

Decay in a timber pole can initiate both from the perimeter progressing inwards and from the pith zone progressing outwards, as illustrated in Figure 4.5.1. It is observed also that both the lag time and decay rate of treated perimeter sapwood as well as corewood of a timber pole are different from that observed from small stake tests.

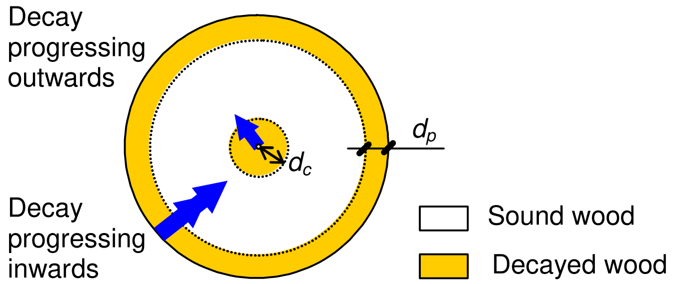


Figure 8.1 Decay patterns of round poles.

8.4.2 *Model parameters for decay progressing inwards*

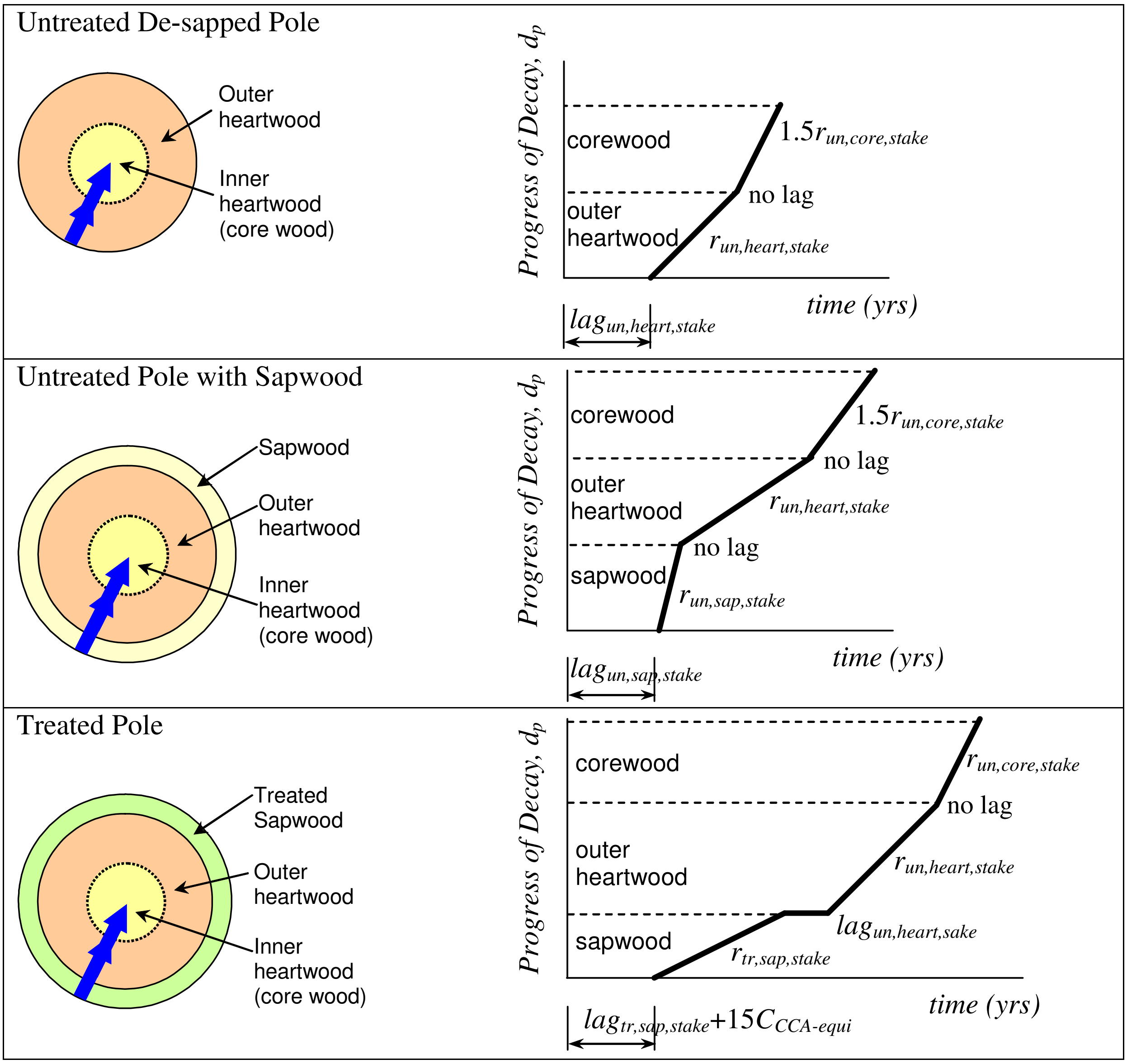


Figure 8.2 Decay of poles progressing inwards

8.4.3 Model parameters for Decay Progressing Outwards

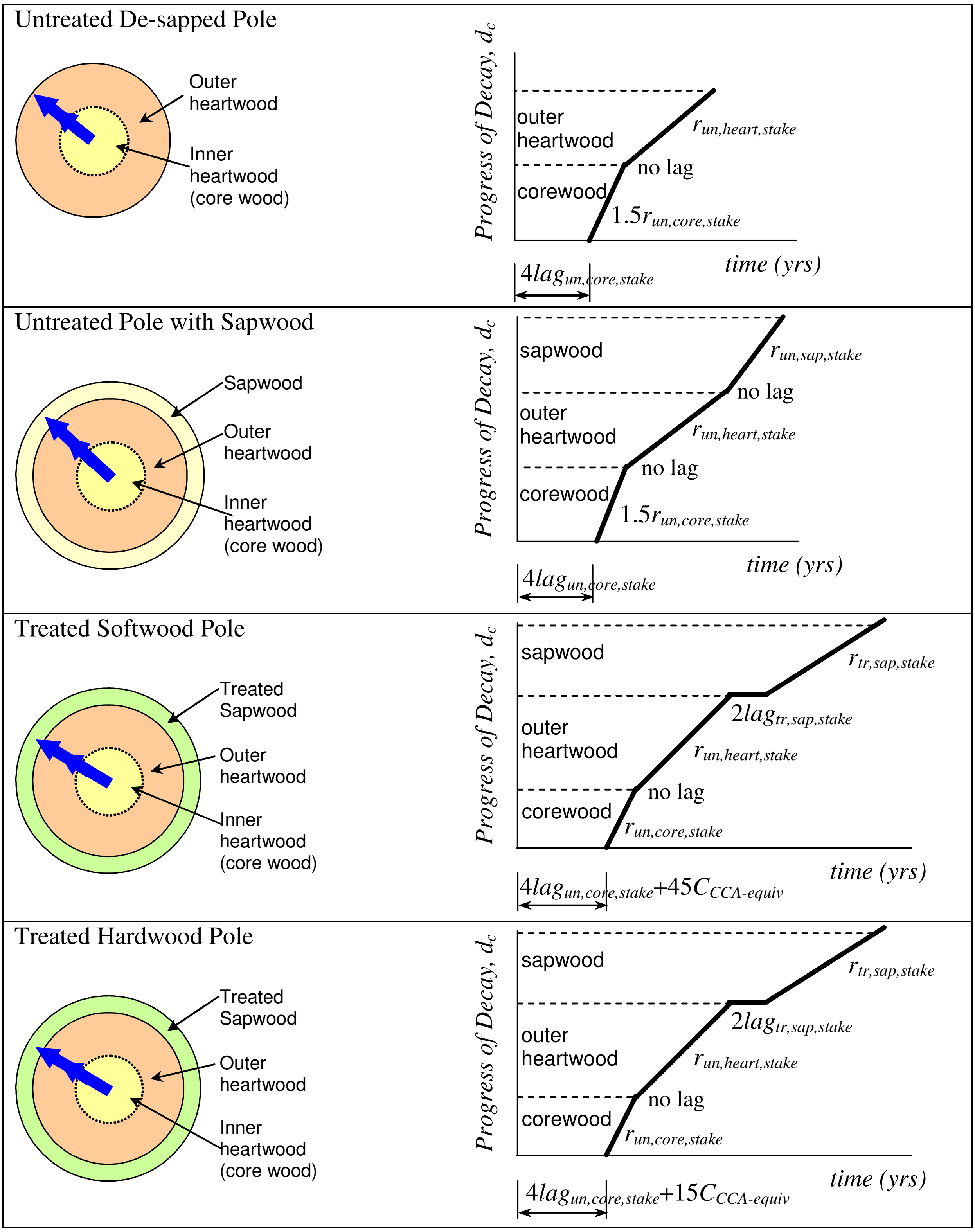
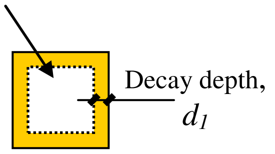
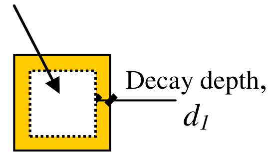
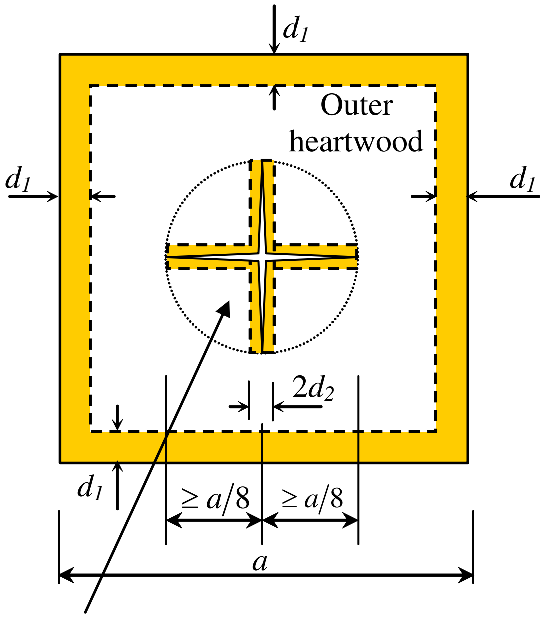
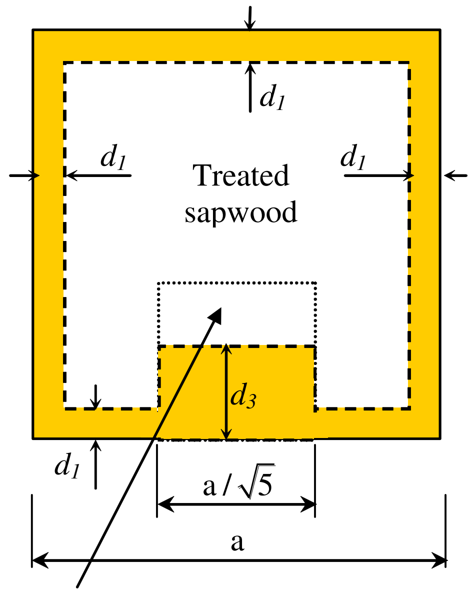


