

EASTERN SUBTERRANEAN TERMITE (ISOPTERA: *Reticulitermes flavipes* (Kollar))
ENTERING INTO BUILDINGS AND EFFECTS ON THERMAL PROPERTIES OF
BUILDING MATERIALS

By

CYNTHIA LINTON TUCKER

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Windswake Farm

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TABLE OF CONTENTS

	<u>page</u>
ACKNOWLEDGMENTS	4
LIST OF TABLES	8
LIST OF FIGURES	9
ABSTRACT	11
CHAPTER	
1 INTRODUCTION	13
2 LITERATURE REVIEW	16
Evolution of Termites	16
Important Subterranean Termites in the United States	17
Termite Caste System	18
Process of Tunnel Formation	20
Feeding Habits	22
Building Construction and Its Relevance to Termite Exploitation	23
Building Codes	23
Building code history	24
USA code history:	24
Concrete Construction Standards	25
Wood Framing Standards	27
Termite Control Options	28
Physical Barriers	30
Heat Transfer Concepts	31
Insulation	33
Thermal Transmission	33
3 ABILITY OF EASTERN SUBTERRANEAN TERMITES TO MOVE THROUGH CRACKS	35
Introduction	35
Materials and Methods	36
Termites	36
Effect of Crack Width on Penetration and Consumption by Caste	37
Effect of Termite Head Capsule Dimension on Penetration Through Cracks	38
Data Analysis	38
Results	39
Effect of Crack Width on Penetration and Consumption by Caste	39
Effect Termite Head Capsule Dimension on Penetration Through Cracks	40
Discussion	41

4	METHODS TO PREVENT PENETRATION OF CONCRETE-PIPE INTERFACES BY THE EASTERN SUBTERRANEAN TERMITE.....	52
	Introduction.....	52
	Materials and Methods	54
	Termites.....	54
	Pipe Sleeve Experiment.....	54
	Pipe Sleeve Treatments.....	54
	Pipe Sleeve Experimental Arena.....	55
	Termite Blocker Experiment.....	56
	Treatments.....	56
	Termite Blocker Experimental Arena.....	57
	Data Analysis.....	58
	Results.....	59
	Pipe Sleeve Experiment.....	59
	Termite Blocker Experiment.....	61
	Discussion.....	62
5	DEVELOPMENT OF A METHOD TO EVALUATE THE EFFECTS OF EASTERN SUBTERRANEAN TERMITE DAMAGE TO THE THERMAL PROPERTIES OF BUILDING CONSTRUCTION MATERIALS	72
	Introduction.....	72
	Materials and Methods	73
	Termites.....	73
	Termite Damage to Construction Materials.....	74
	Thermal Imaging.....	75
	Data Analysis.....	75
	Results.....	76
	2x4s.....	76
	Plywood.....	77
	Rigid Foam Board Insulation.....	78
	Discussion.....	79
6	EFFECTS OF EASTERN SUBTERRANEAN TERMITE DAMAGE ON THE THERMAL PROPERTIES OF COMMON BUILDING MATERIALS.....	85
	Introduction.....	85
	Materials and Methods	87
	Termites.....	87
	Test Arena.....	87
	Thermal Imaging Setup.....	89
	Data Analysis.....	89
	Results.....	90

Structural Lumber.....	91
Wood Based Siding.....	92
Foam Insulation.....	95
Discussion.....	96
7 CONCLUSION.....	117
LIST OF REFERENCES.....	119
BIOGRAPHICAL SKETCH.....	130

LIST OF TABLES

<u>Table</u>		<u>page</u>
3-1	Percentage of termite castes located on the bottom of the arena that passed through various crack widths and consumption of filter paper by termites in arena at 5 d.	44
4-1	Effect of pipe sleeve composition and length and termiticide treatment on Mean consumption (g) of cardboard (\pm SE) on top of the concrete slab by termites.	65
5-1	Percent damage and surface temperature increase for building materials heated for 15-min. Damaged materials were exposed to eastern subterranean termites (n=300) for 8 wk.	81
6-1	Mean \pm SE percent termite survivorship, damage (g), percent damage, and percent increase in heat transfer index (HTI) between undamaged and building material damaged by subterranean termites (n=300) and after 8 wk.	101

LIST OF FIGURES

<u>Figure</u>	<u>page</u>
3-1 Termite caste location and consumption test arena.	45
3-2 Head capsule Petri-dish test arena.	46
3-3 Linear regression comparing the maximum soldier head capsule measurements	47
3-4 Linear regression comparing the maximum worker head capsule measurements.....	48
3-5 Soldier head capsule width.	49
3-6 Worker head capsule width.....	50
3-7 Larval head capsule width.	51
4-1 Pipe sleeve experimental arena.....	66
4-2 Termite blocker experimental arena	67
4-3 Typical pipe sleeve experiment arenas at 28 d.	68
4-4 Foam pipe sleeves exposed to eastern subterranean termites for 28 d in termiticide-treated and untreated arenas.....	69
4-5 Polyethylene pipe sleeves exposed to eastern subterranean termites for 28 d in termiticide-treated and untreated arenas.	70
4-6 Mean cardboard consumption (g) (\pm SE) after 8 wk by termites in arenas without termite blocker around copper and CPVC pipes, with or without foam or polyethylene sleeves.	71
5-1 Images of a 2x4 sample after exposure to 300 termites for 8 wk.	82
5-2 Images of a plywood sample after exposure to 300 termites for 8 wk.	83
5-3 Images of a rigid foam insulation sample after exposure to 300 termites for 8 wk.....	84
6-1 Differences in heat transfer index between undamaged materials and materials damaged by subterranean termites after an 8 wk period.....	102
6-2 The 2x4 samples.	103
6-3 Natural log linear regression of 2x4 samples.....	104
6-4 The 2x6 samples.	105

6-5	Natural log linear regression of 2x6 samples.....	106
6-6	The OSB samples.....	107
6-7	Natural log linear regression of OSB samples.....	108
6-8	The T1-11 samples.....	109
6-9	Natural log linear regression of T1-11 samples.....	110
6-10	The 5-ply samples.....	111
6-11	Natural log linear regression of 5-ply samples.....	112
6-12	The EXP samples.....	113
6-13	Natural log linear regression of EXP samples.....	114
6-14	The ISO samples.....	115
6-15	Natural log linear regression of ISO samples.....	116

Abstract of Dissertation Presented to the Graduate School
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Cynthia Linton Tucker

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Reticulitermes flavipes (Kollar), were introduced to the top of an arena with a divider of various crack widths. Termites were not able to pass through cracks $\leq 610 \mu\text{m}$, and feed on the bottom of the arena. The minimum crack width permitting termites to pass was $711 \mu\text{m}$ for workers and larvae or $813 \mu\text{m}$ for soldiers. The percentage of termites passing through a crack increased as crack width increased from 711 to $5000 \mu\text{m}$. For $5000 \mu\text{m}$ cracks that did not restrict access to the bottom filter paper about 74% of the termites passed through and consumed ~ 40 mg filter paper. As crack size decreased to $711 \mu\text{m}$ only 35% of termites passed through, however, consumption of filter paper on the bottom (~ 38 mg) did not significantly decrease. This suggests that any crack $\geq 711 \mu\text{m}$ would not limit termite damage in a structure. Head capsule dimensions (length, width, and depth) were measured for termites passing through various crack widths. As crack width increased, the maximum head capsule dimension of termites that passed through the crack also increased linearly. Depth of head capsule was best correlated with crack width that allowed termites to pass through it.

