TUNNELING BEHAVIOUR AND BARRIER PENETRATION OF SUBTERRANEAN TERMITES WITH SPECIAL REFERENCE TO *Coptotermes gestroi* (Wasmann) (ISOPTERA: RHINOTERMITIDAE)

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by

YEOH BOON HOI

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°C	degree Celsius
a. i.	active ingredient
cm	centimeter
d	day
fig.	figure
h	hour
i. d.	inner diameter
Kg	kilogram
KPa	kilopascal
LD	lethal dose
ppm	parts per million
RH	relative humidity
wk	week

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LIST OF PUBLICATIONS & SEMINARS

Publications

1. **Yeoh BH** & CY Lee. 2006. Evaluation of several novel and conventional termiticide formulations against the Asian subterranean termite, *Coptotermes gestroi* (Wasmann) (Isoptera: Rhinotermitidae). In *The Proceedings of the Third Conference of Pacific Rim Termite Research* Group (6 – 7 March). Guang Zhou, China.

2. Lee CY, LT Quah, **BH Yeoh**, YF How, KF Chong, BK Yeap, EK Tan, SY Foo, SG Lam-Phua, LC Ng, P Koh. 2006. Insecticide resistance in field collected populations of the German cockroach, *Blattella germanica* (L.) from Singapore. In: *The proceedings of Pest Summit* (10 – 12 Aug.). Grand Copthorne Waterfront Hotel, Singapore.

3. **Yeoh BH** & CY Lee. 2007. Tunneling patterns of subterranean termites *Coptotermes gestroi* (Wasmann), *Coptotermes curvignathus* Holmgren and *Coptotermes kalshoveni* Kemner (Isoptera: Rhinotermitidae). In *The Proceedings of the Forth Conference of Pacific Rim Termite Research Group* (26 – 27 Feb.). Kaohsiung, Taiwan.

4. **Yeoh BH** & CY Lee. 2007. Soil arthropods associated with termite bait monitoring stations in Malaysia. *Sociobiology* 49 (3): 187-196.

5. **Yeoh BH** & CY Lee. 2007. Evaluation of termiticide performance against the Asian subterranean termite, Coptotermes gestroi (Wasmann) (Isoptera: Rhinotermitidae). *Sociobiology* 50(2): 457-468.

6. **Yeoh BH** & CY Lee. 2007. Tunneling activity, wood consumption and survivorship of *Coptotermes gestroi*, *Coptotermes curvignathus* and *Coptotermes kalshoveni* in the laboratory. *Sociobiology* : In press.

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1. **Yeoh BH** & CY Lee. Soil invertebrates associated with termite bait monitoring stations. *In* The Regional Conference on Ecological and Environmental Modelling (ECOMOD), organised by School of Mathematical Sciences & School of Biological Sciences. Penang, Malaysia. 15 – 16 September 2004.

2. **Yeoh BH** & CY Lee. Soil invertebrates associated with termite bait monitoring stations. *In* 41st Annual Scientific Seminar: Natural Products in the Management of Tropical Diseases, organised by Malaysian Society of Parasitology and Tropical Medicine. Kuala Lumpur, Malaysia. 10 – 11 March 2005.

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4. **Yeoh BH** & CY Lee. Evaluation of several novel and conventional termiticide formulations against the Asian subterranean termite, *Coptotermes gestroi* (Wasmann) (Isoptera: Rhinotermitidae). *In* The Third Conference of Pacific Rim Termite Research Group. Guang Zhou, China. 6 – 7 March 2006.

5. **Yeoh BH** & CY Lee. Tunneling behaviour of three subterranean termites, *Coptotermes gestroi* (Wasmann), *Coptotermes curvignathus* Holmgren and *Coptotermes kalshoveni* Kemner (Isoptera: Rhinotermitidae). *In* 3rd Life Science Postgraduate Conference: Moving Synchrony with the Changes in the World. Penang, Malaysia. 24 – 27 May 2006.

6. **Yeoh BH** & CY Lee. Laboratory performance of several novel and conventional termiticide formulations against the Asian subterranean termite, *Coptotermes gestroi* (Wasmann) (Isoptera: Rhinotermitidae). *In*

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ABSTRAK

Kelakuan menerowong dan penembusan sempadan termitisid oleh anai-anai tanah dengan tumpuan ke atas *Coptotermes gestroi* (Wasmann) (Isoptera: Rhinotermitidae)

Kajian ini menumpu ke atas kelakuan menerowong dan penembusan sempadan termitisid pada anai-anai tanah, terutamanya pada *Coptotermes gestroi*. Di samping itu, transmisi horizontal beberapa bahan toksik antara *C. gestroi* turut dikaji.

Perbandingan kelakuan menerowang tiga spesies *Coptotermes*, iaitu *C. gestroi*, *Coptotermes curvignathus* Holmgren dan *Coptotermes kalshoveni* Kemner dalam medium penerowongan yang berlainan (agar dan pasir) menunjukkan bahawa *C. curvignathus* ialah species yang paling agresif dengan pembinaan terowong yang ekstensif, diikuti oleh *C. gestroi*. *Coptotermes kalshoveni* menunjukkan aktiviti menerowong yang paling rendah, tetapi menunjukkan activiti pemakanan yang paling tinggi dalam tempoh pengajian yang mengambil masa 28 hari. Ini mencadangkan bahawa species ini mempunyai sifat kesetiaan yang tinggi terhadap sumber makanan. Kedua-dua *C. gestroi* dan *C. kalshoveni* didapati lebih menyukai kayu getah, manakala *C. curvignathus* tidak menunjukkan kegemaran yang specifik di antara kayu getah dan kayu pine.

