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Resistance of polyamide and polyethylene cable sheathings to termites in Australia, Thailand, USA, Malaysia and Japan: A comparison of four field assessment methods

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ABSTRACT

Cables sheathed with medium density polyethylene or polyamide were exposed together with highly palatable bait wood to termite faunas in south-eastern and northern Australia, Thailand and southern USA using three methods: below-ground exposure, samples buried horizontally at a depth of 15–30 cm; graveyard method, samples inserted vertically 25 cm deep into the ground; ground contact method, samples placed horizontally on the ground surface, covered with soil and a plastic sheet. Samples were inspected for damage and bait wood replaced annually for six years. No polyamide sample was attacked. Damage to polyethylene was most severe at the Australian sites (across all methods) and in the graveyard method (across all sites), although in Australia in the below-ground method samples experienced greatest damage. Exposing samples together with bait wood within containers for one year, and replenishing bait wood up to three times, i.e. an 'accelerated' test method, compared to the standard procedure of providing new bait wood only once a year, resulted in only very limited damage to cables at Asian sites (Macrotermitinae, *Coptotermes* spp., Malaysia; *Coptotermes formosanus*, Japan), matching the earlier results for Thailand. But 73% of samples were destroyed by *Coptotermes acinaciformis* in northern Australia. The Australian termite fauna responds more aggressively to plastic samples than major pest species of termite elsewhere.

1. Introduction

Subterranean termites can damage a wide range of materials including many plastic products. The susceptibility of plastics to termite attack varies with their chemical structure, hardness and surface finish. Resistance of plastics to termites can be improved through physical and chemical manipulations, such as varying the amount of plasticisers, adding inert fillers or insecticides, or enclosing them in a physical barrier (Gay and Wetherly, 1962; 1969; Beal et al., 1973; Beal and Bultman, 1978; Unger, 1978; Watson et al., 1984; Ruddell, 1985; Boes et al., 1992). The economic implications of termite damage to plastics such as plastic-sheathed underground communication and power cables and pipes can often be considerable (Ruddell, 1985). For example, relatively low-priced polyvinyl chloride (PVC) products may, even after a range of measures to improve their resistance to termites have been taken, still not provide adequate protection (Beal et al., 1973). In many applications more costly alternatives such as polyamides (Nylon), have to be used (Ruddell, 1985). Further, a given material may prove resistant to one species of termite but not to another (Beal et al., 1973; Beal and Bultman, 1978; Watson et al., 1984).

Many studies on the resistance of plastics to termites were conducted under both laboratory and field conditions during the

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1960s through the 1980s (see references above), but few if any have been published since. Some commercial-in-confidence experiments were conducted in Australia but were not published for proprietary reasons. Further, information on suitable assessment methods for plastics is also rather limited (Tsunoda et al., 2010).

This paper provides results from a six year field study (the main trial) conducted in Australia, Thailand and the southern USA. The trial evaluated the performance of two reference materials, a polyamide and a polyethylene, with known resistance levels against termites in Australia based on previous CSIRO laboratory and field trials (Watson et al., 1984; unpubl.; Lenz unpubl.). Three methods of exposing the materials to subterranean termites were compared.

Following this, the specific question of the resistance of these materials to termites at other sites in southern Asia was addressed in a one year trial conducted in Malaysia, Japan and for comparison also in Australia, employing an 'accelerated test' method.

2. Materials and methods

In the main trial, resistance of the plastic cable sheathings against termite attack was evaluated in the field through three methods of exposure each year for six years. The cable samples were placed with bait wood and other samples, which were part of another trial (Lenz et al. in prep). The arrangement of all samples was randomised.

2.1. Experimental plastic materials

Cables sheathed with one of two common plastic formulations were exposed to foraging termites. Both cable types were supplied by the former Telecom Australia Research Laboratories, Melbourne, Australia. They have served as standard reference materials in CSIRO field trials in Australia for many years (Watson et al., 1984; unpubl.; Lenz unpubl.).

Plastic cable specifications were:

Polyamide jacketed cable ("Grilamid", Nylon 12); product of Emser Werke Ag., Ems, Switzerland; compound density 1020 kg m^{-3}; 2.0 $\pm$ 0.3% carbon black; several proprietary stabilisers; Shore D hardness of 63. This product is considered resistant to termite attack (Ruddell, 1985).

Polyethylene sheathed cable ("Alkathene", medium density polyethylene (MDPE)); product of ICI Australia Ltd.; with 5% butyl rubber; compound density 932 kg m^{-3}; 2.5 $\pm$ 0.5% carbon black; antioxidant – Lowinox WSP at 0.09% level; Shore D hardness of 47. This product is considered susceptible to termite attack.

Cylindrical cable samples were 30 cm long with a 1.4 cm outside diameter, including the 0.2 cm thick outer plastic sheathing. The ends of each sample were covered with a cylindrical 0.5 cm deep metal cap, leaving a 29 cm length of cable with a surface area of $\approx$131 cm^2 exposed to foraging termites. The trial evaluated the ability of termites to attack the smooth surface of the two types of cables without access to their end edges.

2.2. Bait wood

Plastic samples have no inherent food value for termites. In any field trial assessing their resistance to termite attack, samples must be placed side-by-side in direct contact with highly palatable and preferred wood (bait wood) to attract and sustain termite activity adjacent to the plastic samples.

Bait wood stakes (2.5 $\times$ 5.0 $\times$ 30.0 cm) of *Pinus radiata* sapwood from New Zealand were used in Thailand and the USA, and locally grown *P. radiata* stakes with the same dimensions and of similar quality in Australia. Two of the installation methods (see Section 2.3) required the use of additional wooden "feeder" strips (10 cm wide $\times$ 0.5 cm thick). These were sourced from locally available timber, *P. radiata* in Australia, rubberwood [*Hevea brasiliensis* (Willd. ex Adr. de Juss) Muell. et Arg.] in Thailand, and southern yellow pine (*Pinus* spp.) in the USA.

2.3. Methods of exposure in the main trial

The termite resistance of the plastics was evaluated using three published methods of exposing plastic or timber samples in contact with the soil to subterranean termites.

2.3.1. Below-ground (horizontal) exposure method

In this method samples are installed horizontally on the base of a trench at a set but variable target species-specific distance below the soil surface, and are in contact with a significant supply of bait wood, thus producing conditions favourable for a build-up in termite numbers and sustained presence of termites at the samples (Lenz et al., 1992).