Figure 8.3 Decay of poles progressing outwards

8.5 Decay parameters of Square Posts

Table 4.6.1 Cross-sections of square posts and decay paterns

<table>
<tr><th></th><th>UNTREATED HARDWOOD</th><th>TREATED SOFTWOOD</th></tr>
<tr><td>Small size
100x100
150x150</td><td>Outer heartwood
</td><td>Treated sapwood
</td></tr>
<tr><td>Large size
200x200
250x250</td><td>
Corewood</td><td>
Outer heartwood
(20% of total section area)</td></tr>
</table>

8.6 Service Life

The service life of timber is assumed to be the time at which its residual strength decreases to 70% of its original strength. For example, for a timber pole of diameter D subject to perimeter decay only, then the decay depth at service life, d_L, is

$$d_L = \begin{cases} \frac{1}{2}\left(1-0.7^{1/3}\right)D & \text{when subject to bending;} \\ \frac{1}{2}\left(1-\sqrt{0.7}\right)D & \text{when subject to tension.} \end{cases} \tag{8.10}$$

Then the service life L is estimated from Eq. (1.1) using the associated decay lags and decay rates of the timber element under consideration.

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Appendix A. Soil Moisture

A.1 Background

It is simple and instructive to use approximate procedures to examine the effect of the soil on a pole buried therein. In the following we recall that if timber is in contact with a soil that has a soil suction value of less than 1.5 MPa, it will itself eventually come to equilibrium at a moisture content above the fibre saturation point. Timber above the fibre saturation point has a tendency to decay quickly. The following computations are based on using simple Green-Ampt procedures (Jury et al 1991) applied to ideal soils with properties taken from Rawls et al. (1991).

A.2 Notation

In soil mechanics (e.g. Jury *et al.*) the following notation and definitions tend to be used:

θ	= moisture content (kg/kg)
θ_D	= $\theta_2 - \theta_1$
θ_1	= moisture content at time zero
θ_2	= moisture content induced by an idealised wetting front
H	= hydraulic heads (m of water)
h	= matric potential (m of water) ….. capillary suction force (negative)
h_b	= bubbling pressure
p	= applied surface pressure
J_m	= mass flow rate of water (m^3/sec)
ρ_w	= 1000 (kg/m^3) density of water
g	= 9.807 (m^2/sec) gravity constant
i	= infiltration rate
I	= total infiltration
S	= sorptivity
r^o	= rainfall rate
$k(h)$	= saturated hydraulic conductivity
k_{sat}	= saturated hydraulic conductivity
D_w	= soil water diffusivity

x = horizontal distance

y = distance in any direction

z = vertical distance (usually positive upwards)

z_F = distance between surface and wetting front

Note that the pressure in *Pa* is derived from:

$$\text{matric potential (Pa)} = g\rho_w h \approx 10^4 h$$

Note that when we talk about matric potential we call it a *positive* suction force or a *negative* pressure.

A.3 Darcy's Law (Saturated Soils)

$$J_m = k_{sat}\left(\partial H / \partial z\right) \tag{A.1}$$

k_{sat} = saturated hydraulic conductivity

H = p + z = hydraulic head

A.4 Buckingham-Darcy Law (Unsaturated Soil)

When a soil is unsaturated, it has an internal suction that is denoted by a matric potential *h*

$$J_m = -k(h)\,\partial H / \partial y \tag{A.2}$$

where

H = $h + z$

h = matric potential

z = height above datum

and *y* denotes the distance in any direction.

We also have the water conservation equation (Jury *et al*., p.104)

$$\frac{\partial J_w}{\partial y} + \frac{\partial \theta}{\partial t} = 0 \tag{A.3}$$

and the diffusivity relationship

$$D_w(\theta) = K(\theta)\,dh / d\theta \tag{A.4}$$

Note that

$$H = h + z \tag{A.5}$$

Hence for flow in the horizontal direction

$$J_m = K(h)\left[\frac{\partial h}{\partial x}\right] \tag{A.6}$$

$$J_m = D_w(\theta)\frac{\partial \theta}{\partial x} \tag{A.7}$$

where D_w is the soil water diffusivity.

Also for flow in the vertical direction

$$J_M = -K(h)\left[\frac{\partial h}{\partial z} + 1\right] \tag{A.8}$$

$$J_m = D_w(\theta)\frac{\partial \theta}{\partial z} - k(\theta) \tag{A.9}$$

A.5 SOME INTERESTING STEADY STATE SOLUTIONS

A.5.1 Evaporation From a Water Table (Jury et al., p.96)

Assume that the unsaturated hydraulic conductivity is given by

$$K(h) = \frac{k_{sat}}{1 + \left(h/a\right)^N} \tag{A.10}$$

We assume that at the water table $h = 0$ and at the surface $h = \infty$. The steady flow upwards from the water table to the surface is given by

$$J_m = k_{sat}\left[\frac{-a\pi}{LN\sin\left(\pi/N\right)}\right]^N \tag{A.11}$$

where L is the depth of the water table.

A.5.2 Downward Flow Under Constant Infiltration (Jury et at., p.99)

Using the value $N = 2$, Jury (1991) have derived the exact solution for a gravity flow and the solution near the surface is given by

$$\text{Jm} = -\text{K(h)} \tag{A.12}$$

where h refers to the matric potential of the soil near the surface. Hence Eq. (A.12) can tell us the moisture content of the soil near the surface under steady irrigation conditions.

A.6 Van Genuchten Relationships (See van Genuchten 1980)

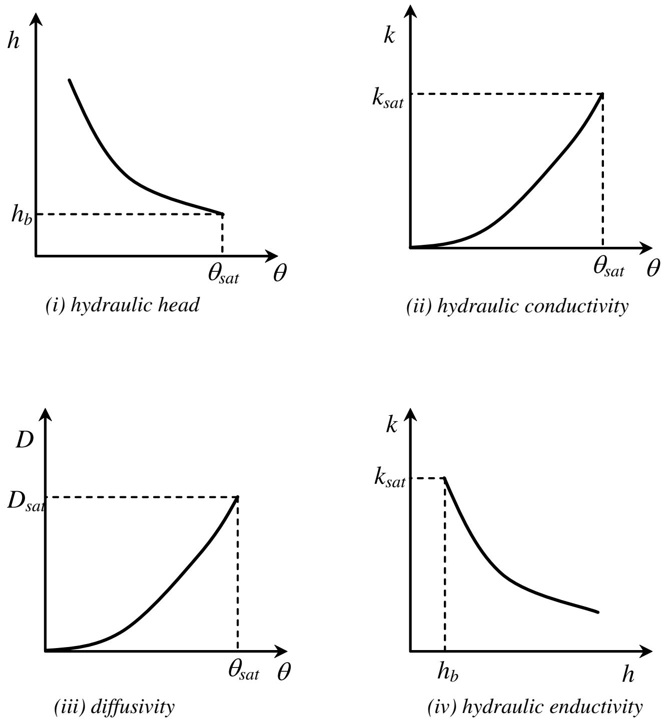


Figure A.1. Illustration of some soil moisture relationships.