Ketoksikan secara sentuhan bagi enam insektisid gred teknikal (bifenthrin, chlorfenapyr, chlorantraniliprole, fipronil, imidacloprid and indoxacarb) pada *C. gestroi* ditentukan dengan aplikasi topikal. Keputusan menunjukkan bahawa bifenthrin adalah insektisid sentuhan yang paling toksik ke atas *C. gestroi*. Kajian dilanjutkan untuk menentukan penembusan sempadan termitisid dan aktiviti menerowong anai-anai tersebut dengan menggunakan tujuh formulasi termitisid, Biflex® (bifenthrin) 24 % EC [FMC], Terminator® (chlorfenapyr) 24 % SC [WellTech Healthcare Co. Ltd, Thailand], DPX-E2Y45 (chlorantraniliprole) 18.5 % SC [DuPont Professional Products], Termidor® (fipronil) 2.5 % EC [Bayer Environmental Science], DPX HGW86-198 10 % SC [DuPont Professional Products], Premise® (imidacloprid) 20 % SC [Bayer Environmental Science] dan indoxacarb 14.5 % SC [DuPont Professional Products]. Daripada kajian ini, didapati bahawa kesemua termitisid yang dikaji didapati berupaya menghentikan atau menekan aktiviti menerowong anai-anai, sama ada termitisid tersebut adalah bersifat menolak atau tidak. Gerak balas anai-anai dalam tanah yang dirawat dengan termitisid turut mencadangkan bahawa sifat menolak sesuatu termitisid mungkin bergantung kepada kepekatan yang digunakan.

Formulasi termitisid dikaji dengan lebih melanjut untuk menguji pemindahan horizontal di kalang anai-anai (terawat kepada tidak terawat). Mortaliti anai-anai tidak dirawat berbeza bergantung kepada bahan aktif, tempoh masa penderma dirawat dan nisbah penderma : penerima. Peningkatan tempoh masa rawatan dan nisbah campuran mengakibatkan kesan yang lebih ketara kepada populasi yang dikaji.

Tunneling behaviour and barrier penetration of subterranean termites With Special Reference to *Coptotermes gestroi* (Wasmann) (Isoptera: Rhinotermitidae)

ABSTRACT

This study focuses on tunneling behaviour and barrier penetration of subterranean termites especially to *Coptotermes gestroi* (Wasmann). In addition, horizontal transmission of several toxicants among the *C. gestroi* was also studied.

Comparative tunneling behaviour of three species of *Coptotermes*, namely *C. gestroi*, *Coptotermes curvignathus* Holmgren and *Coptotermes kalshoveni* Kemner in different tunneling mediums (agar and sand) revealed that *C. curvignathus* was the most aggressive species with extensive tunnel formation, followed by *C. gestroi*. *Coptotermes kalshoveni* has the least tunneling activity; however, it showed the highest wood consumption rate in the 28 d evaluation period, suggesting higher resource fidelity. Both *C. gestroi* and *C. kalshoveni* were found to prefer rubber over pine wood, while *C. curvignathus* showed no preference between rubber and pine wood.

Contact toxicities of six technical grade insecticides (bifenthrin, chlorfenapyr, chlorantraniliprole, fipronil, imidacloprid and indoxacarb) in *C. gestroi* were determined by topical application. Results indicated that bifenthrin was the most toxic contact insecticide against *C. gestroi*. Further experiments were carried out to evaluate the barrier penetration and tunneling activities of the

termites by using seven formulated termiticides, Biflex® (bifenthrin) 24 % EC [FMC], Terminator® (chlorfenapyr) 24 % SC [WellTech Healthcare Co. Ltd, Thailand], DPX-E2Y45 (chlorantraniliprole) 18.5 % SC [DuPont Professional Products], Termidor® (fipronil) 2.5 % EC [Bayer Environmental Science], DPX HGW86-198 10 % SC [DuPont Professional Products], Premise® (imidacloprid) 20 % SC [Bayer Environmental Science] and indoxacarb 14.5 % SC [DuPont Professional Products]. It was found that all the termiticides tested were able to stop or suppress termites foraging activities, regardless of their repellent or non repellent properties. Response of subterranean termites in termiticide-treated sand suggested that termiticide properties (repellent or non-repellent) may be depended on the concentrations used.

The formulated termiticides were further tested for horizontal transmission activities among the nestmates (exposed to unexposed termites) by using recommended concentration by the manufacturers. Mortalities of unexposed termites varied with different active ingredients, donor exposure duration and donor : recipient ratio. Increased exposure duration and mixing ratio significantly caused a greater effect to the test insects.

CHAPTER ONE

GENERAL INTRODUCTION

Termites, known as “white ants” in the tropics (Weesner 1987, Pearce 1997) from the order Isoptera are wood structure destructor in both agriculture and urban areas (Robinson 1996). Most of the termite species that live in urban areas are either native species or introduced from other region thus becoming cosmopolitan pest (Constantino and Dianese 2001). There are 2700 species of termites identified and classified into 7 families, but only 80 species are categorized as structural and building pests (Edward and Mill 1986, Chung and Lee 1999, Lee and Chung 2003). However, only 17 out of 30 *Coptotermes* sp. are categorized as pests (Edward and Mill 1986, Su *et al.* 2003).

The global damage caused by termites was estimated at US$11 billion in the United States (Su 2002b) and US$ 22 billion to US$40 billion worldwide (Wiseman and Eggleton 1994, Su 2002a). In Malaysia, termite-related pest control efforts accounted for 50 % of total business turnover and was estimated at RM40 million annually (Chung and Lee 1999, Lee 2002a, 2002b, Lee and Chung 2003).

Termite control is generally divided into pre-construction treatment (both chemical and non-chemical method) and post-construction treatment (Chung and Lee 1999, Lee and Chung 2003) which consist of soil treatment, dusting, trenching and baiting.

The term ‘termiticide’ refers to insecticide (chemical) that kills termites. Soil termiticide treatment has been the conventional technique for control of subterranean termites for nearly five decades (Ibrahim et al*.* 2003). The main objective of soil termiticide application is to create a chemical barrier for exclusion of soil-borne subterranean termites from structures (Su et al. 1997b, Miller 2002, Ibrahim et al. 2003, Jones 2003). Chlordane and heptachlor (cyclodiene) have been used for this purpose since 1952 while the organophosphate, chlorpyrifos became available in 1980 (Su and Scheffrahn 1990a). However, the heavy use of cyclodienes continued until their withdrawal in 1987 (Su and Scheffrahn 1990a).