Termites often use plumbing penetrations of concrete slabs to enter a structure. Polyethylene and foam sleeves used to protect pipes from physical damage were found to protect

termites from residual soil termiticide treatments. When pipe sleeves extended beyond the termiticide treatment, termites utilized the sleeves as a protected route through the termiticide-treated sand. However when pipe sleeves terminated within the termiticide treatment, termites failed to pass through the slab. Impasse™ Termite Blocker installed on pipes prevented termites from passing through the slab at pipe penetrations.

Building construction materials (2x4s, 5-ply plywood, and rigid foam board insulation) were exposed to termites for 8 wk and a method for measuring changes in thermal properties was developed by heating one surface and imaging the temperature on the opposite surface. Termites mainly tunneled into 2x4s penetrating the sample resulting in ~35% increase in surface temperature (damaged vs. undamaged samples) despite a small amount of damage (6.7% consumed). Plywood damaged by termites (3.1% consumed), was the most thermally damaged with a temperature increase of 74% (damaged vs. undamaged samples). Insulation was significantly the most damaged with ~12% of the material removed and a temperature increase of ~27% (damaged vs. undamaged samples).

A heat transfer index was developed to compare thermal properties of termite damaged building construction materials (2x4 and 2x6 pine lumber, 5 ply plywood, T1-11 siding, oriented strandboard, extruded polystyrene, and polyisocyanurate insulation). Termite damaged materials had higher heat transfer indices than undamaged materials. The heat transfer index of damaged 2x4 and 2x6 lumber was 37% higher than damaged 5 ply plywood and T1-11 siding; therefore the siding materials were more thermally resistant. As would be expected the insulation materials had lower heat transfer index values than the wood materials. Termite damaged polyisocyanurate was 68% more conductive than the damaged expanded polystyrene insulation.

CHAPTER 1 INTRODUCTION

One of the most economically significant pest termites in North America is the eastern subterranean termite, *Reticulitermes flavipes* (Kollar). The ability of termites to digest wood and the consequent potential to cause significant structural damage to most types of buildings distinguishes termites from the most of other insect pests. The fact that *R. flavipes* termites live in colonies of considerable size only serves to increase their destructive potential.

Subterranean termites evolved in nature as decomposers of dead wood. This capacity for wood digestion, while very useful in terrestrial ecosystems, is a problem for people who build structures using the same materials that the termites have evolved to feed upon. In geographies like Florida with high termite activity, specific building codes are required to minimize the structure's susceptibility to termite damage. In Florida, the building code also requires a termiticide-preventative treatment be applied to new construction.

Subterranean termites typically enter structures through the foundation. A concrete slab may seem impervious, but there are actually numerous potential routes of entry. One entry is the cracks that inevitably develop as the poured concrete cures and settles. Another entry is where plumbing pipes and other utilities penetrate the slab to provide a structure with water, power, and sewer access. Depending upon the space between the pipe and the concrete slab, as well as the material the pipe is wrapped in, termites may find this space to be an easy point of entry.

The structural damage caused by subterranean termites has been documented extensively over the years. The focus of this documentation has been the structural weakening of load-bearing timbers, causing a building to become unsafe and susceptible to collapse. However, termite damage has other effects that have not been considered. One of these is the change in the thermal properties of a structure. If the walls of a building are riddled with termite galleries, it

stands to reason that heat may travel more easily through damaged walls. Thus, a structure damaged in this way will lose heat more rapidly in a cold environment, or gain heat more rapidly in a hot environment. More energy is required for the heating and air conditioning systems to compensate for the loss of insulating properties. The price of this energy is an added cost of termite damage.

The first objective in this dissertation is to determine the minimum crack size that *R. flavipes* termites can travel through, reviewed in Chapter 3. The next objective concerns the passage of these termites through spaces between water pipes and a concrete slab, covered in Chapter 4. The experiments conducted in this chapter will show the effects of different pipe sleeves on termite travel, as well as the effects of the presence and absence of termite blocker associated with the pipes. Chapter 4 will also investigate the possibility of pipe sleeves providing a safe passage for termites through termiticide-treated soil.

The next objective in this dissertation, in Chapter 5, was to establish a method for determining heat transfer using a hot plate to heat termite damaged and undamaged building materials to document the change in surface temperature of a sample through time with a thermal camera. The objective in Chapter 6 was to determine the differences in the rate of heat transfer between termite damaged and undamaged samples of building materials. Materials will include structural timbers, wood-based siding products, and foam insulation. These experiments will show which materials can sustain more damage from termites before losing their insulating ability, and therefore are best for use in structures located in geographies with high termite activity.

The final objective of this dissertation is to obtain a better understanding of the activities of *R. flavipes* termites within structures. A clearer understanding of their means of entry into

structures will allow for more effective prevention of this entry. Knowledge of the termites' effects on thermal properties will allow a more informed selection of building materials with reduced adverse effects if damaged by termites. By understanding how subterranean termites interact with a structure, we may more effectively protect structures from entry and damage by termites resulting in increased costs to the building occupants.

CHAPTER 2 LITERATURE REVIEW

Evolution of Termites

Termites are believed to be closely related to cockroaches and have evolved from an ancient ancestral cockroach lineage. The most primitive living termite, *Mastotermes darwinensis* (Froggatt), has a similar wing structure to cockroaches and females of this termite species lay their eggs in an ootheca (Snyder 1948). Presently, there is a primitive cockroach, *Cryptocerus punctulatus* (Scudder), which burrows into and consumes decaying wood and has protozoa in its digestive tract similar to those in termites (Guthrie and Tindall 1968). These similarities suggest that the Order Isoptera diverged from the ancient ancestral cockroach lineage ~200 million years ago (Nalepa and Bandi 2000).

All termites are eusocial insects. Subterranean termites are most commonly found within the soil, thriving in an environment of high humidity and darkness. Subterranean termites are also known to invade man-made structures, utilizing the wood within the structures as a food source (Forschler 1999a). As cryptic, subterranean insects, termite workers are blind and possess relatively thin, water-permeable exoskeletons. Like most termites, subterranean termites subsist primarily on cellulosic materials such as wood, roots, and grasses (Waller and LaFage 1987, Tayasu et al. 1997). Worker termites transfer nutrients to immatures, soldiers and reproductives via stomodeal and proctodeal trophallaxis. Subterranean termites typically live in large numbers that can range from 50,000 to several million individuals in a colony (Su et al. 1993). Native subterranean termites consume numerous species of wood including slash pine, loblolly pine, and sugar maple (Smythe and Carter 1970). Termites have endogenous enzymes (Watanabe et al. 1998) and protozoan symbionts in the hindgut (Ohtoko et al. 2000) which allow termites to digest cellulose and hemicelluloses (Smith and Koehler 2007), reducing these compounds to

simple sugars that can be used in energy production. Their digestive processes recycle nutrients from dead plant materials that few other animals are able to digest (Thorne 1999). Thus, subterranean termites are ecologically important insects because of their contributions to environmental cellulose decomposition.