λ–Formulation

$$\left(h \middle/ h_b \right) = \left(\frac{\theta_{sat}}{\theta} \right)^{\frac{1}{\lambda}}$$

$$\left(\theta \middle/ \theta_{sat} \right) = \left(\frac{h_b}{h} \right)^{\lambda}$$

$$\left(k \middle/ k_{sat} \right) = \left(\frac{\theta}{\theta_{sat}} \right)^{3+\frac{2}{\lambda}}$$

$$\left(k \middle/ k_{sat} \right) = \left(\frac{h_b}{h} \right)^{2+3\lambda}$$

$$\left(D \middle/ D_{sat} \right) = \left(\frac{\theta}{\theta_{sat}} \right)^{2+\frac{1}{\lambda}}$$

a–Formulation

$$\left(h / h_b \right) = \left(\frac{\theta_{sat}}{\theta} \right)^a$$

$$\left(\theta / \theta_{sat} \right) = \left(\frac{h_b}{h} \right)^{\frac{1}{a}}$$

$$\left(k / k_{sat} \right) = \left(\frac{\theta}{\theta_{sat}} \right)^{3+2a}$$

$$\left(k / k_{sat} \right) = \left(\frac{h_b}{h} \right)^{2+\frac{3}{a}}$$

$$\left(D / D_{sat} \right) = \left(\frac{\theta}{\theta_{sat}} \right)^{2+a}$$

Values in terms of the a-formulation for typical soils are given in Appendix B.

M N Q–Formulation

$$k / k_{sat} = \left(\frac{h_b}{h} \right)^N \qquad N = 2 + \frac{3}{a}$$

$$\left(h / h_b \right) = \left(\frac{\theta_{sat}}{\theta} \right)^M \qquad M = a$$

$$\left(k / k_{sat} \right) = \left(\frac{\theta_{sat}}{\theta} \right)^Q \qquad Q = 3 + 2a$$

A.7 THE GREEN-AMPT APPROXIMATIONS

A.7.1 Effective Suction Head at a Wetting Front

A.7.1.1General formulation

See Mein and Larsen (1971, 1972), James and Larse (1973), and Jury (1991).

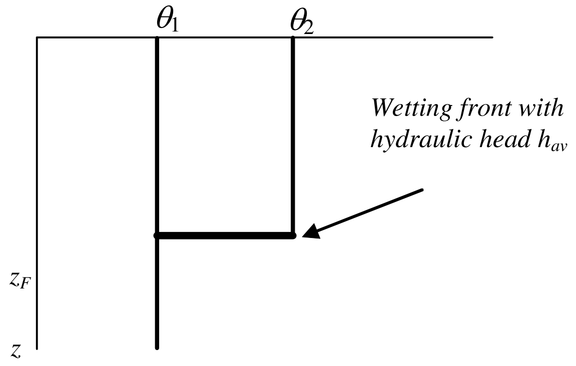


Figure A.2 Moisture profile for the concept of a wetting front.

The simple solutions of the Green-Ampt approximation are based on the assumption that water flow advances as a front. To use the Green-Ampt approximation we must first estimate the matric head associated with this front. This head is taken to be given by

$$h_{av} = \frac{\int_{k_1}^{k_2} h(k)\,dk}{k_2 - k_1} \tag{A.13}$$

Note: The Green-Ampt approximation assumes that we have a flow under a head h_{av} and a permeability $k(\theta_2)$.

A.7.1.2Head formulation

$$h_{av} = \frac{h_2}{\left(1-\frac{1}{N}\right)}\left[\frac{1-\left(h_2/h_1\right)^{N-1}}{1-\left(h_2/h_1\right)^{N}}\right] \tag{A.14}$$

For case $h_1 >> h_2$

$$h_{av} \approx \frac{h_2}{\left(1-\frac{1}{N}\right)}$$

If $h_1 >> h_2$, and $h_2 = h_b$ then $h_{av} = \dfrac{h_b}{\left(1-1/N\right)}$

A.7.1.3Moisture formulation

$$h_{av} = \frac{h_b}{\left(1-\frac{1}{N}\right)}\cdot\left(\frac{\theta_{sat}}{\theta_2}\right)^{M}\left[\frac{1-\left(\theta_1/\theta_2\right)^{M(N-1)}}{1-\left(\theta_1/\theta_2\right)^{MN}}\right] \tag{A.15}$$

For case $\theta_2 >> \theta_1$

$$h_{av} \approx \frac{h_b}{\left(1-\frac{1}{N}\right)} \cdot \left(\frac{\theta_{sat}}{\theta_2}\right)^M$$

If $\theta_2 = \theta_{sat}$, and

$\theta_2 >> \theta_1$ $$h_{av} = \frac{h_b}{\left(1-\frac{1}{N}\right)}$$

A.7.2 Adsorption During Flooding and Ponding

A.7.2.1 Flooding

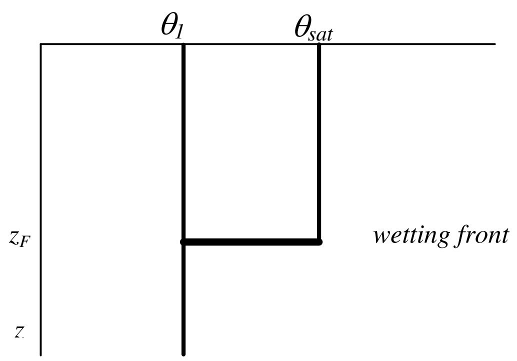


Figure A.3 Moisture profile during ponding.

i	= rate of infiltration
I	= total water infiltrated = $z\theta_D$
θ_1	= initial moisture content
θ_D	= $\theta_{sat} - \theta_1$
z_F	= depth to wetting front

The flow equation is

$$i = k_{sat}\left[\frac{h_{av}}{z_F}+1\right] \tag{A.16}$$

$$i = \theta_D \frac{dz}{dt} \tag{A.17}$$

where $\theta_D = \theta_{sat} - \theta_1$.

Hence

$$\frac{dz_F}{dt} = \left(\frac{k_{sat}}{\theta_D}\right)\left[\frac{h_{av}}{z}+1\right] \tag{A.18}$$

Assume that ponding occurs from time zero.

Hence

$$\int_o^{z_F} \frac{z}{z + h_{av}} dz = \frac{k_{sat}}{\theta_D} \int_o^t dt \tag{A.19}$$

Integrating Eq. (A.19) leads to

$$z_F - h_{av} \ \ell n \left(1 + \frac{z_F}{h_{av}} \right) = \frac{k_{sat}}{\theta_D} t \tag{A.20}$$

This will be called the flooding equation.

A.7.2.2Ponding

Eq. (A.20) can also be used to obtain the time to move between any two depths of water denoted by z_{F1} and z_{F2} during ponding.

$$\left(z_{F_2} - z_{F_1} \right) - h_{av} \ \ell n \left[\frac{h_{av} + z_{F_2}}{h_{av} + z_{F_1}} \right] = \frac{k_{sat}}{\theta_D} \left(t_2 - t_1 \right) \tag{A.21}$$

A.7.2.3Time to Ponding

Assume that rainfall rate is r^o. This will also be the infiltration rate if the surface has not ponded.

Assume that *at the instant of ponding* the water above the advancing front *just* becomes saturated and the movement of the wetting front soaks up moisture at the rate of rainfall, i.e.

$$r^o = k_{sat} \left[\frac{h_{av}}{z_{pond}} + 1 \right] \tag{A.22}$$

The time to ponding t_p is given by

$$t_p \cdot r^o = z_{pond} \, \theta_D \tag{A.23}$$

Combining Eqs. (A.22) and (A.23) leads to

$$t_p = \frac{h_{av} \theta_D}{r^o \left[\frac{r^o}{k_{sat}} - 1 \right]} \tag{A.24}$$

Then Eqs. (A.23) and (A.24) can be combined to give z_{pond}.

Note that a necessary condition for ponding to occur is $r^o > k_{sat}$.