The samples were oriented perpendicular to the long axis of the flat-bottomed trench, and parallel to each other at a depth of 15 cm (Thailand, USA), and 30 cm (Australia). The depth of the trenches depended on the preferred foraging range below the soil surface of the termite fauna at a given site and specifically the depth in the soil at which termites are still active even during dry conditions (*e.g.* Lenz et al., 1992; Sornnuwat et al., 2003).

The base of each trench was first lined with feeder strips. Samples were then laid in random linear sequence on top of the feeder strips. Each sample was sandwiched between two *P. radiata* bait wood stakes, *i.e.* two bait wood stakes separated the experimental samples from each other. Cables, treated wood samples and bait wood were placed contiguously. This arrangement was covered with a layer of feeder strips. By moving along the feeder strips underneath and on top of the arrangement of samples and bait wood, termites could readily access the materials in the entire trench (Fig. 1A).

Next, heavy-gage wire mesh with wide openings was laid over the top feeder strips. The mesh did not impede termite foraging but protected samples against mechanical damage from digging tools when the trenches were re-opened for inspection. Finally the trench was back-filled with soil up to the level of the surrounding soil surface.

The inspection procedure involved removing any soil from the trench down to the wire mesh, then the mesh and remains of the top feeder strip first. The plastic samples were removed, cleaned with a soft brush under water and then evaluated visually for damage by termites. Next, any wood debris and loose soil in the trench was removed and the base clad with new feeder strips. The cleaned specimens and new bait wood stakes were re-positioned in their assigned sequence on top of the feeder strips, and, as in the initial installation, covered with another layer of feeder strips, protective mesh and soil.

2.3.2. Graveyard (in-ground vertical) exposure method

With this method, commonly employed for the evaluation of wood products for in-ground use (see *e.g.* Snyder, 1924; Gay et al., 1957; Butterworth and Mac Nulty, 1966; Becker, 1972; Beesley, 1985), and also for plastic materials, samples are inserted vertically for most of their length into the soil, and spaced evenly along parallel rows. Samples within a row and rows at their ends are connected to each other with wooden feeder strips that are buried with their flat broad sides vertical to a depth just below the soil surface and connected to all samples (Fig. 1B). This increases the likelihood of contact with and potential attack on samples as foraging termites can move readily along the feeder strips (Beesley, 1985).

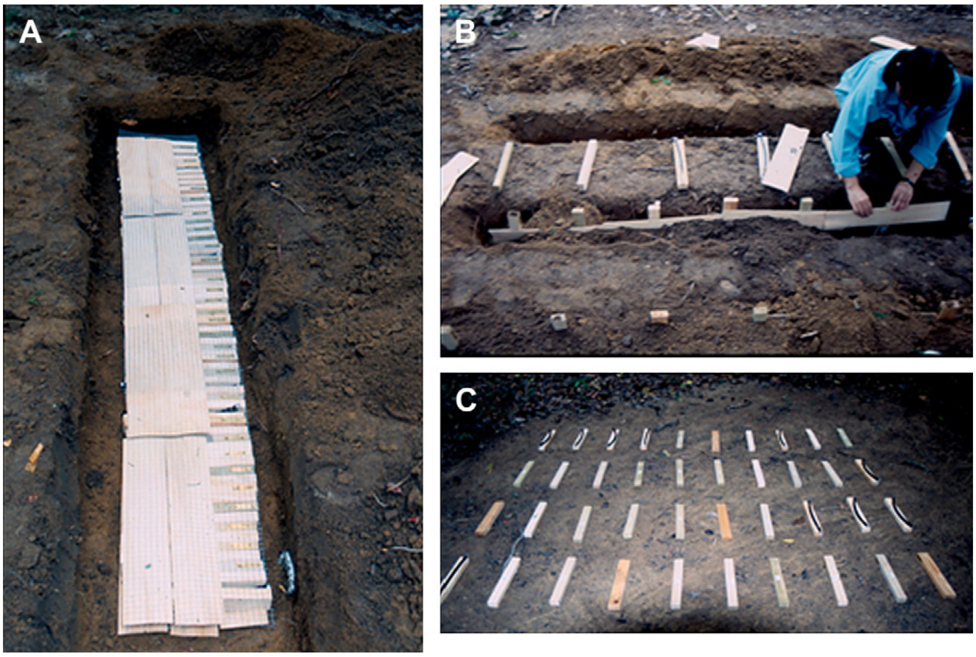

Fig. 1. Examples of installations with the three main field methods used in this study for exposing plastic samples to termites: (A) below-ground exposure method (for details see Section 2.3.1); (B) graveyard method (for details see Section 2.3.2); (C) ground-contact method (for details see Section 2.3.3).

Plastic samples were oriented lengthwise and attached with rubber bands to a bait wood stake on one of its broad faces, and together with the samples of treated timber, installed vertically into the soil to about 25 cm of their length in random sequence in four ≈3 m long rows with spacing of 25 cm between specimens and 1.0 m between rows. The opposite broad side of each bait wood stake was in direct contact with the feeder strip.

During each inspection, the plastic samples were carefully removed from the soil, detached from any wooden debris, cleaned with a soft brush under water, evaluated for termite damage and fastened to a new bait wood stake. Each plastic sample and bait wood arrangement was then re-inserted into its original position. Feeder strips were neither disturbed nor replaced.

2.3.3. *Ground contact (soil surface) method*

In this method, samples are laid on a vegetation-free soil surface and then covered with loose soil followed by a sheet of plastic. The plastic sheet creates moister conditions that favour termite activity.

Our protocol was adapted from a South African assessment method that uses much smaller samples (wooden 'pencil' stakes) for rapid screening of termite resistance at sites with a high termite hazard (Conradie and Jansen, 1983). A 2.5 × 3.5 m area of ground was cleared of vegetation. Then plastic samples were attached to wooden bait stakes as described in Section 2.3.2 and, along with the samples of treated timber, were placed in random sequence with one of their broad faces flat on the soil surface, in four parallel rows of 10 (Fig. 1C). The distance between samples as well as the rows was ≈20 cm. Samples were then covered with a ≈3–4 cm layer of soil and a plastic sheet. The sheet was 'camouflaged' with soil and tree branches to reduce disturbance from animals and human activities as well as to hold it in place.

With this method retrieval and re-installation of samples during an annual inspection was faster and simpler than with the other two methods. Each plastic sample was attached to a new bait wood stake before placing it back in its original position.

2.4. *Replication rate in the main trial*

Three replicate sets each of polyamide and polyethylene samples were installed for each of the three exposure methods on each of the main test sites (except Darwin, Australia which received six replicate sets – see Section 2.6.2), with five replicates of each material in each set. A total of 15 replicates per site for each of the three test methods were exposed to termites.