More efforts were put into searching for better termiticide candidates following rising of public concerns. Pyrethroids and organophosphates had been marketed as repellent termiticides after the usage of chlordane was banned in many parts of the world. Repellency is a chemical attribute of the substance and it may occur the first time that the chemical is encountered (Thorne and Breisch 2001). With proper application, these chemicals will stop termites from entering the protected structures. However, the effectiveness of the soil termiticide is very much dependent on soil properties such as soil type, soil pH, clay content, particle size, organic matters, soil compactness and moisture condition (Mampe 1990, Forschler and Townsend 1996, Gold et al. 1996, Robinson 1996, Baskaran et al. 1999, Hu 2005).

Newer termiticide candidates focus on the non repellent properties. These compounds will not be detected by the termites. Termites will not be excluded from the treated area, but instead be killed. It was believed that these non repellent termiticides will have a delayed mode of action (Shelton and Grace 2003), where termites will not be able to associate the death of their nestmates with the chemicals. Hence more termites will come into contact with the treated substrate and get killed. Many of the marketed non repellent termiticides also claimed that they have the ability to transfer the lethal chemical from contaminated nestmates to other healthy nestmates.

Understanding termite behaviour is important in determining the effectiveness of a termiticide. The possibility of toxic transfer among termites also needs to be verified, especially when recommended concentration of termiticides may be too high and actually kills termites before they make contact with other nestmates.

Therefore, the objectives of this study are:

1. To study the tunneling behaviour of subterranean termites from the genus *Coptotermes* (Wasmann), i.e. *Coptotemes curvignathus* Holmgren, *C. gestroi* (Wasmann) and *C. kalshoveni* Kemner.
2. To determine the contact toxicity of six selected termiticides (using technical grade termiticides) in *C. gestroi* via topical application.
3. To study the laboratory performance of seven different termiticide formulations against *C. gestroi* using two different experimental approaches.
4. Finally, to study the possibilities of horizontal transmission of the termiticides from the chemically – treated nest mates (donor) to healthy nest mates (recipient) of *C. gestroi* at three exposure durations and five donor: recipient ratios.

CHAPTER TWO

LITERATURE REVIEW

2.1 Termites in general

Termites are believed to be the most successful social insects living in the planet as they have a relatively long lifespan and utilize cellulose, the most widely found compound in this world (Robinson 1996). They are the most important pest causing damage to wooden constructions and other wood products in most of tropical and subtropical regions of the world (Robinson 1996, Sornnuwat 1996, Kuriachan and Gold 1998). Approximately 2200 – 2700 species of termites are identified under the order Isoptera, which falls within 7 families and 82 genera (Harris 1971, Edward and Mill 1986, Pearce 1997, Lee and Chung 2003). In Peninsular Malaysia, Tho (1992) had classified a total of 175 termite species into 42 genera.

Generally, termites can be classified into three groups based on their habitat: the drywood termites, dampwood termites and subterranean termites. Drywood termites are usually found to infest structures above the soil surface and do not require high levels of moisture. They utilize wood at different locations. They can even be found infesting wood on the 10th and 15th floors of commercial buildings (Robinson 1996). The infestation is normally unnoticed because drywood termites do not construct mud tubes and they have a relatively small colony. However, infested wood may show sign of blistering and small piles of faecal pellets once the colony has been established for years (Robinson 1996).

Dampwood termites usually infest wood that has contact with the soil or wood with relatively high moisture content. This group of termite is not found in Malaysia.

Subterranean termites establish large colonies in soil or above ground that are connected to the soil. These are the primary group of termites in tropical climates. Some species from this group are also successful in temperate climates. Subterranean termite damages are easily distinguished through the mud tube they construct. They cause considerable damages in buildings and structures in the urban area. The most destructive species in South East Asia are from the genus *Coptotermes* (Kirton et al. 2000, Kirton and Wong 2001, Lee 2002a, 2002b, Lee and Chung 2003).

2.2 Termites as beneficial insects

Unlike what people always have in their mind, not many termite species are pest on living trees. They feed on dead vegetation, thus helping to recycle nutrients in the natural environment (Chey 1996). Hopkins (1966) reported that wood decaying rate in the forest surface was termite activities-dependent. A study carried out in Pasoh Forest Reserve (Negeri Sembilan, Malaysia) showed that termites are capable of removing 38.8 kg of leaf litter per hectare weekly (Abe and Matsumoto 1979a).

Many studies on distribution and abundance of termites in both primary and secondary forest had been done to understand the role of termites in the ecosystem (Matsumoto 1976, Abe and Matsumoto 1979b, Eggleton et al. 1995).

Termites make use of soil in building their nest (mound). Macrotermitidae, the fungus-growing termites are the predominant termites in both tropical and subtropical ecosystem. Their mounds show a clear impact on the ecology as they affect the topography of that area (Harris 1971). Besides that, modification to the soil by termites will also enrich it with nutrients, thus providing food sources to other organisms (Nutting and Haverty 1987). Such modifications also change the soil porosity, and compaction when termites tunnel (Whitford 1996).

Termites also play a role in reducing soil erosion by replacing top soil level with those from the lower level (Whitford 1996).

2.3 Economic importance of termites

The pest status of termite is based on the damages caused by the termites to buildings and forestry. Termites are found to be attacking sugarcanes, cottons and nuts (Peters et al. 1996). Plants that are under pressure, such as under disease attack or water retention are more susceptible to termite attacks (Harris 1971). Apart from causing damages to the root and foliate, termites, especially those from the subfamily Macrotermitinae (*Odontotermes* spp. and *Macrotermes* spp.) also attack the base of trees that is close to the soil (Pearce 1997).