The Order Isoptera has been divided worldwide into seven families (Mastotermitidae, Kalotermitidae, Sterritermitidae, Hodotermitidae, Rhinotermitidae, Termopsidae, Termitidae), 281 genera and ~2,600 to 2,761 species (Thorne et al. 2000, Myles 2000, respectively). The Nearctic region of the world, composed of the U.S.A., Canada, and Northern Mexico, has 38 representative termite species (Eggelton 2000). Weesner (1965) documented the termite distribution in the U.S.A. and determined that species distribution becomes richer as one moves south within the U.S.A. Overall, *Reticulitermes spp.* has the widest distribution in the region. The most commonly encountered species, *Reticulitermes flavipes* (Kollar), is a subterranean termite found throughout the eastern U.S.A. with a range extending from Toronto, Canada through Florida. This species is a major structural pest capable of forming large colonies and constructing intricate tunnel networks to provide protection and access to resources.

Important Subterranean Termites in the United States

In the United States, the most economically important subterranean termites are represented by three genera of the family Rhinotermitidae: *Coptotermes*, *Reticulitermes* and *Heterotermes* (Light 1934, Kofoid 1946). The genus *Reticulitermes* contains six species of termite considered to be economically important (Su and Scheffrahn 1990b). Kofoid (1946) listed the termites of economic importance in the family Rhinotermitidae included: *Heterotermes aureus* (Snyder), *R. calipennis* (Banks), *R. flavipes* (Kollar), *R. hagai* (Banks), *R. hesperus* (Banks), *R. humilis* (Banks), *R. lucifugus* (Rossi), *R. tibialis* (Banks), *R. virginicus* (Banks). In

addition, the species *Amitermes (Amitermes) wheeleri* (Desneux) in the family Termitidae is considered to be economically important.

The Formosan subterranean termites, *Coptotermes formosanus*, are an invasive species in the U.S.A. Since its accidental introduction, *C. formosanus* has become one of the most destructive termites in the Hawaiian Islands (Tamashiro et al. 1990). It became established in Texas, Louisiana, and South Carolina during the 1960s and in Florida in 1980's (Su and Scheffrahn 2000).

Termite Caste System

Members of the termite colony are divided into castes, each of which has a specialized function within the colony. The reproductive caste, consisting of primary reproductives and secondary reproductives, carry out tasks of reproduction and species distribution. The soldier caste is responsible for nest and colony defense. Termites in the worker caste carry out the majority of tasks, such as building and repairing the nest and tending the termite larvae and reproductives. The needs of the colony determine what individuals will become workers, soldiers, or reproductives. When there is a suitable balance of these three basic castes, a healthy, productive, efficient colony can result (Thorne 1999).

Newly hatched larvae are able to develop into any caste in Rhinotermitid termites, but the persistence of this developmental plasticity varies between different species of termite (Krishna 1969). The earliest instar termites are often referred to as larvae. These larvae, also known as white immatures, are defined as having no significant cuticular sclerotization (Thorne 1996) and they are dependent on a liquid diet provided by the workers (McMahan 1969). As the termite larva molts and matures, the termite's exoskeleton changes from white to a light tan. This change is most evident in the head capsule. Third instar workers are referred to as 'true workers' if there is no divergence to a soldier or reproductive developmental line (Noirot and Pasteels

1988). Soldiers comprise a low percentage of individuals in the colony, approximately 1-2% in *R. flavipes* (Howard and Haverty 1980, 1981, Haverty and Howard 1981, Grace 1986, Thorne et al. 1997) and in *R. virginicus* (Pawson and Gold 1996). Therefore, the majority of the termites in the colony are workers (Kofoid 1934).

The division of labor within the colony, in which casts perform specialized tasks, is unique to social insects and allows the colony to function efficiently to ensure its survival and growth. Workers are the most numerous caste in the subterranean termite colony and are responsible for the majority of resource acquisition and nutrient cycling within the colony. Soldiers and larvae are almost entirely dependent on workers for hydration and nutrients. Workers provide social grooming to their nestmates during feeding behavior, reducing the chances of bacterial and fungal growth within the colony. Workers also construct tunnels within the soil and mud tubes above the soil. Although the soldier caste is primarily responsible for defense, termite workers are also capable of defending the colony to some extent.

In subterranean termites, the reproductive caste consists of primary and secondary reproductives (Lee and Wood 1971, Thorne 1999). Primary reproductives play a major role in the dispersal as alates and founding of colonies, excavation of the first galleries, and feeding and care of the first young (Light 1934). The primary reproductives consist of males (kings) and females (queens), which are highly sclerotized, pigmented, have compound eyes, and develop from winged adults (Krishna 1969). Colony size and maturity are central to determining the production of winged primary reproductives, or alates (Nutting 1969).

There are three types of secondary reproductives that develop functional reproductive organs without leaving the parent colony (Lee and Wood 1971). Neotenics develop functional reproductive organs without becoming alates, and brachypterous neotenics possess wing buds

and develop from juveniles that have already developed wing buds (Lee and Wood 1971). Apterous neotenic do not possess wing buds and develop from juveniles that have not developed wing buds. Supplementary reproductives act as substitutes for the king or queen if one or both should die, or supplement the egg production of the queen after the subterranean termite colony is established (Lee and Wood 1971, Potter 2004). There may be several hundred supplementary reproductives within the colony because as individuals they are not as prolific as the queen (Lee and Wood 1971). In *Reticulitermes* spp., secondary reproductives also help to expand the foraging territory of the colony (Forschler 1999a). All of the offspring in the colony are produced by either primary or secondary reproductives. Termite reproductives differ from those of social Hymenoptera in that the colonies contain ca. 50% males and 50% females (Kofoid 1934).

Soldier termites are more highly specialized than are the workers. The soldier caste is traditionally considered the defensive caste (Wheeler 1928, Kofoid 1934). *Reticulitermes* spp. soldiers have a distinctively modified head with elongated mandibles. Their mandibles are effective against certain predators like ants, and certain species have also developed a chemical defense system (Lee and Wood 1971). Soldier termites develop from a pre-soldier stage that develops from a larva or worker (Lee and Wood 1971). Soldier termites may act aggressively toward competitors, predatory ants, and even other termites. Because of the soldiers' modified mandibles, soldiers cannot chew wood and are entirely dependent on trophallaxis from worker termites for food (Traniello et al. 1985, Su and LaFage 1987).