2.5. *Inspection procedure*

Samples were inspected annually for six years. Termite presence on or contact with samples and bait wood was recorded. When possible, the species or genus of termite responsible for damage or plastering on samples was identified (see Section 2.6) either from live termites or their characteristic building activity (pattern of deposited faecal material, galleries and coating on and around samples).

Following clean-up of samples, the entire surface area of a cable was inspected carefully with the naked eye and any damaged areas further with a 10× magnifying hand lens by either the first author alone or together with another person. In some instances, damage was highly variable and could occur in more than one position on a cable sample. The damage was categorised into four ratings for simplicity and ease of analysis: 'undamaged (OK)', 'nibbled' (N), 'attacked' (A) and 'destroyed' (D) (Table 1). Only the most severe damage rating found on each sample was used in the analyses.

2.6. *Main sites and their subterranean termite faunas*

Sites are listed by latitude from South to North.

2.6.1. *Australia, New South Wales, Griffith, Conapaira south state forest*

This open eucalypt forest (32° 54′S, 146° 14′E) near Griffith, New South Wales, is situated in the south-eastern part of the continent.

Table 1
Rating system for damage to cable samples.

Damage rating	Abbreviation	Definition
Undamaged	OK	No damage
Nibbled	N	Surface roughened or pitted very shallowly (less than 0.3 mm), and only in a few, restricted regions ≤100 mm^2 (≤1% surface area of sample)
Attack	A	Surface shallowly or deeply pitted, over extensive areas (>100 mm^2), but material not penetrated
Destroyed	D	Material penetrated so that metal core is exposed, allowing corrosion and thus loss of data or electrical conductivity and capacity

The climate is semi-arid with mean annual rainfall of 400 mm and a mean annual temperature of 16.3 °C. Tree-nesting *Coptotermes acinaciformis* (Froggatt) and *Coptotermes frenchi* (Hill) are the dominant species. Other common wood-feeding species include *Heterotermes brevicatena* Watson & Miller, *Heterotermes ferox* (Froggatt), *Schedorhinotermes reticulatus* (Froggatt), and *Nasutitermes exitiosus* (Hill). Species in the genera *Amitermes*, *Microcerotermes*, *Occasitermes* and *Ephelotermes* (Termitidae) are also encountered. The trial commenced in April 1996.

2.6.2. Australia, Northern Territory, Darwin, Humpty Doo naval station

The naval station (12°36′S, 131°16′E) lies near Darwin, Northern Territory, within the wet and dry tropics of coastal northern Australia. Mean annual rainfall is 1666 mm and the mean annual temperature is 27.6 °C. On this site the mound-building form of *C. acinaciformis* is common in the eucalypt woodlands. In more open areas the Giant Northern Termite, *Mastotermes darwiniensis* Froggatt, dominates. Other wood-feeding genera such as *Heterotermes*, *Schedorhinotermes* and *Microcerotermes* are represented with several species. In June 1996, three sets of samples were installed against each of the two economically most important target species, *i.e.* three sets adjacent to mounds of *C. acinaciformis*, and three sets within active foraging territories of *M. darwiniensis*.

2.6.3. Thailand, Phuket Province, Bang Kanoon forest plantation

The Bang Khanoon forest plantation (Department of Natural Resources and Environment) on Phuket Island (8°00′N, 98°22′E), is located in SW Thailand. The island lies in the humid tropics and experiences a mean annual rainfall of 2518 mm and a mean annual temperature of 27.4 °C. A partly cleared section of the plantation was used for the trial. The termite fauna is dominated by species of fungus-culturing termites (Macrotermitinae) with the key genera *Macrotermes*, *Microtermes* and *Odontotermes* represented by one or more species each, plus *Hypotermes makhamensis* Ahmad. Other main target species are *Coptotermes gestroi* (Wasmann), *Globitermes sulphureus* (Hagen) and *Nasutitermes* sp. (Sornnuwat et al., 2003; 2004; Vongkaluang et al., 2005). The trial commenced in November 1997.

2.6.4. USA, Mississippi, Gulfport, Harrison experimental forest

The Harrison experimental forest (30°37′N, 89°08′W) with mixed deciduous trees and *Pinus* spp. plantations lies within the Desoto National Forest 20 km north of the city of Gulfport and the coastline of the Gulf of Mexico in southern central Mississippi (Lenz et al., 2009). The region experiences a humid, subtropical climate with mean annual rainfall of 1830 mm and mean annual temperature of 16.7 °C. The termite fauna of the site is comprised of three species of *Reticulitermes* [*Reticulitermes flavipes* (Kollar), *Reticulitermes virginicus* (Banks) and *Reticulitermes malletei* Clément et al.] with *R. flavipes* as the dominant species. The trial commenced in May 1996.

2.7. Analysis of results from main trial

Since termite damage develops over a period, the number of cable samples for each damage rating behaved differently over time. All cables commenced the experiment with an ‘undamaged’ rating; the number of ‘undamaged’ cables could either remain the same or decrease over time. The number of ‘nibbled’ cable samples could remain the same or increase, but also decrease, as greater damage occurred and cables were re-rated to the more severe ‘attacked’. The same situation applied for ‘attacked’ cables as they could be re-rated as ‘destroyed’. The total number of ‘destroyed’ cable samples could only remain the same or increase over time. These complications necessitated that only ‘undamaged’ cable samples were analysed statistically.

The data (number of ‘undamaged’ cable samples) was analysed by repeated measures, two-way ANOVA, with method of exposure and location as the two factors, and year as the repeated measure. There was a significant three–way interaction, therefore data from each year were separately analysed with two-way ANOVA. The later years showed a significant interaction between the two factors (method of exposure and location); data from these years were analysed for each method of exposure with one-way ANOVA using location as the factor. All *posthoc*-pairwise comparisons were Bonferroni-corrected (Sokal and Rohlf, 1995).

The *Mastotermes* sites in Darwin had the species present only a few times; other species, mostly *C. acinaciformis* and *Schedorhinotermes* spp. dominated. Hence the data from the *Mastotermes* and *Coptotermes* sites were pooled.