Also note before ponding, the water moves downwards at an average rate of

$$\frac{dz_F}{dt} = \frac{r^o}{\theta_D} \tag{A.25}$$

A.7.2.4Moisture Redistribution

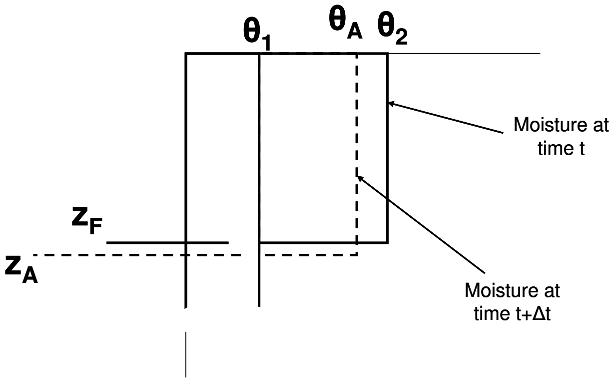


Figure A.4 Moisture profile during redistribution.

From the Buckingham-Darcy Law

$$i = k(\theta)\left[\frac{h_{av}}{z} + 1\right]$$

Hence assuming that the dominant effect is to change the moisture content behind the wetting front

$$i = -z\frac{d\theta}{dt}$$

Hence

$$-{d\theta_D}/{dt} = \frac{k(\theta)}{z}\left[\frac{h_{av}}{z} + 1\right] \quad \text{(A.26)}$$

Eq. (A.26) can then be used to estimate the change in moisture content $\Delta\theta$ in time Δt. The corresponding increase in z_F during that time is given by the conservation of moisture, i.e.

$$\Delta\theta \cdot z_F = \Delta z_F \cdot \theta_D \quad \text{(A.27)}$$

A.8 Effect of a block of rainfall

A.8.1 Case $r^o > k_{sat}$ and $t_{rain} > t_{pond}$

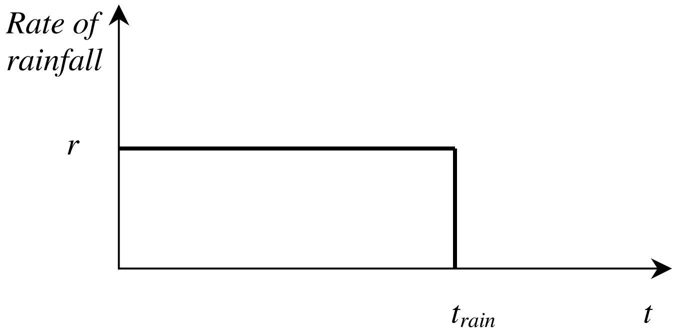


Figure A.5 Notation for a block of rainfall.

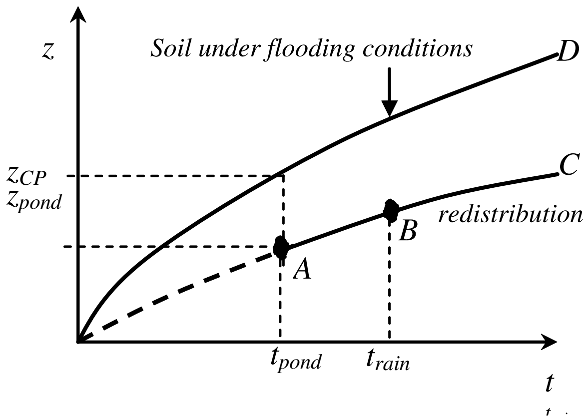


Figure A.6 Depth of the wetting front for the case $t_{rain} > t_{pond}$.

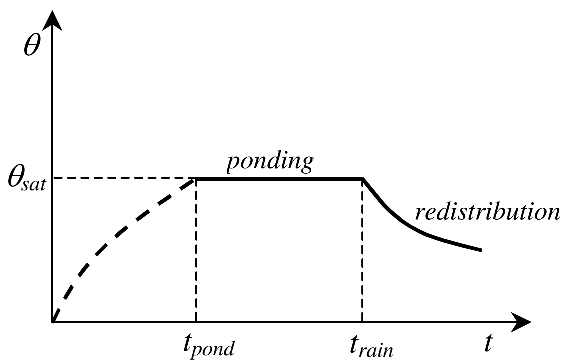


Figure A.7 Moisture content at the surface for the case $t_{rain} > t_{pond}$.

Consider a block of rain as shown in Figure A.5. The resulting movement of the wetting front and moisture is shown schematically in Figures A.6 and A.7. The time and location of the wetting front are computed from the equations in Section A.7.2.4. The movement of the wetting front during redistribution is computed from the equations in Sections A.7.2.2 and A.7.2.3.

A.8.2 Case $r^o > k_{sat}$ and $t_{rain} < t_{pond}$

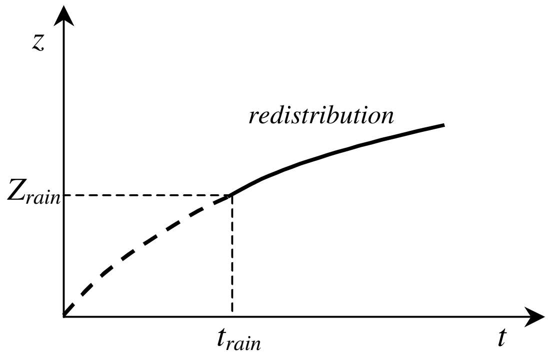


Figure A.8 Depth of the wetting front for the case $t_{rain} < t_{pond}$.

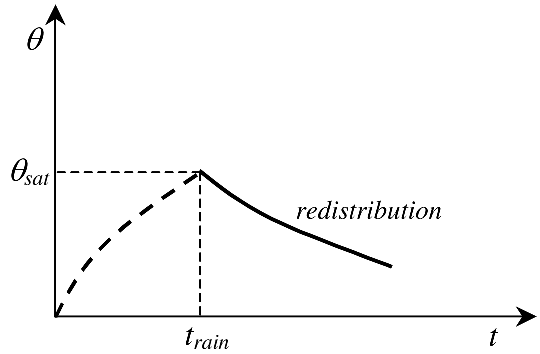


Figure A.9 Moisture content at the surface for the case $t_{rain} < t_{pond}$.

The progress for the wetting front and moisture content are shown schematically in Figures A.8 and A.9. For this case the redistribution commences before ponding occurs. The shape of the curve for the wetting front for $T < T_{rain}$ can be approximated by assuming that it is similar to the curve for curve shown in Figure 11, i.e. the value of z_F is obtained from

$$\frac{z_F}{z_{FF}} = \frac{z_{pond}}{z_{CP}} \tag{A.28}$$

where z_{FF} denotes the depth of the front for the case of flooding.

For any value of z_F, the value of θ is obtained from

$$\theta \, z_F = r^o t \tag{A.29}$$

The redistribution curve is again computed according to the equations in Section 6.4.

A.8.3 Case $r^o < k_{sat}$

For this case there can never be ponding. The moisture content at the surface, denoted by $\theta_{surface}$, is estimated from the gravity flow, Eq. (A.12),

$$r^o = K(\theta_{surface}) \tag{A.30}$$

For simplicity, it may be assumed that at the commencement of redistribution, we have a block with moisture content $\theta_{surface}$ and depth z_F given by

$$r^o t_{rain} = z_F\, \theta_{surface} \tag{A.31}$$

The equation in Section A.7.2.4 can again be used to compute the redistribution graph.

A.9 Relationship Between Humidity and Matric Potential

The relationship between humidity H and matric potential Ψ(Pa) is given by

$$\Psi = \rho_w \frac{RT_k \ell n(H)}{0.018} \tag{A.32}$$

where R = gas constant = 8.31 *J/moL K*, T_k is the temperature in degrees Kelvin and ρ_w = density of water = 1000 kg/m^3.

Table A.1 shows values of the matric potential at a temperature of 300°*K*.

Table A.1. Relationship between matric potential and relative humidity of air

Corresponding values of water potential Ψ in equilibrium with relative humidity of the air H at 300°*K*	
Ψ(Pa)	H, %
-10^3	99.9993
-10^4	99.993
-10^5	99.93
-10^6	99.28
-10^7	93.03
-10^8	48.58
-2×10^8	23.60
-5×10^8	2.70

A.10 Soil Parameters

Table A.2. Representative parameter values for free water flow in soils

Soil Type	**Power parameter** ***a***	**Bubbling pressure** h_b (*cm*)	**Saturated moisture content** θ_{sat} (cm^3/cm^3)	**Saturated hydraulic conductivity** k_{sat} (*cm/hr*)
sand	4.0	12	0.40	21.0
loamy sand	4.4	9	0.41	6.00
sandy loam	4.9	22	0.44	2.60
loam	5.4	48	0.45	0.70
silt loam	5.3	79	0.49	1.30
silty clay loam	7.8	36	0.48	0.40
sandy clay loam	7.1	30	0.42	0.20
clay loam	8.5	63	0.48	0.20
sandy clay	10.4	15	0.43	0.10
silty clay	10.4	49	0.49	0.10
clay	11.4	41	0.48	0.05

A.11 Wetting by a Rain Block

For the case of 5mm rain that occurs during a one hour rainfall, the time taken for the soil to dry out so that the matric potential of the moisture block increases to above 1.5 MPa (the 'permanent wilting point" for plants, cf Siau) is shown in Table A.3 below. The computations have been done according to the procedure recommended in the previous sections, using the assumption h_1 = 100 MPa. Rainfall ponding effects are taken into account. It is assumed that the water table is effectively infinitely deep and that the soil is dry when the rain commences. It is noted that the ground will be effectively "wet" most of the time unless the rainfall is less than say 5 mm per month.