Process of Tunnel Formation

A newly founded colony is usually associated with a wood food source. As time passes, the colony grows and this food source is consumed the termites must search for additional resources. Subterranean termites will construct subterranean tunnels and above ground shelter

tubes in their search for food resources. Tunneling involves movement of soil particles, and the process begins with an individual termite. In moist sand, subterranean termites construct the tunnel network by pushing their heads forward through the moist sand, then pressing the sand grains from side to side with their head, body, or mandibles (Ebeling and Pence 1957). The smaller grains of sand are taken into the buccal cavity (Ebeling and Pence 1957), combined with saliva and feces (Noirot 1970), and cemented to the wall of the tunnel to make a smooth, hard surface. The termites are also able to carry sand grains to the surface to deposit excess soil particles or construct above ground shelter tubes.

Above ground shelter tubes may be constructed during the search for food and after an adequate food source has been located. Above ground foraging begins with the movement of termites on the surface of the soil, trees, buildings, or other structures. As the termites search, they may find nearly any type of cellulosic material to be an adequate food source, including a wooden structure (Ebeling 1975). In the process of searching above ground, the termites leave a faint pheromone trail (Stuart 1969, Runcie 1986). Once a food source has been located, the chemical trail is reinforced with additional pheromone, causing other termites to be recruited to the food source (Thorne 1996). Deposits of chewed cellulose, soil, feces and saliva are laid at the food source and the tunnel network opening. Soldiers can be seen at the openings as the workers quickly build the shelter tube (Snyder 1948, Reinhard et al. 1997). The completed shelter tube protects the termites from predators and desiccation. The shelter tubes may not protect the termites during extreme temperature changes, and they may retreat to the more stable environment of their subterranean tunnel network (Potter 2004).

The subterranean tunnel network provides the termite colony with a protected route of travel, giving them access to food and moisture resources. As the colony grows and searches for

food, the tunnel network increases in size. Tunnel construction in the soil does not initially begin with the deposition of a trail pheromone, as is the case of above ground shelter tube construction. Tunneling simply begins with the movement of soil particles (Ebeling and Pence 1957). After tunnel construction, pheromones for trailing and recruitment are laid inside tunnels to direct termite activity.

Tunnel construction may be described as non-random and may be influenced by temperature, moisture gradient, food sources (Ettershank et al. 1980), guidelines (Pitts-Springer and Forschler 2000) and soil compaction (Tucker et al. 2004). Puche and Su (2001c) found no indication that *R. flavipes* were able to detect wood in sand over distance. However, the excavation of new tunnels and the movement of the termites within existing tunnels network are both essential for resource acquisition. Once tunnels are constructed to resources, individual termites may randomly select which resources to forage on (Su et al. 1984, Jones et al. 1987).

Feeding Habits

The food gathered by worker termites is the basic energy source of the colony (Lee and Wood 1971). It consists of living or dead plant material that is either partially or almost entirely decomposed (Lee and Wood 1971). Subterranean termites may feed on a wide variety of food including sound wood, decaying wood, parts of living trees and shrubs, plants, books, cardboard, and paper. The major nutritional ingredient in all of these foods is cellulose (Noirot and Noirot-Timothee 1969). Cellulose, a carbohydrate continuously produced by plants, is the most common organic compound on earth and is an abundant potential food source (Light 1934).

Subterranean termites may also chew through non-nutritive materials such as foam insulation (Gyuette 1994, Smith and Zungoli 1995abc, Ogg 1997), plastic, and rubber products (Sternlicht 1977). Subterranean termites have also been known to damage or penetrate drywall, plaster, and even stucco (Potter 2004).

Termite soldiers and larvae, as well as some nymphs and reproductives, are unable to feed themselves and are fed via stomodeal and proctodeal trophallaxis from the workers. Proctodeal feeding occurs in the lower termites that contain protozoan intestinal fauna (Wheeler 1928, Noirot and Noirot-Timothee 1969). It consists of liquid excretions from the rectal pouches. Proctodeal feeding allows larvae to ingest the protozoa necessary for cellulose digestion, and allows gut refaunation in worker termites after a molt (Wheeler 1928). Stomodeal food may often be regurgitated as clear liquid (probably saliva) and is the only way reproductives can get nourishment (Noirot and Noirot-Timothee 1969).

Building Construction and Its Relevance to Termite Exploitation

Subterranean termite control begins by excluding termites from a structure, thereby preventing them from damaging building materials by their feeding and tunneling. Understanding the relationship between termite biology and construction design is essential to termite control and the prevention of termite damage within a structure. The best time to provide protection against termites is during the planning and construction of the building. Improper design and construction of buildings, resulting from lack of knowledge or indifference to termite problems, can greatly increase the chances of termite infestation. Building codes set a standard that allow for flexibility of termite treatment options and protection against termites.

Building Codes

Building code is a set of rules that specify the minimum acceptable level of safety for constructed objects such as buildings and other structures. The main purpose of the building codes is to protect public health, safety and general welfare as they relate to the construction and occupancy of buildings and structures (IBC 2006). The building code becomes law of a particular jurisdiction when formally enacted by the appropriate authority.

The relevance of establishing building code standards is to protect a structure and the property owner from avoidable property loss due to structural failure (Allen 1999). Subterranean termites can damage the structural load bearing members by tunneling into the wood. They can also tunnel into and damage wooden sheathing and insulation products affecting the building envelope.

Building code history: For thousands of years, building codes and regulations have protected the public. The earliest known code of law referred to as The Code of Hammurabi, king of the Babylonian Empire, written in 2200 B.C. assessed severe penalties, including death, if a building was not constructed safely. The regulation of building construction in the United States dates back to the 1700s. By the early 1900s, special interest groups, such as the insurance industry, joined others with similar concerns to develop a model code. This first model building code gained widespread popularity among legislative authorities (Kofiod 1934).

USA code history: Since the early 1900s, the system of building regulations was based on three regional model codes: the Building Officials Code Administrators International (BOCA), Southern Building Code Congress International (SBCCI), and the International Conference of Building Officials (ICBO) (Miller et al. 2002). Although the regional code development has been effective and responsive to the regulatory needs of the local jurisdictions, in the early 1990s it became obvious that the country needed a single coordinated set of national model building codes. The nation's three regional model code groups decided to combine their efforts and in 1994 formed the International Code Council (ICC) to develop codes that would have no regional limitations (IBC 2006).

The first edition of the International Building Code was published in 1997. By the year 2000, International Code Council has completed the International Codes series and ceased

development of the legacy codes in favor of their national successor. The International Building Code applies to all structures in areas where it is adopted, except for one and two family dwellings, which falls under the International Residential Code (IBC 2006).

Parts of the International Building Code reference other codes including the International Plumbing code, International Mechanical code, National Electric Code and various National Fire Protection Association Standards. Therefore, if a municipality adopts the International Building Code, it is adopts those parts of the other codes referenced by the International Building Code. Often, the plumbing, mechanical, and electric codes are adopted with the Building Code. Currently the International Building Code has been adopted by 45 states. Each state has their own state and local codes that tailor the International Building Code and International Residential Code to suite the uniqueness of the state and region (IBC 2006, Miller et al. 2004).