Coptotermes gestroi is the most economically important species in South East Asia (Su et al. 1997a, Kirton and Brown 2003, Lee et al. 2003a, Kirton 2005, Kirton and Azmi 2005). In Peninsular Malaysia, 85 % of buildings infested by termites in urban area were caused by *C. gestroi* (Kirton and Azmi 2005). While in Thailand, 90 % of termite infestations in urban area were also caused by *C. gestroi* (Sornnuwat et al. 1996c). Although this termite species causes less damages in rural or suburban areas, it is still considered as an important termites species in these areas (Sornnuwat et al. 1996c, Kirton and Azmi 2005). Human activities has spread this species to countries beyond its native range, such as United States, Brazil, Madagascar, Mauritius and West Indies (Scheffrahn et al. 1994, Su et al. 1997a, Scheffrahn and Su 2005, Woods 2005, Jenkins et al. 2007). It is suspected that this termite species was transported to other locations via dispersal flights from shipboard infestations (Su et al. 1997a, Scheffrahn and Su 2005), private, commercial, governmental or military maritime transport of infested goods or containers (Scheffrahn et al. 2004, Jenkins et al. 2007)

Another *Coptotermes* species, *Coptotermes. formosanus* Shiraki is the most serious structural pest in Hawaii (Lai et al. 1983), United States (Su and Scheffrahn 1990b), Japan, Taiwan (Su and Hsu 2003) and China. It attacks living plants and finished products or almost any material that contains cellulose (xylophagous) (Lai et al. 1983).

2.4 Basic biology of termites with emphasis on *Coptotermes* spp.

2.4.1 Identifying characters

Most of the termite identifications are done based on soldier morphology. *Coptotermes* is easily distinguished from any other termite genus. It has the soldier caste with a pear-shaped head, armed with long saber-shaped mandibles. The soldiers possess a frontal gland which is placed dorsally and towards the anterior part of their head. The frontal gland contains a milky sticky fluid, which is secreted for defence purposes. This fluid gives the soldier its white coloration (Thapa 1981, Tho and Kirton 1990, Tho 1992, Chey 1996, Woods 2005). Besides having a white coloured body, the colour of the head (of the soldier) may range from yellow to orange (Thapa 1981, Tho 1992).

Soldiers of *C. gestroi* have a postmentum at least as wide at the waist as it is at the apex. It has a pair of more slender and slightly more incurved mandibles. *C. gestroi* possesses a distinct pair of pale, crescent shaped spots just antero-dorsal of the ocelli (Kirton and Brown 2003). This species has a maximum head width of 1.34 – 1.53 mm and maximum height of 0.58 – 0.68 mm.

Coptotermes curvignathus is relatively bigger in size compared to other *Coptotermes* species found in Malaysia (Tho 1992). Its head width ranges from 1.28 – 1.57 mm and the head height ranges from 1.51 – 1.85 mm.

Coptotermes kalshoveni is generally a smaller species with head width measuring 0.80 – 1.02 mm and head height measuring 1.02 – 1.20 mm.

2.4.2 Life cycle

Unlike other social insects, termites undergo incomplete metamorphosis. Their life cycle begins with a nuptial flight of the alates in the evening (O'Toole 2003). In Florida and West Indies, flights of *C. gestroi* occurred at night from January to March (Scheffrahn and Su 2005), The flight has a relatively short distance and will normally reach a maximum of 400 m (Stuart 1969). Its flight direction depends very much on the wind flow. Swarming is generally synchronized over wide areas, but it also depends on environmental conditions or seasonal phenomenon such as wind, rain and soil moisture (Nutting 1969, Robinson 1996). Ferraz and Cancello (2001) found that the peak swarming period for *C. gestroi* (formerly *C. havilandi*)occurs from August to October (end of winter and early spring) in Brazil. They also noticed that sporadic swarming occurs almost throughout the year. Isolated colonies of *Reticulitermes* also shows a sporadic swarming pattern (Robinson 1996). Peak flying season of *C. gestroi* is correlated with the beginning of the rainy season (Ferraz and Cancello 2001). Flights of *C. formosanus* happens on warm, still nights before sunset (Robinson 1996). Certain termite species have flights during the day. *R. hesperus* Banks in California swarms between 1000 h and 1500 h on warm fall days, following a light rain (Robinson 1996). In cooler area, such as Ontario, Canada, swarming of *R. flavipes* (Kollar) is limited to indoors (Robinson 1996). Drywood termites normally swarm after sunset or late in the evening and extend into evening. *Incisitermes snyderi* and *Marginitermes hubbardi* will swarm in May and June during the early evening but after dark (Robinson 1996).

After the flight, alates will drop to the earth while pairing occurs. The male will follow behind the female (tandem behaviour) and both will shed their wings (Ross 1956, Stuart 1969). The pair will then look for moist or decaying wood. They will burrow into the cracks between the wood and make a small hollow and seal the hollow. Mating will take place in the small chamber (Pearce 1997, Chung and Lee 1999, Lee and Chung 2003, O'Toole 2003). Eggs will be produced in 5 – 10 days after mating and they will hatch within 21 – 39 days (O'Toole 2003). A *Coptotermes* queen can lay about 100 eggs per day throughout its life (Pearce 1997). Larvae will then hatch from the eggs.

These larvae (or nymphs) are capable of developing to become members of any caste.

2.4.3 Colony structure

A termite colony consists of winged and wingless reproductives, sterile workers, soldiers, and nymphs. The primary reproductives are the queen and the king (the royal pair). They are highly sclerotized and pigmented. The main role of winged primary reproductives is egg production and dispersal by colonizing flights. In most termite colonies, there is only a pair of primary reproductives. However, when the royal pair die, they will be replaced by numerous supplementary reproductives (Robinson 1996). The supplementary reproductives are either with or without small wingpads and are slightly larger and more pigmented than workers.

Workers and soldiers are the sterile caste that lack sclerotization (Weesner 1987). They are wingless and lack compound eyes. They do not even have ocelli (Ross 1956, Thorne 1996, Pearce 1997). Workers are the majority caste in a termite colony (Robinson 1996, Pearce 1997). These non-reproductive individuals will forage for food, chew wood, papers and other cellulose–based materials, carry the food to their nest and feed other caste members (Thorne 1996). They are also responsible to repair the nest and construct mud tubes.