2.8. Container method for ‘accelerated’ assessment in Malaysia, Japan and Australia

Overall low incidences of termite attack on the plastic cable samples by the diverse termite fauna in Thailand, including the economically most destructive SE Asian *C. gestroi* (Sornnuwat, 1996; Lee, 2002; Kirton and Azmi, 2005; Kirton and Brown, 2005), raised the question whether this was a phenomenon restricted to Thailand or whether in other regions in southern Asia species of *Coptotermes* and other genera would similarly leave the plastic samples largely unscathed. A limited trial was therefore established that exposed cable samples within containers to termite attack for just one year in Penang, Malaysia, against several species of *Coptotermes*, including *C. gestroi*, and Macrotermitinae (see Section 2.8.1.1) and in southern Japan to *Coptotermes formosanus* (see Section 2.8.1.2). For comparison, a similar trial was also conducted in Darwin, Australia, with the mound-building form of *C. acinaciformis* (see Section 2.6.2) and compared with the below-ground exposure method (see Section 2.3.1). On all sites containers were placed within areas of known high termite activity.

The primary difference between this method and that of the main experiment was the frequency of cleaning samples and replacing bait wood. The usual termite response to non-edible materials is to cover them with ‘plastering’: a combination of faeces, partly digested wood and mud. This happened in varying extents to cable samples in all experiments and locations. Once sections of cable surface are plastered they are usually not attacked at later times. During the year of the experiment, cable samples were removed, cleaned of plaster, and returned with new bait wood several times. However, samples were evaluated for termite damage only after completion of the trial. This process exposes the cable samples to multiple incursions of termites (C-Y Lee unpubl.), and thus was considered to be an ‘accelerated’ test relative to the main experiment.

On the Malaysian site (a patch of rainforest), installation of plastic samples by any of the three exposure methods used in the main trial was not practical due to the large number of shallow tree roots and dense vegetation. Hence, samples together with bait wood were placed within containers with access holes for termite entry. The containers were buried to a depth so that their lids were flush with the soil surface. Lids were covered with plastic sheet and a ≈5 cm thick layer of soil.

A similar approach was used at the site in southern Japan, and for comparison also in Darwin, Australia. Although details of container type and bait wood species differed between sites, the principle of placing samples together with a larger supply of bait wood within a container applied to all sites. Details for the three sites were as follows:

Penang, Malaysia: Five rectangular plastic boxes (40 × 30 × 15 cm; 18 l), with a removable lid and several entry holes through the base and the sides were installed. The boxes were filled with boards of rubber bait wood, and five replicate samples of both types of plastic per box were placed at random horizontally amongst the wood. The samples were removed, cleaned and re-installed together with fresh bait wood every three months.

Kagoshima, Japan: Three plastic buckets (28 cm deep, diameter at the top 28.5 cm, at base 22.5 cm, lid raised by 2 cm, ≈16 l), with entry holes at the sides and the base cut out (to accommodate fully the 30 cm long cable samples and the 35 cm long boards of *Pinus thunbergia* Parl bait wood), were installed. Five replicate samples of both types of plastic per bucket were positioned at random vertically between wooden boards. Each bucket was located next to a different colony of *C. formosanus*. Samples were removed, cleaned and re-installed with fresh bait wood after six months.

Darwin, Australia: Three steel drums (32 cm high × 30 cm diameter; 22 l, flat lid), with entry holes at the base and the sides, were installed. Five replicate samples of both types of plastic per drum were installed at random vertically between boards (27 cm long) of the bait wood *Eucalyptus regnans* F. Muell. For comparison, the same number of samples was installed in a trench using the below-ground exposure method as described in Section 2.3.1, but using stakes of *E. regnans* as the bait wood. One drum and one trench each were installed on opposite sides of three mounds of *C. acinaciformis*. Samples were removed, cleaned and re-installed together with fresh bait wood every three months.

2.8.1. Additional sites for the container trial and their termite faunas

2.8.1.1. Malaysia, Penang, Universiti Sains Malaysia, Minden Campus. The Minden Campus (5°21′N, 100°18′E) of the Universiti Sains Malaysia is located on Penang Island on the north-eastern coast of Peninsular Malaysia. The climate is equatorial. The mean annual rainfall of 2670 mm is generally evenly distributed throughout the year. The mean annual temperature reaches 27.3 °C. The trial was installed in 2001 on a 2.5 ha patch of rainforest with an abundant termite fauna with *Microcerotermes crassus* Snyder, *C. gestroi* and *Coptotermes curvignathus* Holmgren, and several species of fungus-culturing termites, including *Microtermes pakistanicus* Ahmed, *Macrotermes gilvus* (Hagen), *M. carbonarius* (Hagen) and species of *Odontotermes*, (Lee, 2009).

2.8.1.2. Japan, Kagoshima Prefecture, government forest, Kyoto University experimental site. The “Living Sphere Simulation Field (LSF)” of the Research Institute for Sustainable Humanosphere (RISH) of Kyoto University is located in Fukiage-Cho (31°00′N, 130°23′E), Hioki-city in the Kagoshima Prefecture in the SW of Kyushu Island of southern Japan. The region has a warm temperate climate with a mean annual rainfall of 2265 mm and a mean annual temperature of 18 °C. *C. formosanus* is abundant in the forest of largely *P. thunbergia* Parl. *Reticulitermes speratus* (Kolbe) is also present at high density. The one year trial commenced in 2004.

3. Results

3.1. Results for the main trial

With few exceptions, all plastic samples were contacted by termites within the first year of exposure. However, judging by the extent of plastering material on the cable surfaces, termite activity was often restricted to a narrow strip along the line of contact between the curve of the cylindrical cable and the flat surface of the bait wood stake in the graveyard and ground contact methods (see Sections 2.3.2 and 2.3.3). In general, plastering was far more extensive, often covering the entire cable surface of samples, in the below-ground exposure method where they were completely surrounded by wood (see Section 2.3.1).

All samples of polyamide remained ‘undamaged’ throughout the six year trial irrespective of the exposure method and termite fauna. Hence, all results mentioned and discussed below refer only to the samples of medium density polyethylene (Table 2).

At Australian sites *C. acinaciformis*, both the tree-nesting form in Griffith and the mound-builder in Darwin, caused most of the damage to the samples. Species of *Schedorhinotermes* and *Heterotermes* were also commonly encountered. In Phuket *C. gestroi* and *Macrotermes* spp. were the termites most frequently contacting samples. In Gulfport it was *R. flavipes*.

3.2. Main trends

Results (Table 2) showed three broad trends: (**1**) damage ratings were most severe in Darwin, followed by Griffith and least severe in Gulfport and Phuket; (**2**) damage ratings were most severe in the graveyard method of exposure; and (**3**) the number of ‘undamaged’ cable samples decreased over time; these factors were each highly statistically significant (Location $F_{3,31} = 37.542$, $p < 0.001$; Method $F_{2,31} = 11.178$, $p < 0.001$; Year $F_{5,155} = 53.372$, $p < 0.001$). However, within these broad trends there was important variation as shown by the significant interaction effect in the repeated measures two-way ANOVA (Year × Location × Method interaction $F_{30,155} = 1.863$, $p = 0.008$).