Concrete Construction Standards

Building foundations and concrete minimum building standards are addressed in the codes (IBC 2006). One primary function of a foundation is to transfer the structural loads from a building safely into the ground. The foundation design is an integral part of every building. The foundation supports a number of different kinds of loads: dead, live, wind, and snow loads (Allen 1999). If the concrete is not strong enough or the ground below settles, the concrete may crack allowing subterranean termites to access the structure from below. Termites entering the structure from cracks hidden from the exterior foundation may go undetected for a long period of time and may result in significant termite damage to the structure. Currently the building code requires the concrete slab to be a minimum of 150 cm above grade to allow a termite inspection area around the structure (IBC 2006).

A satisfactory foundation for a building should meet three general requirements. First, the foundation, including the underlying soil and rock, must be safe against structural failure that

could result in collapse. Second, during the life of the building, the foundation must not settle in such a way to damage the structure or impair its function. Finally, the foundation must be feasible both technically and economically, and practical to build without adverse effects to surrounding property. Satisfying the aforementioned requirements of a foundation would minimize the risk of concrete cracking, reducing the possibility of undetected subterranean termite entry into a structure.

A concrete foundation can be considered an initial barrier to termites if there are no concealed cracks. The Australian Standard AS 3660.1 specifies for buildings constructed on sub-floors that the concrete slab can form an integral part of the termite barrier system (AS 1995). Lentz et al. (1997) reported that cracks ranging from 0.5-4.0 mm, made by splitting slabs, can allow termite access through the slab. They determined that the smallest crack width penetrated varied by termite species, and was 3.1 mm for *Coptotermes acinaciformis*, 1.5 mm for *Sherorhinotermes breinli*, 1.8 mm for *Heterotermes vagus*, and 1.4 mm for *H. validus*. Minimum concrete strength standards are established by the building codes to reduce the potential for foundation shrinkage and cracking (IBC 2006).

The quality of a building floor or slab made of concrete is highly dependent on achieving a hard and durable surface that is flat, relatively free of cracks (ACI 2004). There are several components that contribute to the properties of the final product, such as mixture ratios, quality of concreting, and joining techniques. The timing of the concreting operations, especially finishing, jointing, and curing, is critical. Failure to address foundation and concrete design can result in unsatisfactory characteristics in the wearing surface such as cracking, low resistance to wear, dusting, scaling, high or low spots, poor drainage, and increased potential for curling.

Concrete floor slabs using portland cement, regardless of consistency, will start to experience a reduction in volume as soon as they are placed and will continue as long as water and/or heat are released to the surroundings. Because of the drying and cooling rates are dissimilar at the top and bottom of the slab, the shrinkage will vary throughout the depth, possibly causing the final product to be critically distorted and reduced in volume.

The American Concrete Institute (ACI) has published a guide containing recommendations for controlling random cracking and edge curling (ACI 2004). ACI also acknowledges that even with the best foundation design and proper construction techniques; it is unrealistic to expect crack-free and curl-free concrete floor slabs. Therefore, it should be expected that some cracking and curing to occur on every project and that such occurrences may not adversely impact the slab adequacy if the design or the quality of the construction is sufficient (Campbell et al. 1976, Ytterberg 1987). Therefore, since concrete cracking and shrinkage is always possible, then other termite control measures should be employed.

Wood Framing Standards

Minimum standards for single and multi-family dwellings are established in the international building code (IBC 2006). Design of exterior wall framing must be adequately sized for strength and support. Exterior walls must be strong enough to support both live and dead loads. Walls must also be able to resist lateral wind loads and in some regions, seismic and hurricane forces (Allen 1999, Miller et al. 2002). Top plates are doubled and lapped at corners and at bearing partition intersections to tie the building into a strong structural unit. In addition to establishing minimum standards for strength and design of wood framing, standards have also been established to prevent termite infestation.

The building codes establish minimum standards for termite prevention and control to protect the materials in service from current and future termite attack. Because termites can

readily damage and consume cellulose products, a wooden structure needs to be protected.

When wood is in contact with the soil, the building code allows the use of termite resistant wood, in critical termite prone areas, such as yellow cypress (*Chamaecyparis nootkatensis*), western red cedar (*Thuja plicata*) and eastern white cedar (*Thuja occidentalis*) (IBC 2006), these species of wood have natural substances that prevent termite attack. Grace and Yamamoto (1994) determined that the heartwood of *Chamaecyparis noothatensis* (yellow cypress, or Alaska cedar) and *Chamaecyparis obtuse* (hinoki) resists attack by the Formosan subterranean termite. Also, wood construction components can be protected against decay and termite attack by application of chromated copper arsenate (CCA) (Grace 1998), ammoniacal copper quat (ACQ), copper azole (CA), or copper, zinc and arsenic ammonia (AZQA) (Tamashiro et al. 1988).

The studs in exterior walls of one and two-story structures are at least 2x4 inches with the 4-inch dimension forming the basic wall thickness. Stud spacing is normally 16 inches in exterior walls. The studs are arranged in multiples at corners and partition sections to provide the rigid attachment of sheathing (Allen 1999).

The high resistance of wood frame construction to seismic, hurricane and other natural forces of nature are provided when exterior sheathing adequately secured to the exterior wall studs. Exterior wall sheathing includes plywood, particle board, and other structural panels such as oriented strandboard, structural insulation, and board lumber. Sheathing is applied in strict accordance with manufacturers nailing requirements to provide a rigid wood frame system. All wooden materials that are not naturally termite resistant should be protected against termite attack to maintain their strength and other physical properties (IBC 2006).

Termite Control Options

Currently there are four major categories of termiticide treatments to protect structures from subterranean termites; liquid soil termiticides, wood-applied termiticides, baiting systems,

and physical barriers. Liquid termiticides are typically classified as repellent or non-repellent and have been used to exclude subterranean termites from structures. Pyrethroids are among the most commonly applied soil termiticides for new construction, and are highly repellent to subterranean termites, deterring termites from tunneling in treated soil without causing significant mortality (Su et al. 1993). Soil termiticides are applied to the soil beneath and around the structure to create a barrier (Su and Scheffrahn 1990a). The newer, non-repellent termiticides include imidacloprid (Kuriachan and Gold 1998), fipronil (Osbrink et al. 2001), and chlorofenapyr (Rust and Saran 2006), all of which are effective at killing subterranean termites.

Soil termiticide treatments have been used since the 1900s and are generally inexpensive and easy to use. A soil termiticide treatment is applied during the construction of a building, and is required by the building code in Florida unless another method of termite protection is approved as a stand-alone treatment (FBC 2004). Liquid soil termiticides are also used for remedial treatments. Currently available soil termiticide treatments degrade and may require reapplication after five or more years (Su et al. 1999, Richman et al. 2006) to maintain long-term protection of structures.