Soldiers normally have large mandibles or other modifications to assist them in defending the colony against their natural enemies (Ross 1956, Borror and White 1970, Harris 1971, Pearce 1997). They consist of 10 – 20 % of the total colony members but the caste proportion varies with time (Haverty and Nutting 1975, Waller and LaFage 1987b) and they are sterile females (Borror and White 1970). Soldiers are not capable of feeding on their own, but depend on workers to feed them via trophallaxis.

Alates are the minorities in a colony (Ross 1956) and will be produced by colonies aged 3 – 4 years old (O'Toole 2003). The winged male and female alates are potential founders of new colonies (Mampe 1990, Robinson 1996, Pearce 1997, Lee and Robinson 2001). Alates are normally darker in colour.

Caste differentiation in termites are not genetically linked (Robinson 1996). The main factors in caste differentiation are the pheromones and hormones produced by the reproductives and soldiers. It is believed that both reproductives and soldiers produce pheromones that will inhibit the development of like forms in the colony (Mampe 1990, Robinson 1996). The chemicals are transmitted to the nymphs through mutual feeding and social grooming (Mampe 1990, Robinson 1996).

2.4.4 Nesting habits

The nests of subterranean termites may be found in the soil under buildings. Termites move up or down in the soil to meet changing moisture and humidity conditions (Cowie et al. 1989).

It was proven that moisture content does not affect termites tunneling activity when they first emerged, but when termites move further from their nesting site, they have a tendency to look for areas with higher moisture content (Su and Puche 2003).

Coptotermes gestroi is the pest of pine in the natural habitat (Tho and Kirton 1990, Tho 1992). This destructive termite species is frequently found infesting wooden structures in houses, cargo on-board ships and sailing vessels (Kirton and Brown 2003, Jenkins et al. 2007).

Coptotermes curvignathus is the primary pest of agricultural and forestry tree crops (Tho and Kirton 1990). They are associated with inland areas, causing deaths of living young and mature trees (Tho and Kirton 1990, Tho 1992, Chey 1996). This species is also a pest in rubber tree in South East Asia and Indo-China (Rao 1974). This is a polyphagous termite species that feed on *Hevea brasilensis*, *Shorea* spp., *Pinus* spp., *Albizia* spp., *Araucaria* spp., *Tectona grandis*, *Acacia mangium* and *Eucalyptus* spp. (Cowie et al. 1989, Chey 1996). It is an important termite pest when highly susceptible pine was introduced for plantation in Malaysia (Tho and Kirton 1990).

Coptotermes kalshoveni is found in lowland plantations, infesting dead tree stumps or fallen logs and mangrove swamps (Tho 1992). They are more commonly found in coastal areas and will infest buildings in open urban centres and housing estates (Tho and Kirton 1990).

2.4.5 Food preference, feeding behaviour and foraging behaviour

Ngee et al. (2004) had studied laboratory preference of 15 Malaysian wood species and 14 Japanese wood species against 4 Malaysian subterranean termites, including *C. gestroi* and *C. curvignathus*. In their study, they found that rubber, jelutong and terentang were the most preferred wood species.

Termite feeding activity is influenced by wood type, wood extractives (Smythe et al. 1965, Smythe and Carter 1970, Jones et al. 1983, Waller 1988, Kard and Mallette 1997, Cornelius and Lax 2005), seasonal changes (Allen et al. 1980, Waller and LaFage 1987b), physical characteristics of wood (Sen-Sarma 1963 in Smythe and Carter 1970), fungal decay (Smythe et al. 1965, Delaplane 1991, Getty and Haverty 1998, Cornelius et al. 2002, Cornelius et al. 2004), wood hardness or differences between sapwood or heartwood (Kard and Mallette 1997), wood size (Evans et al. 2005), moisture content (Delaplane and LaFage 1989, Delaplane 1991, Nakayama et al. 2004, 2005, Indrayani et al. 2007), food availability (Reinhard et al. 1997, Hedlund and Henderson 1999, Arab and Costa-Leonardo 2005), history of wood damage (Delaplane 1991), termite colony origin (Su and LaFage 1987a), termite caste composition (Smythe et al. 1965, Su and LaFage 1987a), nutritional status of worker (Su and LaFage 1987b), temperature (Smythe et al. 1965, Smythe and Williams 1972, Nakayama et al. 2004, Arab and Costa-Leonardo 2005, Indrayani et al. 2007) and soldier proportion (Su and LaFage 1987a).

Termites' foraging populations can be estimated using multiple mark-release-recapture method. Colonies of *C. gestroi* in Malaysia are estimated to have 3.1 x 10^5 foragers (Lee et al. 1998, Lee 2002a). In Thailand, foraging population of the same termite species is estimated to range from 1.13 – 2.75 x 10^6 per colony (Sornnuwat et al. 1996a) with the maximum foraging distance of 5 m (Sornnuwat et al. 1996b) while *C. formosanus* is estimated to have about 1 - 7 million termites and their foraging territory ranged about 1300 – 3500 m^2 depending on the colony's age (King and Spink 1969, Su and

Scheffrahn 1988, Robinson 1996). In Australia, *C. acinaciformis* (Froggatt) is estimated to contain 0.4 – 19.1 million individuals (Evans et al. 1999).

Eastern subterranean termites, *R. flavipes* has a smaller foraging population that consists of 0.2 – 0.9 million termites with foraging territory of 18 – 2361 m^2 (Grace et al. 1989, Grace 1990, Su et al. 1993, Robinson 1996). It has been recorded that *R. flavipes* can forage for a maximum distance of 7 – 79 m (Grace et al. 1989, Grace 1990, Su et al. 1993, Robinson 1996). Another *Reticulitermes* termite, *R. speratus* (Kolbe) is found to have foraging territories that ranged from 6.0 – 56. 6 m^2 per colony of 109400 – 466400 individual (Tsunoda et al. 1999). Western subterranean termite, *R. hesperus* Banks has a smaller foraging group compared to *R. flavipes* with only 78930 – 830581 foragers (Haagsma and Rust 1995).