Table A.3. Time to dry soil

SOIL	time to dry soil [days]	
	rain=25 mm	rain= 5 mm
1. SAND	*	153.4
2. loamy SAND	*	*
3. sandy LOAM	*	38.5
4. LOAM	72.5	9.5
5. silt LOAM	9.5	1.5
6. silty clay LOAM	81.5	3.5
7. sandy clay LOAM	316	15.5
8. clay LOAM	33.5	1.5
9. sandy CLAY	*	65.5
10. silty CLAY	59.5	3.5
11. CLAY	74.5	9.5

Note:
Rainfall is assumed to fall within a one hour period
Initial condition is h_1 = 100 Mpa ("air dry")
* indicates that the time to dry is greater than 300 days

A.12 Moisture due to the Water Table

Table A.4 shows computed predictions of the depth of dry soil that will be found in protected locations such as under a house. The computation was undertaken through a finite difference formulation of Eq. (A.8). The soil moisture content at a depth of 2.0 m is taken as a boundary condition and is assumed to be above the water table. It is noted that the top 0.5 m remains damp unless the soil suction is less than 0.5 Mpa.

Table A.4. Effect of soil moisture at a 2.0 m depth on the depth of dry surface soil

SOIL	**Depth of dry soil** (mm)	
	$h_{2.0}$=0.1 Mpa	$h_{2.0}$=0.5 Mpa
1. SAND	20	300
2. loamy SAND	24	323
3. sandy LOAM	28	348
4. LOAM	33	370
5. silt LOAM	32	365
6. silty clay LOAM	51	444
7. sandy clay LOAM	47	426
8. clay LOAM	56	459
9. sandy CLAY	66	492
10. silty CLAY	66	492
11. CLAY	71	506

Note:

$h_{2.0}$ denotes the suction of the soil moisture at a depth of 2.0 m below groundline

The soil surface is assumed to have a soil moisture suction of 100MPa

A soil is deemed to be "dry" when the soil moisture suction is >1.5 Mpa

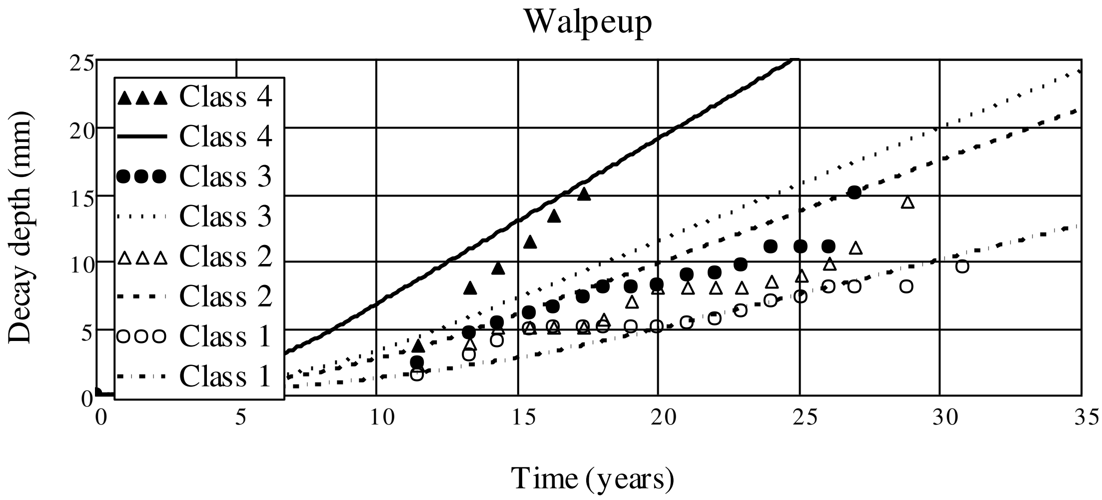
A.13 Concluding Comments

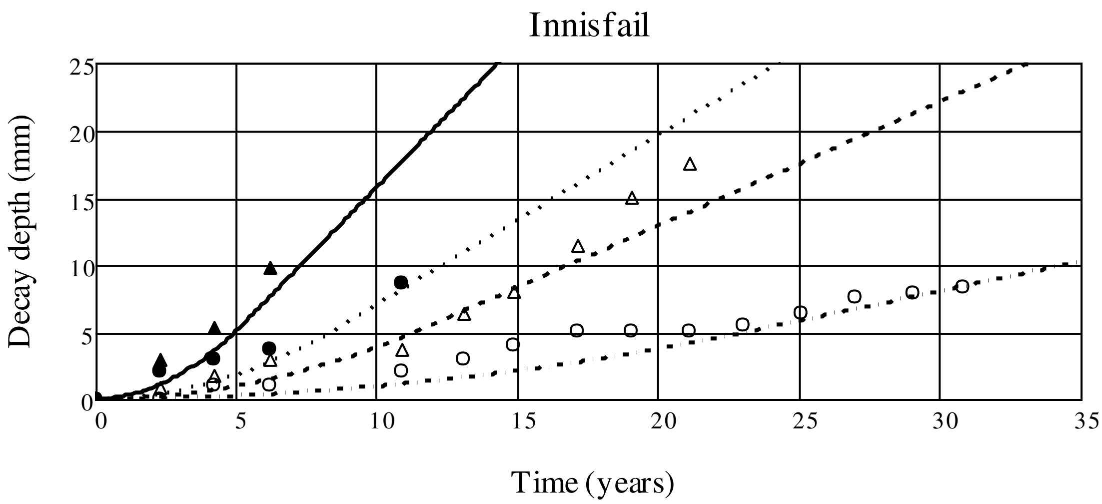
On the basis of the computed moisture characteristics shown in Tables A.3 and A.4, an assumption was made to use the concept of a dry month as a climate parameter. This is because it appears that typically the surface of timber below the ground line will be below the fibre saturation point if the monthly rainfall is less than 5 mm.