In Florida, currently registered termite baiting systems approved for application at new construction contain hexaflumuron (Foos 2006), noviflumuron (Foos and Daiker 2003), or diflubenzuron (FBC 2004). These compounds are chitin synthesis inhibitors (CSIs) that prevent the successful molting and development of subterranean termites. This disruption in termite growth causes the decline of the colony to the point of colony death. Hexaflumuron, the most extensively studied CSI active ingredient, has been proven to eliminate subterranean termite activity with several species of subterranean termites (Su 1994, Clement et al. 1996, Su and Scheffrahn 1996, Peters and Fitzgerald 1999, Sajap et al. 2000, Rojas and Morales-Ramos 2001,

Grace and Su 2001). Noviflumuron, also produced by Dow Agrosiences, can eliminate colonies of *Reticulitermes* in about half the time as colonies baited with hexaflumuron (Smith et al. 2002). Karr et al. (2004) reported that the lethal dose of noviflumuron for *R. flavipes* termites was found to be at least two-to three-fold lower than that of hexaflumuron. Su and Scheffrahn (1993) determined that *R. flavipes* and *C. formosanus* consumed diflubenzuron resulting in >90% mortality for both species in 9 wk.

Physical Barriers

Physical particle barriers of impenetrable materials, such as sieved soil particles (Ebeling and Pence 1957, Su and Scheffrahn 1992, Yates et al. 2000) and steel mesh (ABSAC 1992, Grace et al. 1996, Lentz and Runko 1994), have been demonstrated to effectively exclude subterranean termites. For physical barriers to be effective, they must be constructed of materials that cannot be moved or chewed through by termites and create no gaps that termites can move through. Sieved soil particles must be specific size range to be large enough to prevent manipulation by termite mandibles and small enough to not provide gaps to allow termite movement through. Research has documented the effective size range for a soil particle barrier is dependent upon the head capsule width of the termite species. Tamashiro et al. (1987, 1991) documented that *Coptotermes formosanus* Shiraki could not penetrate basaltic particles with diameters in the range of 1.7-2.4 mm. Su et al. (1991) found that particle barriers of 1.18-2.80 mm in size effectively prevented penetration of both *R. flavipes* and *C. formosanus*.

A physical barrier made of a fine stainless steel mesh wire known as “Termimesh[®]” was developed in the early 1990s (ABSAC 1992, Lentz and Runko 1994). Termimesh is typically placed in critical areas, such as along control joints and around pipe penetrations, before the concrete slab is poured. This mesh wire barrier, with an aperture of 0.45 by 0.66 mm, has been proven effective to prevent access of large termites such as, *C. formosanus* (Grace et al. 1996),

C. acinaciformis (Froggatt), *Mastotermes darwiniensis* Froggatt, and *Schedorhinotermes breinli* (Hill) (Lentz and Runko 1994). Smaller termites, such as *Heterotermes vagus* (Hill) with a maximum head width of only 0.76 mm, were able to move through this mesh wire (Lentz and Runko 1994).

Impasse® (Syngenta Crop Protection, Greensboro, NC) is an insecticide-impregnated vapor retarder that contains the pyrethroid lambda-cyhalothrin sandwiched between construction grade polymer layers. Like Termimesh, Impasse is used to repel termites from cracks in the slab or gaps created plumbing or utility penetrations (Harbison 2003, Wege et al. 2003). Impasse barrier became available in 2002 with the intent to cover the entire undersurface of the foundation. Su et al. (2004) found that Impasse placed over a sand plot and covered with a concrete slab prevented termite penetration. The Impasse termite system later focused on Impasse termite blocker, installed around plumbing and utility pipes penetrating the slab. Impasse termite blocker is applied in the preconstruction phase and is embedded in the concrete around the pipe penetrations when the building foundation is poured.

Heat Transfer Concepts

Heat is a form of energy that is sometimes expressed as the intensity of molecular vibration within a material. Heat is always transferred in the direction of decreasing temperature. There are three different types of heat transfer: radiation, convection, and conduction. In all cases, a temperature difference must exist for heat transfer to occur (Bueche and Wallach 1994).

Radiation is the movement of energy by means of electromagnetic waves. Radiative heat transfer does not require that objects be touching to transfer heat (Bueche and Wallach 1994).

Convective heat transfer occurs when a fluid, as a liquid or a gas, comes in contact with a material of a different temperature. Natural convection occurs when the changes in the localized densities of a fluid, due to differences in thermal energy, drive the flow of the fluid. Forced

convection occurs when the fluid flow is due to localized differences in pressure (Bueche and Wallach 1994).

Conduction takes place within the boundaries of a solid body by the transfer of thermal energy between molecules within the material. The rate at which heat is conducted through a material is proportional to the area available to the heat flow and the temperature gradient along the heat flow path. For a one-dimensional, steady state heat flow the rate is expressed by Fourier's equation (Healy and Flynn 2002):

$$Q=k*A*(\Delta T/d)$$

Where:

k =thermal conductivity, W/m-K

Q =rate of heat flow, W

A =contact area, m

d =distance of heat flow, m

ΔT =temperature difference, Kelvin

Thermal conductivity, k , is an intrinsic property of a material which describes the material's ability to conduct heat (ASHRAE 2005). This property is independent of the materials size, shape, or orientation. For non-homogeneous materials the term "relative thermal conductivity" is generally used and is appropriate because the thermal conductivities depend on the thickness of the layers and their orientation with respect to heat flow. Another inherent thermal property of a material is its thermal resistance, R or R -value (Bueche and Wallach 1994), as defined below:

$$R=A*(\Delta T/Q)$$

Resistance is a measure of how a material of a specific thickness resists the flow of heat.

The relationship between k and R is shown by combining the previous two equations to form:

$$k=d/R$$

This equation shows resistance is directly proportional to the material thickness for solids (Bueche and Wallach 1994).

Insulation

The use of cellular thermal insulation has increased in recent years due to its energy saving potential. There are many organic and inorganic substances that are capable of being processed to form stable cellular foam insulation. In order to be successfully processed, the substance must have the capability of being processed as a fluid, mechanically expanded by foaming with a gas while in a liquid state, and then solidified while maintaining a cellular matrix established during the foaming process. Rigid cellular materials are most often used for thermal insulation within structures, but flexible and semi-rigid materials are available. The most common types of organic, cellular insulations are manufactured using polyurethane and polyisocyanurate, and resins of polystyrene, urea-formaldehyde, and phenol-formaldehyde. The most common inorganic, cellular insulation (Perlite and vermiculite) is produced from glass (Yost 1991).

Thermal Transmission

The most important physical property of cellular thermal insulation is thermal transmission. In cellular insulations, thermal energy is transferred by three different mechanisms: conduction through the solid portion of the foam, conduction through the gaseous portion, and radiation through the cellular matrix from cell wall to cell wall (Skochdopole 1961). Convection heat transfer within cells is generally not considered, because the cell size is usually too small to support significant convective movement (Skochdopole 1961).

For many products, measures are taken to minimize the heat transfer contribution from one or more of these mechanisms. For example, chlorofluorocarbon blowing agents are commonly introduced not only to help foam the fluid but also to reduce conduction through the gaseous

portion of the foam. The use of facings laminated or bonded to chlorofluorocarbon-blown foams can also decrease thermal transfer.