Studies showed that different termite species showed different tunneling geometry (Robson et al. 1995, Campora and Grace 2001, Cornelius and Osbrink 2001, Su 2001). Termites have an efficient food searching system, by adjusting their exploration activities (Hedlund and Henderson 1999). They will minimize their total tunnel length to one location in a search area (Hedlund and Henderson 1999). Once they find a suitable food source, they will follow the direct foraging route to reduce the amount of energy used (Reinhard et al. 1997, Hedlund and Henderson 1999, Campora and Grace 2001, Cornelius and Osbrink 2001, Puche and Su 2001, Swoboda and Miller 2004, Arab and Costa-Leonardo 2005). The recruitment is food amount or quality dependent (Waller and LaFage 1987a, Waller 1988, Lenz 1994, Cornelius and Osbrink 2001, Su 2005a). Mackay et al. (1985) noticed that *Gnathamitermes tubiformans* (Buckley) attacked surface of tissue with high nitrogen content which provides higher energy to the termites. Jander and Daumer (1974) reported that termites follow pheromone trail blindly. The traffic organization provides cues to lead disoriented termites to the correct path (Jander and Daumer 1974).

Termites make branches while tunneling. This is a better tunneling strategy where it lowers the energy expenditure (King and Spink 1969, Robson et al. 1995, Reinhard et al. 1997, Hedlund and Henderson 1999, Campora and Grace 2001) while increases the chances to locate new food source. By connecting the tunnels, termites reduce the path to their foraging sites (Hedlund and Henderson 1999). Galleries are combined when termites had locate major or new food source (King and Spink 1969, Hedlund and Henderson 1999, Campora and Grace 2001, Puche and Su 2001, Swoboda and Miller 2004) and more foragers are recruited to the food source (Ettershank et al. 1980, Campora and Grace 2001, Puche and Su 2001). Primary tunnels are normally longer compared to secondary or tertiary tunnels, as this increase the probability of locating food (Hedlund and Henderson 1999).

Termites will also try to save their energy by not searching areas situated far from their foraging site or their nest, especially when they already have access to large food source (Hedlund and Henderson 1999). Puche and Su (2001) also reported that termites are unable to detect the presence of wood in sand over distance. Termites are found to be more readily detecting potential food source on the soil surface than those buried in soil (Ettershank et al. 1980). Reports also showed that when the tunneling system is larger or longer, the strength of the termite cohort will diminish thus less tunnels are formed as the distance from the nest increases (Puche and Su 2001).

2.5 Control of *Coptotermes* spp.

Preventing subterranean termites from infesting a structure is an important management strategy (Yates 2003). Subterranean control is different from other pest control approach where other pest control aim to lower the pest population to an economic level while termite control is more to protecting a specific property (Spear 1970).

2.5.1 Conventional methods

Conventional termite control involves creating a chemical barrier in the soil (Spear 1970, Sajap et al. 2002) excluding termites from the protected structure (Randall and Doody 1934). The major strategies in the management of subterranean termite involve the prevention by soil treatment and remedial control of active infestations by injecting insecticides directly into infestations (Su et al. 1982). This method has dominated the termite control market since the past 50 years (Su et al. 1997b, Miller 2002, Appel 2003, Bläske et al. 2003, Ibrahim et al. 2003, Jones 2003).

Chemical treatment can be divided into pre-construction and post-construction treatment. In both methods, commercial termiticides are formulated whereby the active ingredient will bind to the organic matter or clay in the soil to form a long lasting effect (Robinson 1996).

Pre-construction application will be performed at the time of construction as a preventive effort. On the other hand, post-construction treatment includes injecting liquid termiticides into the inner and outer perimeter of buildings through drilled holes in the concrete.

Trenching involves removing the soil around the building to form a shallow trench. Liquid termiticide will be applied into the trench. The soil will also be treated before being poured back into the trench (Lee and Robinson 2001).

Aqueous termiticide foams with high expansion ratio (Robinson and Barlow 1996) had been introduced in the 1990s (Thomas et al. 1993). The expansion and breakdown properties of the foam makes it a useful carrier for termiticide with the aid of foam-making machines, application tools and new termiticide formulations (Barlow and Robinson 1993, Robinson and Barlow 1993, Thomas et al. 1993). It is believed that foam can be evenly distributed under the slab, providing a continuous chemical barrier (Robinson and Barlow 1993).

Besides applying termiticides to the soil, a second approach will be by laying down a layer of termiticide impregnated plastic prior to construction (O'Toole 2003). The chemical will be gradually released into the soil, forming a protection layer.

Localized chemical treatment is common where insecticide is applied directly onto the infested wooden structures. It can kill termites present the moment chemical is applied while preventing them from spreading (O'Toole 2003). In this method, holes will be drilled at the infested wood to allow chemical injection.

All conventional methods are however only able to give limited protection. This is due to the life span of the chemical used, and the application has to be uniform to avoid gaps between treatments. Termiticides will degrade with time, thus allowing termites to tunnel through the gaps and reach human properties. Re-treatment is necessary to provide proper control.

Termguard Reticulation Systems (Termguard Pty. Ltd., Australia) provides a new termite management concept by delivering underslab and perimeter protection via a continuous horizontal and vertical termite management treatment barrier. It is a piping system laid underneath the building with joints to deliver liquid termiticide at certain time interval to create the continuous chemical barrier. This system claimed that it is able to provide a most cost effective termite management program with its "periodically replenishable system". Nevertheless, no literature has proven the effectiveness of this system against subterranean termite infestations in Malaysia.

2.5.1.1 Repellent termiticides

In general, termiticides applied into the soil are repellent and lethal to termites at low concentrations (0.2 – 1 %) (Robinson 1996).