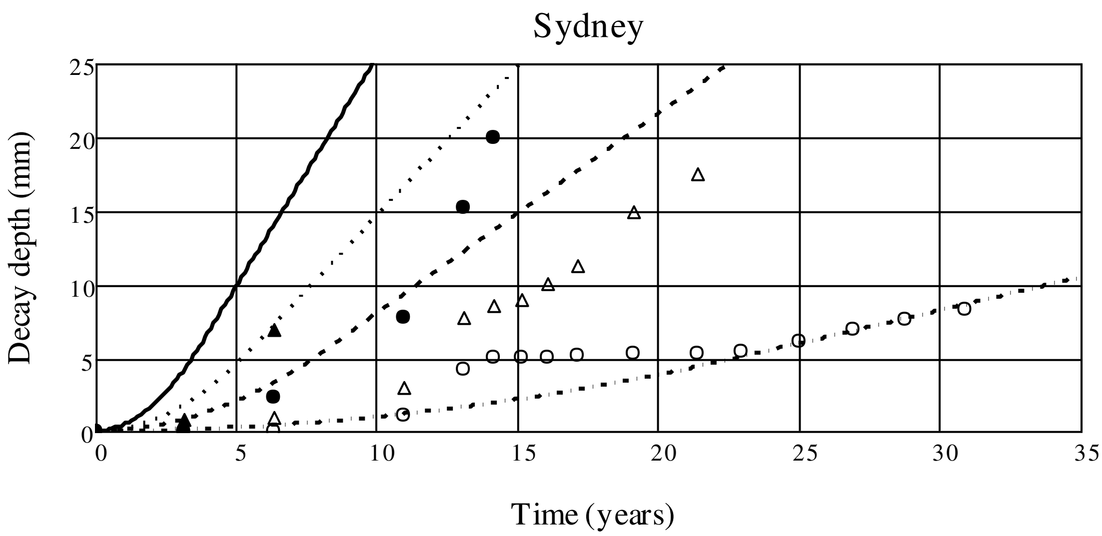
Appendix B. Data on Test Stakes

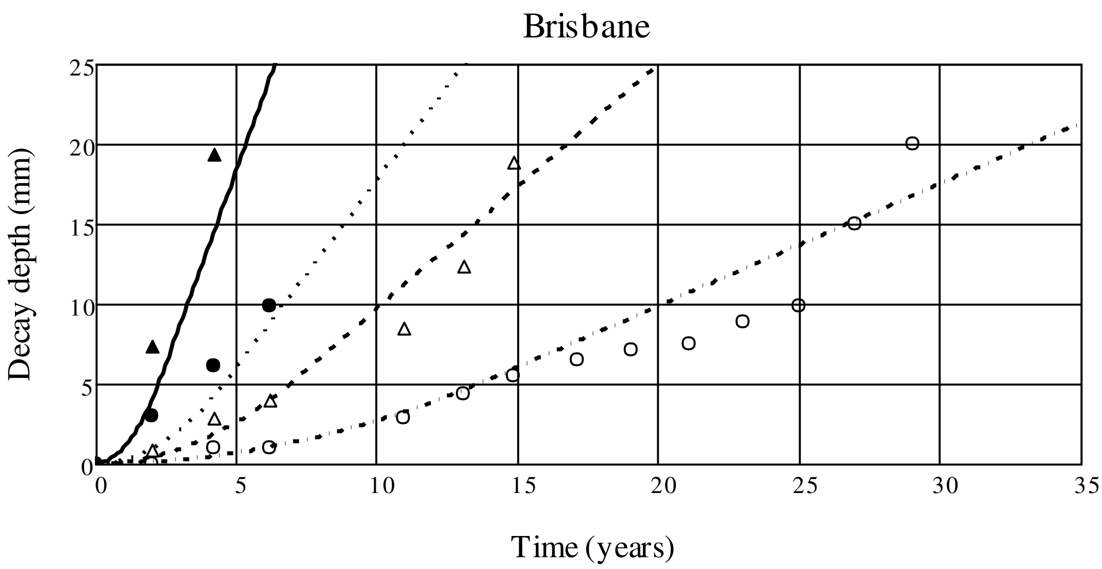
B.1 Data for Untreated Stake specimens

The following figures are plotted data taken from stake Test No. 1. The line curves drawn on the graphs are bilinear functions fitted to the test data. The data is Class Data, i.e. each data point represents the median of data from all specimens within a durability class for that site.


Walpeup
Class 4
Class 4
Class 3
Class 3
Class 2
Class 2
Class 1
Class 1
Decay depth (mm)
Time (years)
0
5
10
15
20
25
30
35


Innisfail
Decay depth (mm)
Time (years)
0
5
10
15
20
25
30
35


Sydney
Decay depth (mm)
Time (years)
0
5
10
15
20
25
30
35



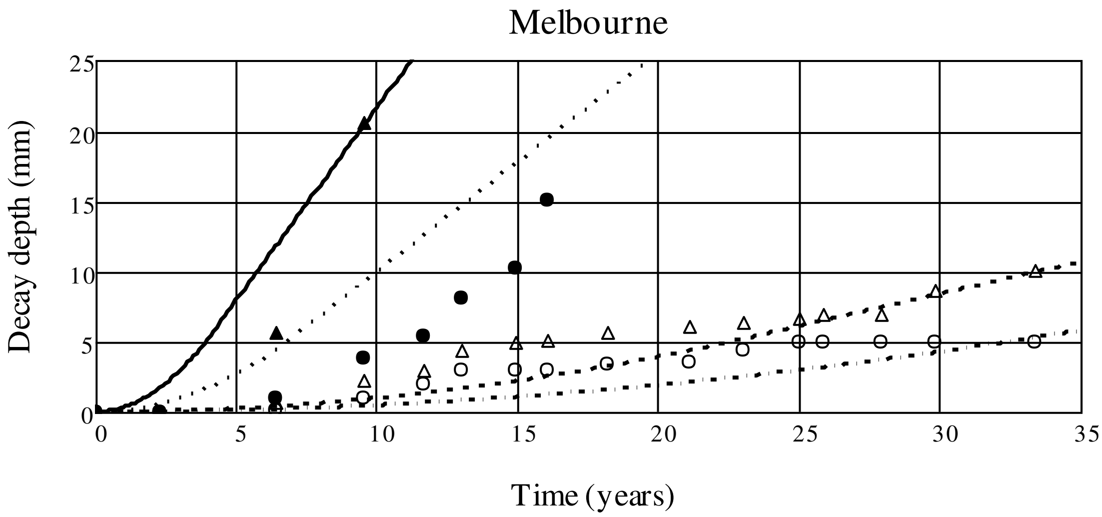
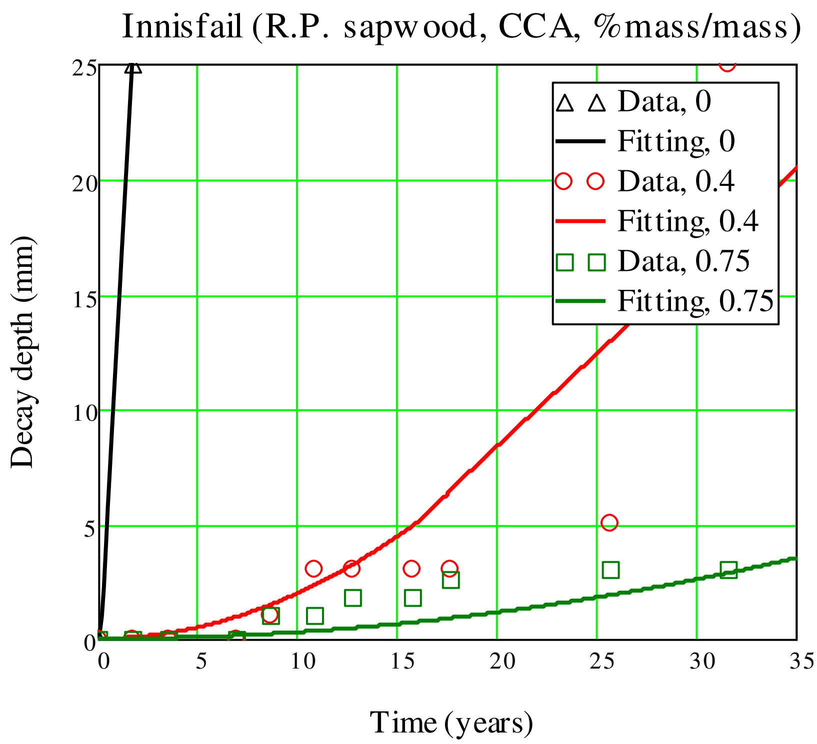


Figure B.1 Data and fitted bilinear curve for untreated heartwood stakes

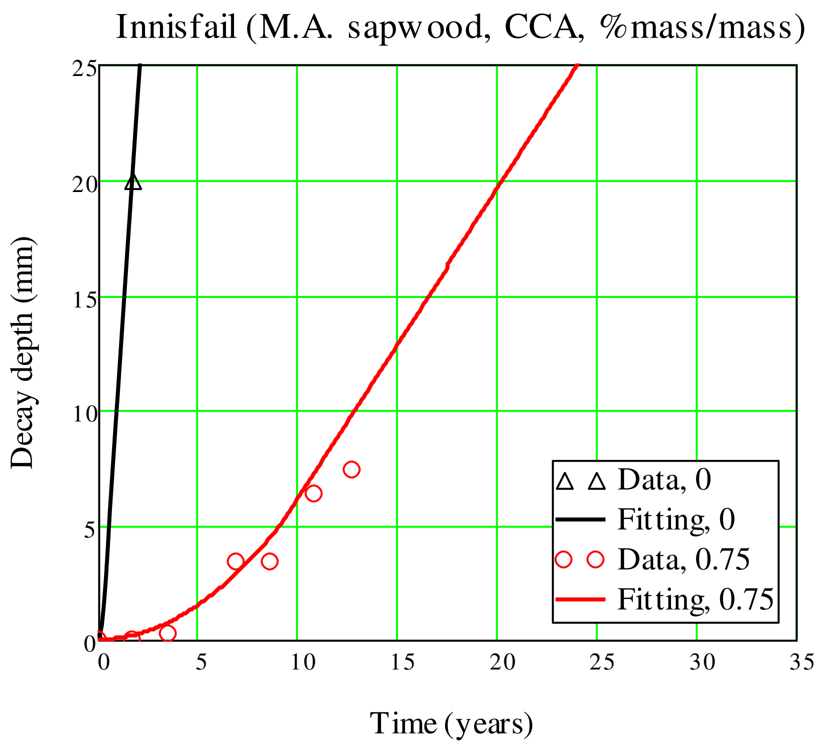
B.2 Data for Treated Stake specimens

The following figures are plotted data taken from stake Test No. 3. The line curves drawn on the graphs are bilinear functions fitted to the test data. The data is Species Data, i.e. each data point represents the median of data from all specimens for a particular substrate/treatment level/site.