3.2.1. Location

The trend of declining damage from Darwin to Phuket is apparent from the number of ‘undamaged’ cables, which decreased from five replicates per set to around 1.5 in Darwin and 2.5 in Griffith during the first year, whereas this number remained close to 5 in Gulfport and Phuket. The number of ‘undamaged’ cables declined consistently over six years in all sites, to almost zero in Darwin and Griffith, down to 2.5 in Gulfport and 3 in Phuket (Fig. 2a).

The number of ‘nibbled’ cables decreased from ≈2 to 1.5 over six years in Darwin, but increased from 2.5 to 3 by the third year in Griffith, then declined to 2.5 by the sixth year, increased from 0.0 to 2.0 over the six years in Gulfport, and from 0.0 to 1.5 in Phuket (Fig. 2b).

The number of ‘attacked’ cables increased in all locations over the six years, and was always higher in Darwin (from 1.0 to 2.8), although the number in Griffith rose more rapidly (zero to 2). The number of ‘attacked’ cables reached one over the six years in Gulfport and Phuket (Fig. 2c).

The number of ‘destroyed’ cables increased in Darwin from zero to 0.5 by the sixth year. The only other location to record a destroyed cable (one) was Griffith, which occurred in the fifth year (Fig. 2d).

3.2.2. Exposure method

The number of ‘undamaged’ cables declined from five replicates per set to approximately 2.5 in graveyard sets, and to approximately 3.5 in surface and below-ground sets during the first year.

Table 2
Termite damage to polyethylene cables from four locations using three methods of exposure. Data are average (±standard error) number of cables for each damage rating.

Location[a]	Method[b]	Rating[c]	Years after installation					
			1	2	3	4	5	6
Griffith	Below	OK	2.3 ± 0.7	1.7 ± 0.3	0.7 ± 0.7	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0
		N	2.7 ± 0.7	3.3 ± 0.3	4.0 ± 0.6	3.7 ± 0.9	3.0 ± 0.6	1.7 ± 0.9
		A	0.0 ± 0.0	0.0 ± 0.0	0.3 ± 0.3	1.3 ± 0.9	1.7 ± 0.3	3.0 ± 0.6
		D	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.3 ± 0.3	0.3 ± 0.3
	Grave	OK	2.0 ± 1.2	1.7 ± 1.2	0.7 ± 0.3	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0
		N	3.0 ± 1.2	2.3 ± 1.5	3.0 ± 0.6	2.0 ± 1.2	1.7 ± 1.2	1.7 ± 1.2
		A	0.0 ± 0.0	1.0 ± 0.6	1.3 ± 0.3	3.0 ± 1.2	3.3 ± 1.2	3.3 ± 1.2
		D	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0
	Contact	OK	3.3 ± 0.9	2.0 ± 0.0	2.0 ± 0.0	1.5 ± 0.4	1.0 ± 0.0	0.5 ± 0.4
		N	1.7 ± 0.9	3.0 ± 0.0	3.0 ± 0.0	3.5 ± 0.4	4.0 ± 0.0	4.0 ± 0.0
		A	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.5 ± 0.4
		D	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0
Darwin	Below	OK	2.7 ± 0.7	1.8 ± 0.6	1.2 ± 0.6	0.5 ± 0.5	0.3 ± 0.3	0.3 ± 0.3
		N	1.2 ± 0.3	1.3 ± 0.3	1.7 ± 0.7	1.8 ± 0.7	1.5 ± 0.5	1.0 ± 0.4
		A	0.8 ± 0.7	1.3 ± 0.6	1.3 ± 0.5	1.7 ± 0.5	1.8 ± 0.5	2.2 ± 0.7
		D	0.3 ± 0.3	0.5 ± 0.3	0.8 ± 0.5	1.0 ± 0.7	1.3 ± 0.8	1.5 ± 0.8
	Grave	OK	0.5 ± 0.3	0.2 ± 0.2	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0
		N	3.2 ± 0.4	2.2 ± 0.7	1.5 ± 0.6	1.0 ± 0.4	0.8 ± 0.4	0.8 ± 0.4
		A	1.3 ± 0.5	2.7 ± 0.6	3.3 ± 0.5	3.8 ± 0.4	4.0 ± 0.4	3.8 ± 0.3
		D	0.0 ± 0.0	0.0 ± 0.0	0.2 ± 0.2	0.2 ± 0.2	0.2 ± 0.2	0.3 ± 0.2
	Contact	OK	1.8 ± 0.7	1.0 ± 0.4	0.3 ± 0.3	0.3 ± 0.3	0.0 ± 0.0	0.0 ± 0.0
		N	2.3 ± 0.3	2.7 ± 0.3	2.3 ± 0.6	2.2 ± 0.7	2.0 ± 0.6	2.0 ± 0.6
		A	0.8 ± 0.4	1.3 ± 0.6	2.3 ± 0.7	2.3 ± 0.7	2.8 ± 0.5	2.8 ± 0.5
		D	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.2 ± 0.2	0.2 ± 0.2	0.2 ± 0.2
Phuket	Below	OK	5.0 ± 0.0	5.0 ± 0.0	5.0 ± 0.0	5.0 ± 0.0	4.3 ± 0.3	3.7 ± 0.3
		N	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.7 ± 0.3	1.0 ± 0.0
		A	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.3 ± 0.3
		D	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0
	Grave	OK	5.0 ± 0.0	3.7 ± 0.9	3.5 ± 1.2	2.0 ± 0.8	1.5 ± 1.2	1.5 ± 1.2
		N	0.0 ± 0.0	1.0 ± 0.6	1.0 ± 0.8	1.0 ± 0.0	0.5 ± 0.4	0.0 ± 0.0
		A	0.0 ± 0.0	0.3 ± 0.3	0.5 ± 0.4	2.0 ± 0.8	3.0 ± 0.8	3.5 ± 1.2
		D	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0
	Contact	OK	5.0 ± 0.0	5.0 ± 0.0	4.3 ± 0.7	3.7 ± 1.3	3.7 ± 1.3	3.3 ± 1.2
		N	0.0 ± 0.0	0.0 ± 0.0	0.7 ± 0.7	1.0 ± 1.0	0.7 ± 0.7	0.7 ± 0.3
		A	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.3 ± 0.3	0.7 ± 0.7	1.0 ± 1.0
		D	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0
Gulfport	Below	OK	5.0 ± 0.0	5.0 ± 0.0	4.0 ± 0.6	4.0 ± 0.6	4.0 ± 0.6	3.3 ± 0.9
		N	0.0 ± 0.0	0.0 ± 0.0	1.0 ± 0.6	1.0 ± 0.6	1.0 ± 0.6	1.7 ± 0.9
		A	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0
		D	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0
	Grave	OK	4.3 ± 0.7	2.7 ± 1.5	1.0 ± 0.6	0.3 ± 0.3	0.0 ± 0.0	0.0 ± 0.0
		N	0.0 ± 0.0	1.0 ± 0.6	1.7 ± 0.9	2.3 ± 1.2	2.3 ± 0.7	2.0 ± 1.0
		A	0.7 ± 0.7	1.3 ± 0.9	2.3 ± 1.3	2.3 ± 1.3	2.7 ± 0.7	3.0 ± 1.0
		D	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0
	Contact	OK	5.0 ± 0.0	4.7 ± 0.3	3.7 ± 0.9	2.7 ± 1.2	2.7 ± 1.2	2.3 ± 0.9
		N	0.0 ± 0.0	0.3 ± 0.3	1.0 ± 1.0	2.0 ± 1.2	2.0 ± 1.2	2.3 ± 0.9
		A	0.0 ± 0.0	0.0 ± 0.0	0.3 ± 0.3	0.3 ± 0.3	0.3 ± 0.3	0.3 ± 0.3
		D	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0