One method of minimizing radiation through the cellular matrix is to increase the foam density, thus providing more material in the cell walls to absorb infrared radiation. Although an increase in density can reduce the radiation component of heat transfer, it simultaneously increases the conduction through the solid portion of foam. Therefore, the lowest thermal transfer for a particular foam material can be found in the optimal balance of solid and gaseous portions within the cellular matrix. For example, the optimum balance for cellular plastics is generally 1.8 to 2.5 lb/ft³ (28.8 to 40.0 kg/m³) (Skochdopole 1961, Norton 1967, Booth and Lee 1985). However, other factors generally need to be considered, such as raw material costs and mechanical strength requirements, so the density of the cellular products typically ranges from 1.0 to 4.0 lb/ft³ (16 to 64.0 kg/m³).

CHAPTER 3 ABILITY OF EASTERN SUBTERRANEAN TERMITES TO MOVE THROUGH CRACKS

Introduction

The eastern subterranean termite, *Reticulitermes flavipes* (Kollar), is one of the most destructive structural pests in North America (Kofoid 1934, Mauldin 1986, Su and Scheffrahn 1990a). Like other subterranean termites, *R. flavipes* inhabits the soil, typically invades structures from the underlying soil, and can avoid detection for long periods of time. Preventing subterranean termite entry from the soil is considered a primary way to protect a structure from termite infestation and damage (Su and Scheffrahn 1990b).

Concrete and good quality mortar will not normally be penetrated by termites providing that all joints are properly sealed (Snyder 1919, 1929). Nonetheless, a concrete slab of appreciable size will crack as it sets and settles (Benboundjema et al. 2005). Most foundation failures are attributed to excessive differential settlement (Allen 1999, Zijl et al. 2001). A pre-existing crack or gap in the concrete slab is of relatively fixed width. *Reticulitermes* spp. are not capable of widening gaps in uncompromised concrete, so their body dimensions are a limiting factor for their moving through gaps. Lentz et al. (1997) reported that the smallest crack width penetrated by termites through concrete was 1.3 mm for *C. acinaciformis* and 1.4 mm for *Heterotermes validus* Hill. Cracks of 0.8 mm or more in width were reported to permit passage of subterranean termites but species were not documented (Johnston et al. 1972, Beal et al. 1989).

The factor determining the crack width penetrated by termites should be the smallest dimension of the termite head capsule. Termites are generally soft-bodied insects with thin, flexible exoskeletons over most of their body. The notable exception to this is the head capsule, a rigid structure which supports the mandibular musculature, allowing the termites to chew

through hard substrates like wood. This rigidity makes the head capsule incapable of being compressed. Therefore, for a termite to travel through a crack, the smallest dimension of the termite head capsule must be less than the width of the crack. Movement through a crack would restrict movement in one-dimension where as movement through particles or a mesh would restrict movement in two-dimensions. The only study correlating termite body dimensions to movement through various particle sizes was Su et al. (1991). No studies have been conducted evaluating the ability of different termite developmental stages for passing through fixed crack widths.

The objectives of this study on *R. flavipes* were to investigate the relationship between crack width and head capsule size for both worker and soldier termites, and evaluate the ability of different termite developmental stages to pass through cracks of different widths and subsequent consumption of matrices on either side of the cracks.

Materials and Methods

Termites

Three colonies of *R. flavipes*, separated by more than 1.5 km in Gainesville, FL, were field collected in 6-liter plastic buckets inserted below ground with their lids accessible above the soil surface. Each bucket was filled with 2-3 moistened corrugated cardboard rolls (15 cm long by 10 cm diam.; Gainesville Paper Co., Gainesville, FL). Termites accessed cardboard rolls through ~10 holes (4-cm diam.) in the sides and bottom of each bucket. Cardboard rolls containing termites were collected and returned to the lab in Ziploc bags (3.8-L). Termites were removed from the cardboard by gently separating the corrugated cardboard and allowing the termites to fall into a 20-L plastic bucket. The termites were then placed on moistened corrugated cardboard and reared at room temperature (~23°C) in plastic boxes (27 by 19 by 9.5 cm) with moistened cardboard for ≤ 1 wk before inclusion in experimental arenas.

Prior to the test, termites were sorted by size and caste. Soldiers and workers were separated from larvae using a 1.18 mm mesh soil sieve (No. 16, Fisher Scientific Company, Pittsburgh, PA). Larvae through the 2nd instar passed through the sieve. The 2nd instar larvae were then separated from white immature larvae using a vacuum aspirator.

Effect of Crack Width on Penetration and Consumption by Caste

The test arena to evaluate penetration by caste and consumption by crack width was an acrylic plastic cylinder (5.08 cm I.D., 127 cm long) with an acrylic divider (1.59 cm thick) placed 5.72 cm from the bottom (Fig. 3-1). An oval opening (1 by 0.5 cm) was cut into the center of the acrylic divider. Two aluminum spacers (2.5 by 1.0 by 0.1 cm) were glued over the oval opening to create a space 1 cm long. Crack widths of 406, 508, 610, 711, 813, 991, and 5,000 μm were created using spark plug feelers (Carquest Corp., Lakewood, CO) and a second acrylic divider with oval opening was glued over the aluminum plates before the glue set to fix plates in place.

Soil was oven-dried at $\sim 177^{\circ}\text{C}$ for 24 h, sifted through a 1.18 mm mesh soil sieve to remove debris, and moistened by mixing 40 ml of distilled water in 400 g soil. Moistened soil was evenly distributed above and below the acrylic dividers within the experimental arena leaving a 0.64 cm void on the top for termite introduction. Pre-weighed filter paper (Whatman #4, ~ 130 mg, 4.3 cm diam.) was placed on the top and bottom of the arena.

Termites were aspirated into groups of 253 insects, consisting of 3 soldiers, 200 workers [$\geq 3^{\text{rd}}$ instar], 50 larvae [2nd instar], that were introduced on top of each arena. The top and bottom of the arena were lidded with a plastic Petri dish (100 mm diam.) and secured with two rubber bands. The experiment was a randomized complete block design. Each crack width ($n =$

7) was evaluated using three termite colonies with four replications per colony, resulting in 84 experimental arenas.

The arenas were opened 5 d after setup, and the numbers of each caste of termites located in the top and the bottom sections were counted. Filter paper was collected, oven dried, and weighed to determine consumption.

Effect of Termite Head Capsule Dimension on Penetration Through Cracks

The arena to evaluate the termite head capsule dimensions and crack width was a Petri dish (55 mm diam.) with an acrylic divider and aluminum plates built as described above. Crack widths of 711, 813, and 991 μm , and were created using spark plug feelers (Carquest Corp., Lakewood, CO) (Fig. 3-2). Groups of 125 termites consisting of 45 soldiers, 60 workers [3rd instar] and 20 larvae [2nd instar] were then introduced to the arena above the crack. The arena was lidded and sealed with Parafilm “M” (Pechiney Plastic Packing, Chicago, IL). Each crack width ($n = 3$) was evaluated using three termite colonies with three replications per colony, resulting in 27 experimental arenas.

The arenas were opened 24 h after setup, and the numbers of each caste of termites located in the top and the bottom sections were recorded. The termites from the top and bottom sections were separated and chilled in a refrigerator for ~30 minutes before measuring. The termites head capsule width, length, and depth were measured using a dissecting microscope with a calibrated ocular micrometer.