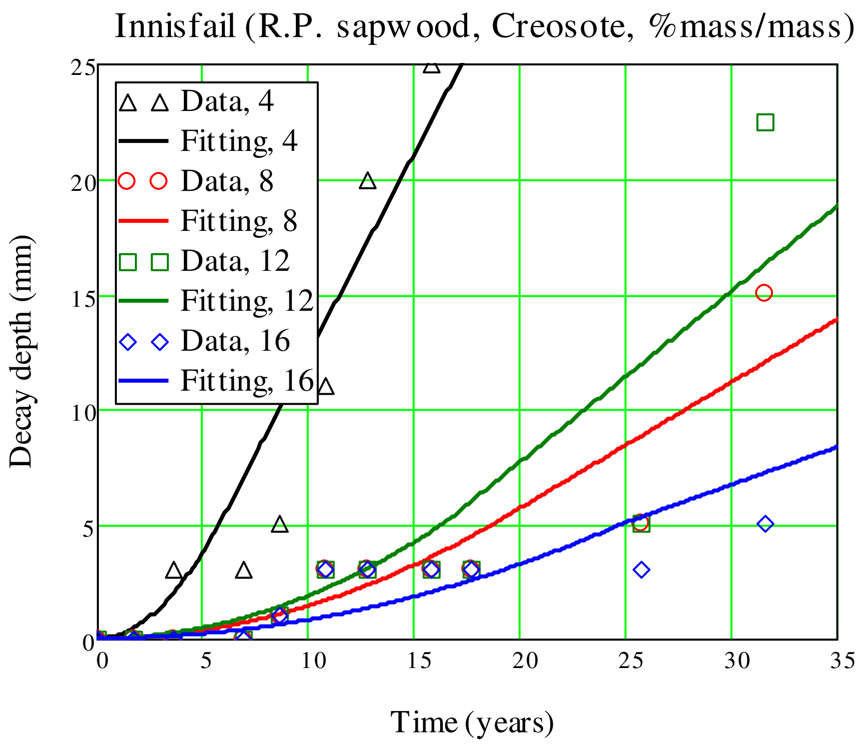
Note: Percentages in the legend are preservative retention in %mass/mass

Figure B.2 *Decay progress of CCA-treated radiate pine sapwood at Innisfail*



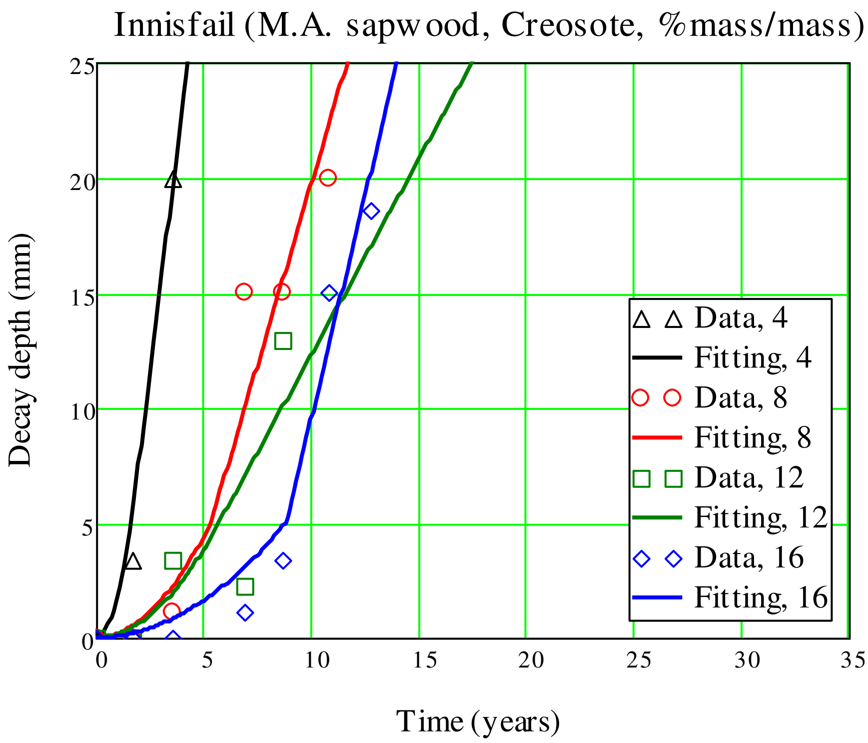
Note: Percentages in the legend are preservative retention in %mass/mass

Figure B.3 *Decay progress of CCA-treated mountain ash sapwood at Innisfail*



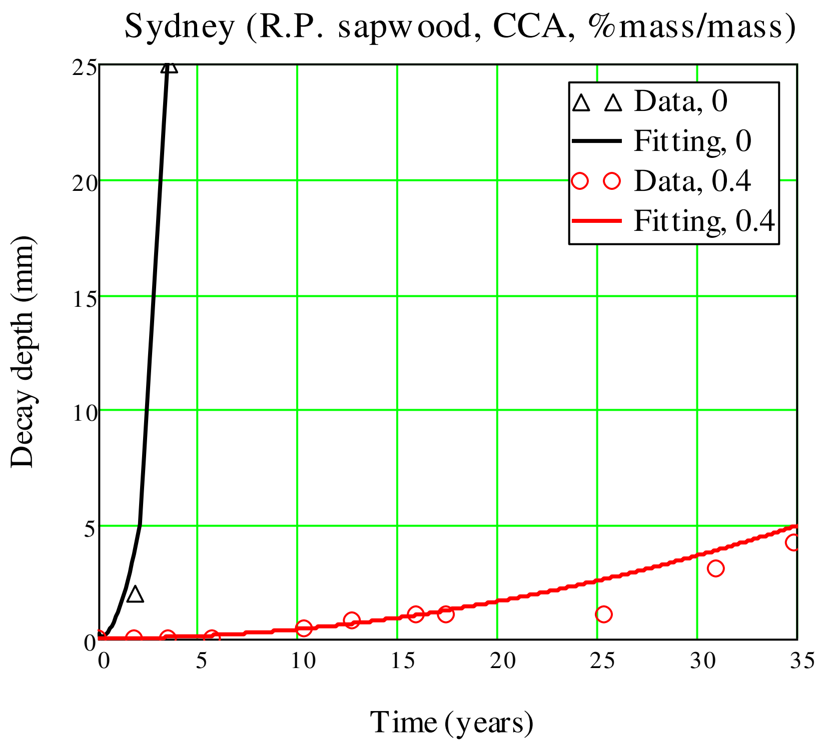
Note: Percentages in the legend are preservative retention in %mass/mass

Figure B.4 *Decay progress of creosote-treated radiate pine sapwood at Innisfail*



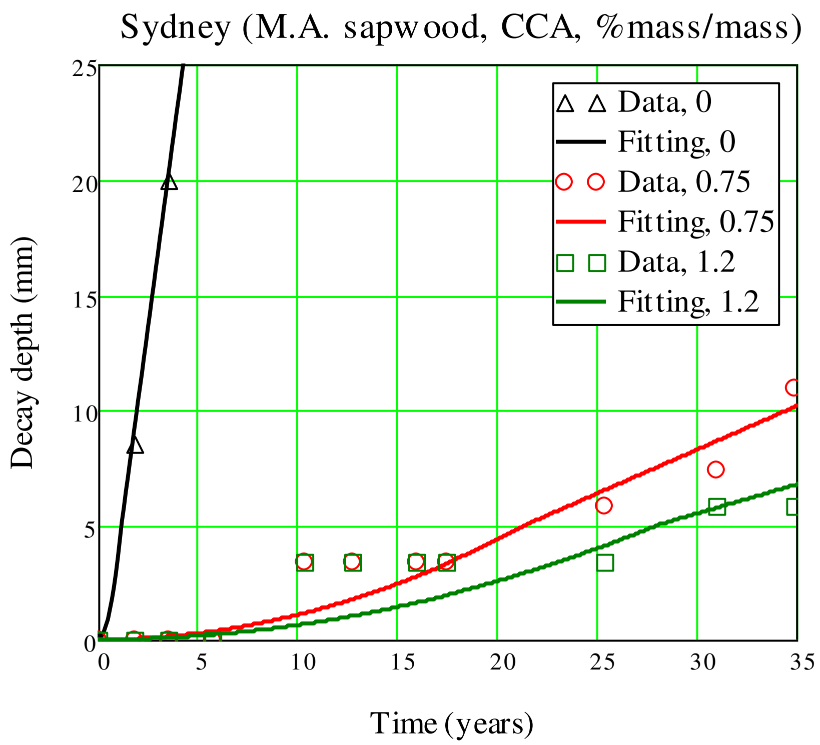
Note: Percentages in the legend are preservative retention in %mass/mass

Figure B.5 *Decay progress of creosote-treated mountain ash sapwood at Innisfail*