[a] Location: Griffith, New South Wales, Australia (33°S), Darwin, Northern Territory, Australia (13°S), Phuket, Thailand (8°N) and Gulfport, Mississippi, USA (31°N).
[b] Method: 'below' = the below-ground exposure method with samples buried 15–30 cm; 'grave' = the graveyard method with samples placed vertically 25 cm deep in the ground with 5 cm protruding out of the ground; 'contact' = on-ground contact method with samples placed on the surface of the ground and covered with soil and a plastic sheet.
[c] Rating: see Table 1 for details.

By the sixth year, the number of 'undamaged' cables had declined to almost zero in graveyard sets, and to around two in both ground contact and below-ground sets (Fig. 3a).

The number of 'nibbled' cables ranged from one to two over six years, without clear differences between methods (Fig. 3b). The number of 'attacked' cables increased in all methods over six years, but was always higher in graveyard sets (from around 0.5 to 3.5), compared with around 0.3 to 1 for both ground contact and below-ground sets (Fig. 3c). Few cable samples were 'destroyed': most of these in the below-ground sets (Fig. 3d).

3.3. *Statistical analysis by year*

The significant three–way interaction in the repeated measures two-way analysis of variance ($p = 0.008$) can be interpreted as significant variation in how the number of 'undamaged' cables changed between the methods of exposure and locations over time. The simplest factor to interpret was time as this effect was a simple decrease in the number of 'undamaged' cables over time. Therefore the data were separated into years, and data from each year were analysed separately using two-way ANOVA.

3.3.1. *Year 1*

There was only one significant effect during the first year: location ($F_{3,33} = 22.482$, $p < 0.001$). The Bonferonni corrected pairwise comparisons showed that Darwin did not differ from Griffith but both had fewer undamaged cables than Phuket and Gulfport, which did not differ from each other. Neither method ($F_{2,33} = 2.093$, $p = 0.139$) nor the location × method interaction ($F_{6,33} = 0.921$, $p = 0.493$) were significant.

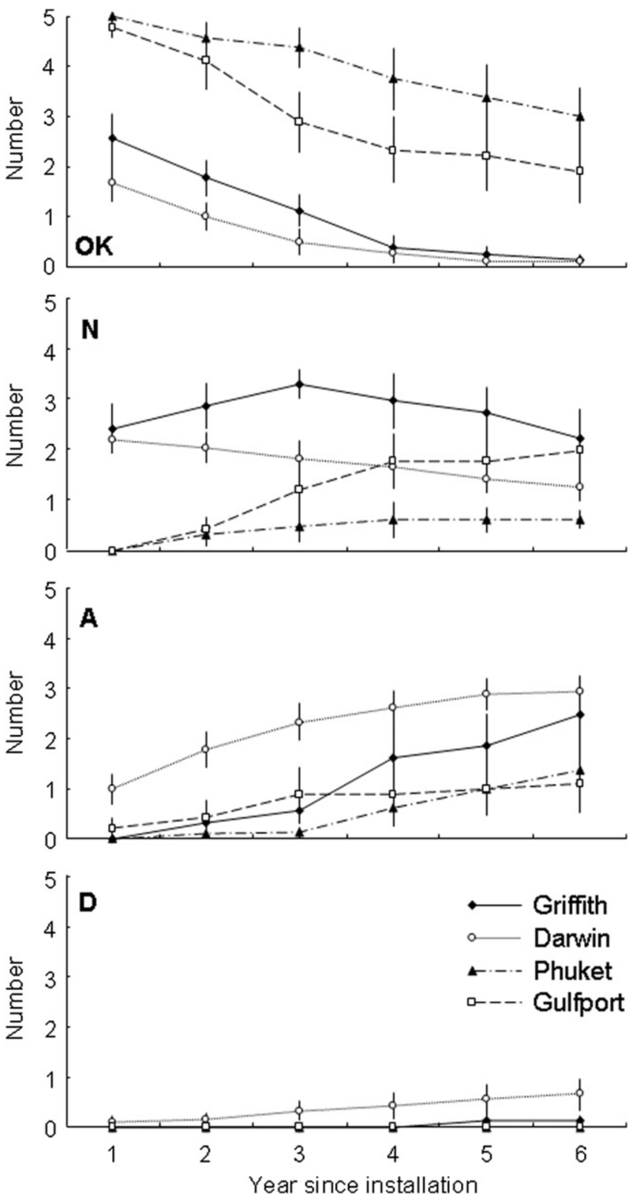

Fig. 2. Average number of medium density polyethylene cables ($n = 45$; for Darwin $n = 90$) at each damage rating for each of the four experimental sites (values combined for all three exposure methods). N.B. OK = 'undamaged'; N = 'nibbles'; A = 'attack'; D = 'destroyed' (see Table 1 for more detail).