Currently, pyrethroids are the main candidates marketed for repellent termiticide. Synthetic pyrethroids were conditionally registered beginning in 1984 for use on cotton and later for use on other major crops including corn, soybeans, and sugarcane. Pyrethroids are highly lipophilic and in aquatic environments tend to adsorb strongly into sediments. Pyrethroids repel termites from the treatment area. An example of pyrethroid termiticide is bifenthrin.

Bifenthrin (2-methylbiphenyl-3-ylmethyl (1*RS*,3*RS*)-3-[(*Z*)-2-chloro-3,3,3-trifluoroprop-1-enyl]-2,2-dimethylcyclopropanecarboxylate) (Figure 2.1) is a third-generation synthetic pyrethroid insecticide, characterized by strong environmental persistence and high insecticidal activity. In Australia it has also been registered as an acaricide on ornamentals. Bifenthrin affects the central and peripheral nervous system of insects, producing sporadic neurotransmission, followed by paralysis and death (Miller and Adams 1982, Abbassy et al. 1983, Matsumura 1985, Miller and Salgado 1985 , Tippe 1987, Soeprono and Rust 2004b). It is effective as a stomach or contact insecticide that affects the nervous system of vertebrates and invertebrates. Bifenthrin acts on the voltage sensitive sodium channels at the nerve cell endings to depolarize the pre-synaptic terminals (Tippe 1987, Casida and Quistad 2004). It has also been shown to affect cellular ATP-ase production. Bifenthrin is highly toxic to fish and aquatic organisms (Siegfried 1993). However, this insecticide is relatively benign to mammals and birds, but its high bio-concentration factor can affect higher-level predators.

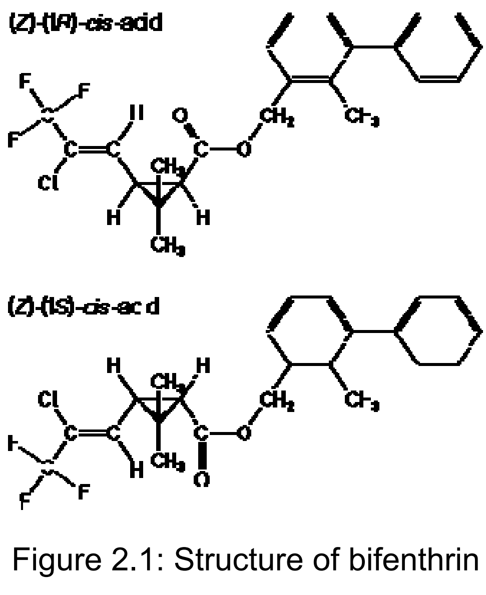

Figure 2.1: Structure of bifenthrin

Chlorpyrifos (*O,O*-diethyl *O*-3,5,6-trichloro-2-pyridyl phosphorothioate) (Figure 2.2) is a broad spectrum insecticide introduced in 1965 (Hayes and Laws 1990). Besides registered for termite control, this compound also has been used for controlling a variety of insects, including cutworms, corn rootworms, cockroaches, grubs, flea beetles, flies, fire ants, and lice (EPA 1986). It acts on pests primarily as a contact poison, with some action as a stomach poison. Chlorpyrifos acts by interfering with the activities of cholinesterase (Ohkawa 1982, Matsumura 1985, Casida and Quistad 2004), an enzyme that is essential for the proper working of the nervous systems of both humans and insects.

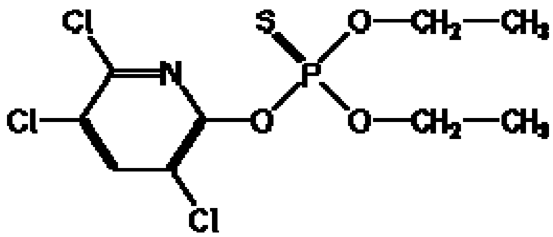

Figure 2.2: Structure of chlorpyrifos

2.5.1.2 Non repellent termiticides

Non repellent termiticides have slowly gained their popularity. Remedial control has relied upon chemical spot treatment of soil and/or infested wooden members. It is important to use non repellent termiticides as it will not prevent termites from foraging into the treated areas (Yates 2003). These chemicals will prevent termite invasion by lethal contact (Su and Scheffrahn 2000). More and more novel termiticides are focusing on the non repellent character.

In Malaysia, two relatively newer non repellent termiticides are available in the market, namely Premise® (imidacloprid) and Termidor® (Agenda® for Malaysia and Singapore) (fipronil) (both manufactured by Bayer Environmental Science).

Imidacloprid ((*EZ*)-1-(6-chloro-3-pyridylmethyl)-*N*-nitroimidazolidin-2-ylideneamine) (Figure 2.3) is a neonicotinoid compound synthesized from the heterocyclic nitromethylenes (Tharp et al. 2000), possessing lethal effects on *R. flavipes* in laboratory test (Ramakrishnan et al. 2000). Gahlhoff and Koehler (2001) found that sublethal doses of imidacloprid reduced grooming behaviour of termites, permitting the soilborne mycopathogen, *Beauveria bassiana* to affect and kill the termites in 7 days. Imidacloprid acts on the insect nervous system by binding to the acetylcholine binding sites (nicotinergic receptor) (Bai et al. 1991, Liu and Casida 1993, Casida and Quistad 2004). This mode of action prevents transmission of information at the binding sites (Schroeder and Flattum 1984, Gahlhoff and Koehler 2001). This blockage leads to the accumulation of acetylcholine, resulting in titanic muscle contractions (Tharp et al. 2000, Thorne and Breisch 2001), a lasting impairment of the nervous system. It is effective on contact and via stomach action (Schroeder and Flattum 1984). The imidacloprid contaminated termite will become sluggish, with limited grooming and tunneling activities (Gahlhoff and Koehler 2001).