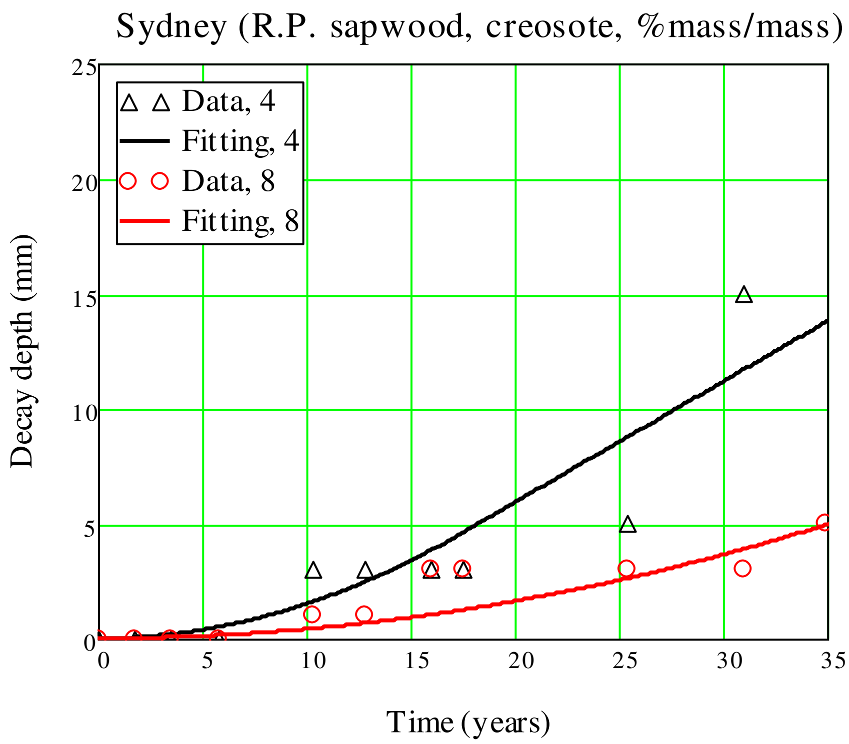
Note: Percentages in the legend are preservative retention in %mass/mass

Figure B.6 *Decay progress of CCA-treated radiate pine sapwood in Sydney*



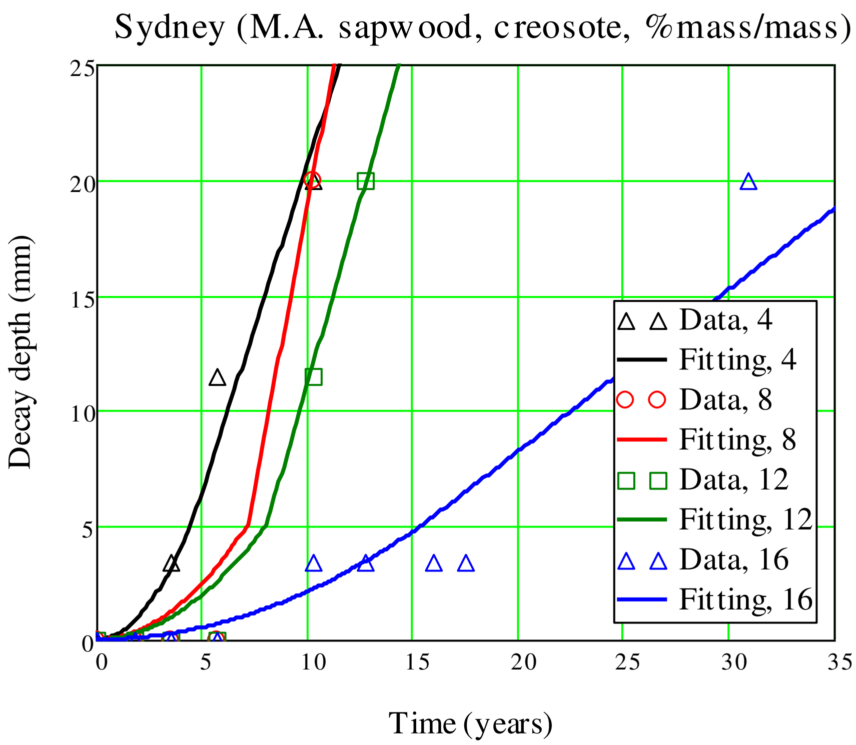
Note: Percentages in the legend are preservative retention in %mass/mass

Figure B.7 *Decay progress of CCA-treated mountain ash sapwood in Sydney*



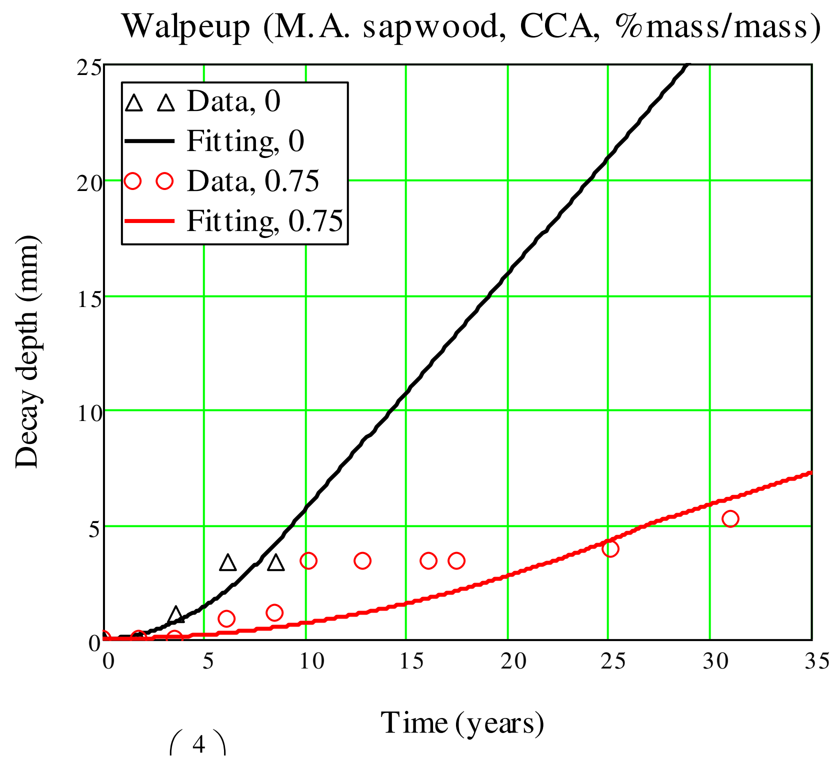
Note: Percentages in the legend are preservative retention in %mass/mass

Figure B.8 *Decay progress of creosote-treated radiate pine sapwood in Sydney*



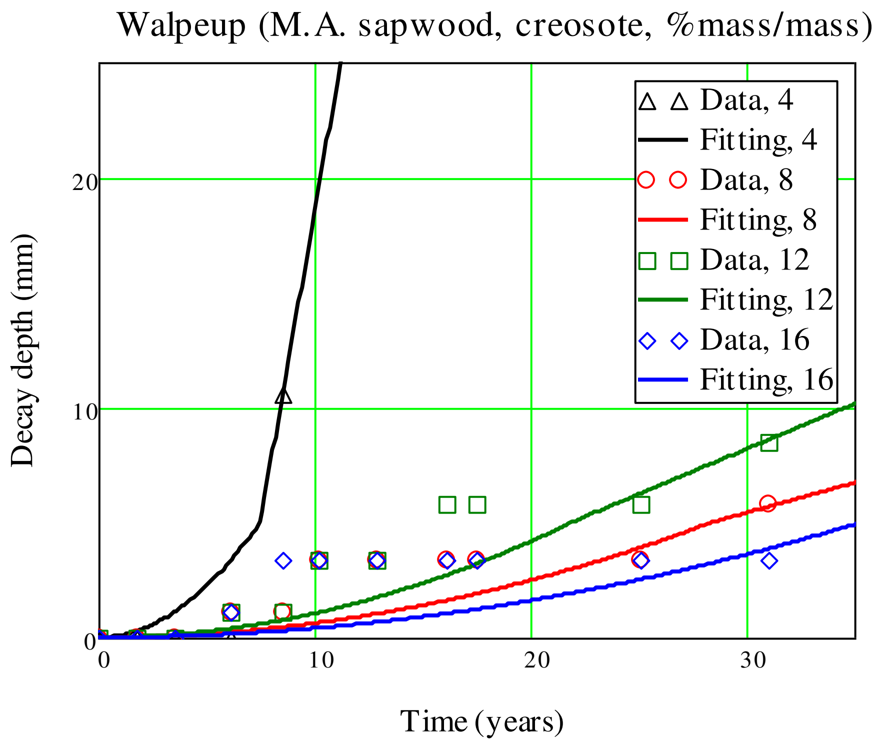
Note: Percentages in the legend are preservative retention in %mass/mass

Figure B.9 *Decay progress of creosote-treated mountain ash sapwood in Sydney*



Note: Percentages in the legend are preservative retention in %mass/mass

Figure B.10 *Decay progress of CCA-treated mountain ash sapwood at Walpeup*



Note: Percentages in the legend are preservative retention in %mass/mass

Figure B.11 *Decay progress of creosote-treated mountain ash sapwood at Walpeup*