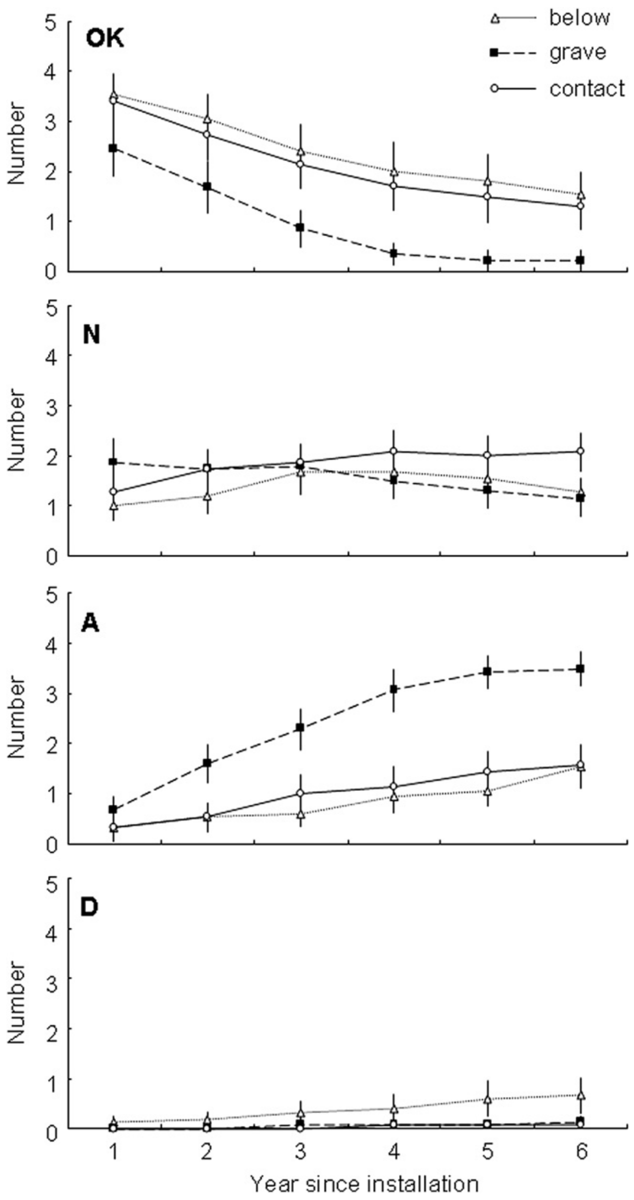

Fig. 3. Average number of medium density polyethylene cables ($n = 60$; for Darwin $n = 120$) at each damage rating for each of the three exposure methods (values combined for the four experimental sites). N.B. OK = 'undamaged'; N = 'nibbles'; A = 'attack'; D = 'destroyed' (see Table 1 for more detail).

3.3.2. Year 2

There were significant effects for location ($F_{3,33} = 27.264$, $p < 0.001$) and method of exposure ($F_{2,33} = 5.415$, $p = 0.009$) during the second year. As seen in the first year, there were significantly fewer 'undamaged' cables in Darwin and Griffith compared to Gulfport and Phuket; within these two pairs of sites numbers were not significantly different from each other. There were significantly fewer 'undamaged' cables in sets of the graveyard method compared with sets from the ground contact and below-ground exposure method, with results from the latter two not significantly different from each other. The location × method interaction was not significant ($F_{6,33} = 0.719$, $p = 0.637$).

3.3.3. Year 3

The results for the third year of test matched those of the second, with significant effects for location ($F_{3,33} = 29.668$, $p < 0.001$) and method of exposure ($F_{2,33} = 7.399$, $p = 0.002$). There were significantly fewer 'undamaged' cables in Darwin and Griffith compared with Gulfport and Phuket; within these two pairs of sites numbers were not significantly different from each other. There were significantly fewer 'undamaged' cables in graveyard method sets compared with ones from the ground contact and below-ground exposure methods, with the latter two methods not significantly different. The location × method interaction was not significant ($F_{6,33} = 1.881$, $p = 0.115$).

3.3.4. Year 4

Although both location ($F_{3,31} = 21.202$, $p < 0.001$) and method ($F_{3,31} = 9.920$, $p < 0.001$) were significant; there was a significant interaction between location and method of exposure ($F_{6,33} = 2.723$, $p = 0.030$) during the fourth year of the trial. Therefore, one-way ANOVAs were performed on each method of exposure. For the below-ground exposure method, locations differed significantly ($F_{3,11} = 24.895$, $p < 0.001$) and Darwin and Griffith had significantly fewer undamaged cables compared with Gulfport and Phuket. For the graveyard method, locations differed significantly ($F_{3,10} = 8.185$, $p = 0.005$) and Darwin, Griffith and Gulfport the same but all had significantly fewer undamaged cables than Phuket. For ground contact exposure, location was only just significant ($F_{3,10} = 3.696$, $p = 0.050$) as the only significantly difference pairwise comparison was Darwin with fewer undamaged cables compared with Phuket.

3.3.5. Year 5

Similar to year 4, location ($F_{3,31} = 22.961$, $p < 0.001$) and method ($F_{3,31} = 11.748$, $p < 0.001$) were significant but with a significant interaction between location and method of exposure ($F_{6,33} = 3.632$, $p = 0.008$) during the fifth year of testing. Therefore, one-way ANOVAs were performed on each method of exposure. For below-ground exposure, locations differed significantly ($F_{3,11} = 34.467$, $p < 0.001$) and Darwin and Griffith had significantly fewer undamaged cables compared with Gulfport and Phuket. For graveyard exposure, locations did not differ significantly ($F_{3,10} = 2.857$, $p = 0.091$). For ground contact exposure, location was significant ($F_{3,10} = 5.546$, $p = 0.017$) as for the previous year as Darwin had significantly fewer undamaged cables than Phuket, and all other comparisons were not significantly different.

3.3.6. Year 6

As for the years 4 and 5, location ($F_{3,31} = 20.137$, $p < 0.001$) and method ($F_{3,31} = 8.524$, $p = 0.001$) were significant but with a significant interaction between location and method of exposure ($F_{6,31} = 2.639$, $p = 0.035$) during the sixth year. Therefore, one-way ANOVAs were performed on each method of exposure. For below-ground exposure, locations differed significantly ($F_{3,11} = 16.528$, $p < 0.001$) as the pattern from the two previous years continued, as Darwin and Griffith had significantly fewer undamaged cables compared with Gulfport and Phuket. For graveyard exposure, locations did not differ significantly ($F_{3,10} = 2.857$, $p = 0.091$). For ground contact exposure, location was significant ($F_{3,10} = 6.512$, $p = 0.010$) as for the previous 2 years as Darwin was significantly less compared with Phuket, and all other comparisons were not significantly different.