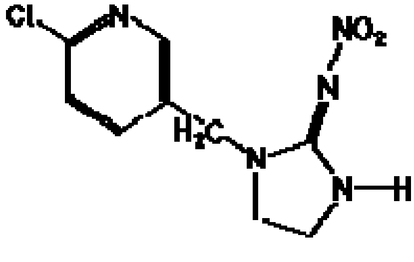

Figure 2.3: Structure of imidacloprid

Fipronil (5-amino-1-[2,6-dichloro-4-(trifluoromethyl)phenyl]-4-(trifluoromethylsulfinyl)pyrazole-3-carbonitrile) (Figure 2.4) is a member of the phenyl pyrazole class of pesticides, which are principally chemicals with a herbicidal effect (Klis et al. 1991, Tingle et al. 2000). It is developed by Rhône-Poulenc between 1985-87 (Tingle et al. 2000, Ibrahim et al. 2003) and placed on the market in 1993 (Connelly 2001). This compound interferes with the passage of chloride ions through the gamma-aminobutyric acid (GABA) regulated chloride channel. This channel normally blocks reactions in some nerves, preventing excessive stimulation of the central nervous system (Cole et al. 1993, Tingle et al. 2000, Soeprono and Rust 2004b, Hu 2005). Fipronil will block the channel from performing its normal inhibitory action (Casida and Quistad 2004). Thus, when fipronil binds to the channel, the nerve is over stimulated, and death eventually occurs. Fipronil works as both stomach and contact poison. Fipronil can be degraded by sunlight to produce a variety of metabolites, one of which [fipronil-desulfinyl (MB 46514)] is extremely stable and is more toxic than the parent compound (Tingle et al. 2000).

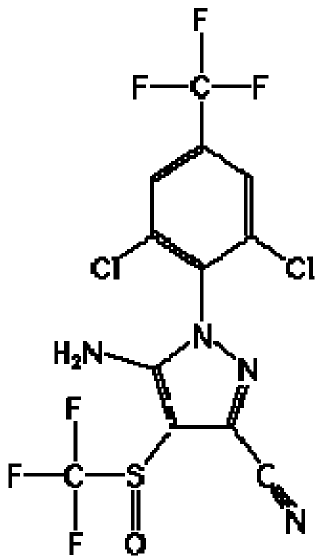

Figure 2.4: Structure of fipronil

Novel non repellent termiticides includes chlorfenapyr, indoxacarb and chlorantraniliprole.

Chlorfenapyr (4-bromo-2-(4-chlorophenyl)-1-ethoxymethyl-5-trifluoromethyl-1*H*-pyrrole-3-carbonitrile) (Figure 2.5) is classified under the pyrrole group that can disrupt energy production. It must be converted to an active metabolite in the midgut of the insects before it can cause this effect (proinsecticide) (Hunt and Treacy 1998, Albers et al. 2002, Brown 2002, Rand 2004, Rust and Saran 2006, Shelton et al. 2006). Once formed, the metabolite uncouples oxidative phosphorylation by disrupting the H proton gradient (Albers et al. 2002, Radcliffe 2002, Rand 2004, Rust and Saran 2006, Shelton et al. 2006) across mitochondrial membranes, thus affecting the ability of cells to produce ATP from ADP, which eventually results in cell death (death of the organism). Chlorfenapyr is lipophilic, binds strongly to soil particles and degrades slowly in soil (Anonymous 2000, Albers et al. 2002).

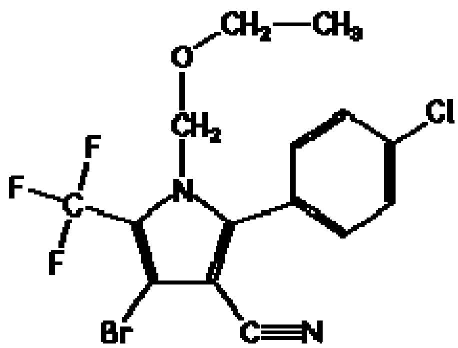

Figure 2.5: Structure of chlorfenapyr

Chlorantraniliprole (3-bromo-4′-chloro-1-(3-chloro-2-pyridyl)-2′-methyl-6′-(methylcarbamoyl)pyrazole-5-carboxanilide) (Figure 2.6) is a new insecticide under the anthraniamide class of chemical. It targets the ryanodine receptor in insects (Portillo et al. 2006, Sanderson 2006), causing insect's muscle to contract, leading to paralysis and ultimately death of the insect. It has been registered under the trade name of Rynaxypyr™ to control *Bemisia tabaci* biotype B and to prevent the transmission of the begomovirus tomato yellow leaf curl virus (TYLCV) (Schuster et al. 2006). This insecticide has also been commercialized under the trade name of Coragen™ SC as a broad spectrum for controlling lepidopteran crop pests (Coates et al. 2005, Portillo et al. 2006). This chemical has proven its efficacy in managing coleopterans (Palmer 2006), dipterans and homopterans via ingestion.

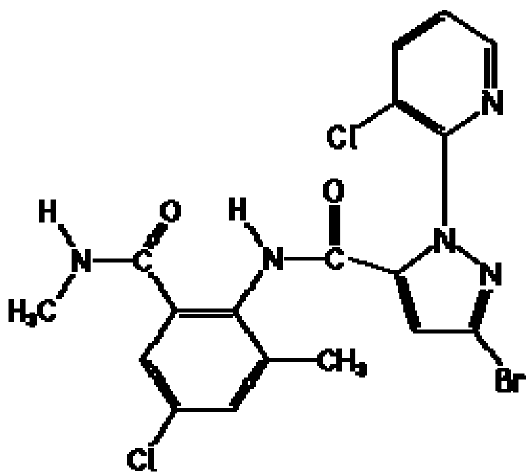

Figure 2.6: Structure of chlorantraniliprole

Indoxacarb (methyl (*S*)-*N*-[7-chloro-2,3,4a,5-tetrahydro-4a-(methoxycarbonyl)indeno[1,2-*e*][1,3,4]oxadiazin-2-ylcarbonyl]-4′-(trifluoromethoxy)carbanilate) (Figure 2.7) from the oxadiazine class of insecticide that has a high insecticidal activity but low non-target organism toxicity (Hu 2005). It acts on sodium channels, neuronal nicotinic acetylcholine receptors and GABA receptors. In insects, indoxacarb is metabolically