3.4. Results for the container trial

All polyamide samples remained intact. Neither the mixed fauna of *Coptotermes* spp. and Macrotermitinae in Penang nor *C. formosanus* in Kagoshima caused much damage to the medium density polyethylene cables despite repeated offers of cleaned surfaces and replenishment of the surrounding bait wood. Between the two sites only one 'nibble' and one 'attack' was observed among a total of 40 samples (Table 3).

In contrast, the plastic layer of 73% of samples ($n = 15$) exposed in the container method in Darwin, was fully penetrated, i.e. destroyed (Table 3). In many cases termites also removed a considerable amount of the plastic sheathing from the cables (Fig. 4). These differences were significant ($\chi^2 = 49.693$, d.f. = 6, $p < 0.001$); with the difference due to Darwin as Penang and Kagoshima did not differ significantly ($\chi^2 = 0.853$, d.f. = 3, $p = 0.837$). The black plastic material was incorporated into some of their constructions of galleries and seals along gaps between bait wood boards.

In the below-ground exposure method, run simultaneously in Darwin, 20% of samples were destroyed. Termites chewed through the plastic but did not remove large amounts of it. Interestingly, there was a significant difference between the damage levels in containers and the below-ground exposure methods ($\chi^2 = 14.905$, d.f. = 3, $p = 0.002$), with greater damage observed in the containers.

Table 3
Damage ratings for medium density polyethylene cables after exposure to termites for 12 months inside a container or trench (=below-ground exposure method) with repeated change of bait wood (see Section 2.8).

Location	Method	Total no. samples	Damage rating/No. samples			
			OK	N	A	D
Penang, Malaysia	Container	25	24	1	–	–
Kagoshima, Japan	Container	15	14	–	1	–
Darwin, Australia	Container	15	–	1	3	11
Darwin, Australia	Trench	15	9	2	1	3

4. Discussion

The three factors tested in the main experiment all showed significant differences. Perhaps most obviously time was important for the level of attack on polyethylene; the longer cable samples were under test the more they were damaged. The next most predictable difference may have been location, with the expectation that cable samples in tropical locations, with more consistently hotter temperatures and greater termite diversity and abundance, as well as termite activity throughout the entire year, would experience greater damage. There were differences between locations, however, the differences did not hold to this expectation. Instead, the cable samples in the two Australian locations, Darwin (tropical) and Griffith (temperate), suffered the highest levels of damage. Perhaps the least clear predictions could be made for method of exposure. The graveyard exposure method showed the most consistently high level of damage, however, it was the below-ground method that had the highest number of destroyed cables – but only in Australian locations.

This variation in pattern demonstrates the significant interactions found between the three factors. For the interaction between location and exposure methods, the local climatic conditions determined the best method of assessment. Soil moisture was most likely lowest in plots of the ground contact method and highest for the below-ground method. In drier habitats in Australia, termites may well have experienced driest conditions in the ground contact method, whereas in the wetter habitats of Phuket and Mississippi conditions may have been too wet in the below-ground method. For these reasons it may well be that the graveyard method proved overall to be best, because cable samples were inserted vertically in the soil, therefore they traversed the full span of exposure depths and soil moisture ranges of all three exposure methods. Consequently, this allowed termites to shift position between depth levels and aggregate where conditions were most suitable for them

Fig. 4. Example of a 'destroyed' cable sample, i.e. penetrated, by *Coptotermes acinaciformis* at the Darwin site from the trial with the accelerated container method. Note that the sample has not only been penetrated but large amounts of the polyethylene have been removed as well.

at any given time whilst still having full access to the bait wood and hence contact with cable samples.

The polyamide samples again proved resistant to termite attack, thus confirming earlier work (Watson et al., 1984; Boes et al., 1992; Rosenblat et al., 2005). However, this does not mean that this material is completely immune from termite attack. Mechanical damage to the smooth surface (scratches, creases, *e.g.* Ruddell, 1985), which can happen *e.g.* during the laying of a cable, will provide access points for termite mandibles, and damage by termites can follow. It is for such a reason that some nylon-jacketed cable products are fitted with an outer sleeve of sacrificial soft PVC. It ensures that the polyamide surface of the cable remains intact during installation. Termites will readily penetrate the PVC sleeve, however, were never shown to extend attack to the nylon surface in both laboratory and field trials (M. Lenz, CSIRO, unpubl.).

One of the unexpected results was the low incidence of attack on plastic samples from the multi-species termite fauna, including several major pest species (Sornnuwat 1996; Sornnuwat et al., 2003) in Phuket, Thailand. This resulted in the additional trial of investigating potential for attack by termite faunas at other Asian sites with an 'accelerated' test method (container method) for two of the pest species of termite considered to be among the most aggressive species towards wood-based and other materials in the built environment around the world, *C. formosanus* and *C. gestroi* (Sornnuwat 1996; Tsunoda, 2005; Chutibhapakorn and Vongkaluang, 2006; Lee et al., 2007; Scheffrahn and Su, 2008; Li et al., 2009; Yeap et al., 2009; Su and Scheffrahn, 2010). Yet despite providing conditions for a repeated build-up of termite numbers at the cleaned samples within a short assessment period, and all the bait wood repeatedly being destroyed as an indicator of high termite activity around the samples, the results did not differ in Malaysia and southern Japan from those obtained earlier in Thailand. In contrast, the Australian *C. acinaciformis* caused significantly more damage in the container method than in the below-ground exposure method although in both bait wood was changed and a cleaned sample surface exposed repeatedly. Perhaps the more confined space within the containers, resembling more closely the feeding situation within trees and allowing termites to better control the microclimate, may have focused termite foraging at the bait wood and the plastic samples.

Australian *Coptotermes* attacked and damaged plastic cable samples far more than any other termite species encountered in these trials. We have no explanation why that may be the case. Perhaps some chemical additives in the plastics, *e.g.* plasticisers, were attractive to the Australian species, but not to their counterparts of Asian origin. Of course, Asian species of *Coptotermes* are able to attack plastic materials. There is enough anecdotal evidence for this. Rosenblat et al. (2005) and Tsunoda et al. (2010) have demonstrated in well-designed laboratory experiments that *C. formosanus* will damage various plastic materials. However, under field conditions, using established and novel assessment methods, termites only slightly damaged a few of the polyethylene plastic samples despite completely destroying all surrounding bait wood.

One of the practical implications for Australia is that one cannot necessarily rely on proof of termite resistance of a plastic material based on trials with species outside Australia. Any candidate materials will have to be re-evaluated in Australia against *C. acinaciformis* and *M. darwiniensis*, Australia's key pest species of termite (Gay and Calaby, 1970).

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