Data Analysis

In the test arena to evaluate penetration and consumption the percentage of the termites that passed through each crack width and survivorship in the arena were arcsine transformed and analyzed with two-way analysis of variance, ($P = 0.05$; SAS 2001), with termite colony and crack width as main effects, and were separated with Student-Newman Keuls (SNK). The effect

of crack width and termite colony consumption (gm) filter paper total and filter paper on bottom of arena were analyzed using one-way analysis of variance (ANOVA) and were separated with Student-Newman Keuls (SNK), ($P = 0.05$; SAS 2001).

Quantiles of the head capsule width and depth for each caste were determined using univariate analysis (SAS 2001) for the total population of termites and termites found below the crack. Also for the soldier and worker termites located on the bottom of the Petri-dish a linear regression was performed to determine the relationship of maximum head capsule measurements (length, width, and depth) and the termite's ability to pass through three crack widths to the bottom of the arena.

Results

Effect of Crack Width on Penetration and Consumption by Caste

Termites began tunneling immediately after introduction to the top of the arena and lived to the end of the test with no significant mortality. Survivorship for each caste averaged 96% for larvae, 97% for workers, and 99% for soldiers. The percentage (number) of termites passing through a crack increased as the crack width increased (Table 3-1). No termites were able to pass through the smallest crack widths of 406 and 508 μm . Only one larva was able to pass through the crack width of 610 μm . The minimum width opening permitting functional access by each caste was 711 μm for workers and larvae and 813 μm for soldiers. The dimensions of 711 and 813 μm did restrict movement of caste members because the proportion of each caste that passed through these dimensions were significantly less than those passing through gaps of 991 μm or greater.

Crack widths of 610 μm and less that prevented penetration by termite workers subsequently prevented feeding on the bottom of the arena (Table 3-1). There was significantly more paper consumed, total and in the bottom of the arena, for crack dimensions $\geq 711 \mu\text{m}$

compared to crack dimensions $\leq 610 \mu\text{m}$. There was no significant difference in paper consumed, total or in the bottom of the arena, for cracks from 710 – 5,000 μm in width, even though a significantly lower proportion of workers were found in the bottom arenas with crack widths of 711 and 813 μm .

Effect Termite Head Capsule Dimension on Penetration Through Cracks

Termite groups placed in the Petri-dish arena immediately began to move about the arena seeking a more hospitable environment. Termites were given two options, to stay on the surface with no food or protection above the crack or to pass through the crack (711, 813, and 991 μm) in search of food and protection. Linear regression analysis of termite head capsule dimensions (length, width, and depth) of termites able to pass through the three crack widths indicated a positive relationship between crack width and head capsule dimensions for both soldiers and workers (Figure 3-3 and 3-4, respectively). As crack width increased, the maximum head capsule dimension of termites that passed through the crack also increased. The head capsule dimension of depth, compared to length and width, had the best correlation to crack width, with r^2 values of 0.96 for soldiers and 0.92 for workers.

Greater than 75% of the soldiers (Fig. 3-5, A) and 50% of the workers (Fig. 3-6, A) had head capsule widths greater than the width of the crack that they passed through. In contrast, the head depth of 100% soldiers (Fig. 3-5, B) and workers (3-6, B) was always \leq to 991 or 813 μm wide cracks they passed through. A low percentage of soldiers (10%) and workers (25%) with head depths greater than 711 μm were able to pass through cracks of this width. No larvae had head capsule depths larger than the most narrow crack width of 711 μm (Fig. 3-7, B), so smaller width cracks would need to be tested to evaluate penetration by larvae. These data further

confirm that head capsule depth is the best predictor of a termite's ability to penetrate fixed crack widths.

Discussion

Previous studies have identified the termite head capsule width, not depth, as a significant factor in the termite being able to penetrate through physical barriers (Su et al. 1991, Lenz and Runko 1994, Grace et al. 1996, Toutountzis 2006). Su et al. (1991) suggested that one colony of *C. formosanus* was not able to move through the interstitial space of large particles forming a uniform particle barrier because the workers and soldiers had a large head capsule width (1.4 mm). Termi-Mesh[®] is marine grade stainless steel wire screen (ABSAC 1992, Lentz & Runko 1994) which is embedded in concrete during construction to form a physical barrier to termites (AS 1995). Grace et al. (1996) found that the Termi-Mesh screen with a rectangular aperture size of 660 by 450 μm was able to exclude *Coptotermes formosanus* Shiraki from all test units. Another study found that smaller termites, such as *Heterotermes vagus* (Hill) workers with a head width of ~ 0.76 mm, were able to pass through the small Termi-Mesh screen (Lentz and Runko 1994), perhaps by aligning the head capsule to the largest dimension of the rectangular aperture, the hypotenuse measuring ~ 799 μm . Our study determined the termite head depth, not head width, is the limiting factor in determining a termite's ability to pass through the small cracks of fixed width.

Our study findings concur with previous recommendations that no cracks greater than 0.396 mm (1/64 inch) should be present in the foundation and between masonry units (Anonymous 1980). Our study also supports previous reports that termites can penetrate cracks that are 0.794 mm (1/32 inch) wide (St. George et al. 1960). Our conclusions were based on head capsule measurements for *R. flavipes* workers and soldiers, which were consistent with those previously reported. Banks (1946) documented *R. flavipes* soldiers have a head capsule

lengths of 1.7-2.3 mm, head capsule widths of 1.0-1.3 mm, and head depths of 0.85-1.1 mm. Similar soldier head capsule measurements for *R. flavipes* were also found by Scheffrahn and Su (1994) and Thorne et al. (1997). The mean morphological worker head capsule measurements collected from four field colonies of *R. flavipes*, were head length of 1.2 mm and width of 1.0 mm (Su et al. 1991).

Our study found that termites consumed significantly less filter paper in arenas where they were confined to the top of the arena (~40 mg) than in arenas where termites accessed the top and bottom through the crack (~64 mg). Cornelius (2003) found that *R. flavipes* wood consumption rates were greater on large blocks of wood than on small blocks of wood. Similar results were found when food consumption rates were measured for different combinations of wood volume and termite group size. Lentz et al. (2003) found that subterranean termites, *R. speratus* (Kolbe), consumed 20% more when provided a food source that was 75% larger in size. These studies as well as this study support the concept that subterranean termites vary their feeding in response available resources. Another plausible explanation for the greater filter paper consumption is that the energy expense of establishing a new tunnel network was compensated for by consuming more filter paper.

Even though the proportion of termite workers passing through crack widths of 711 and 813 μm were significantly less than those in the 991 and 5,000 μm crack width arenas, the total consumption of the filter paper was not significantly different in arenas with crack width ranging from 711 to 5,000 μm . This suggests that, for the 711 and 813 μm crack width arenas, the worker termites able to reach the bottom of the arena efficiently transferred larger amounts of food to nestmates confined to the top of the arena. Therefore, any crack between roughly 700

and 900 μm in width will most likely allow damaging levels of wood consumption in a structure, in spite of the partial exclusion of *R. flavipes* workers and almost total exclusion of soldiers.

The ability of subterranean termites to find cracks depends on their foraging behavior. Campora and Grace (2001) as well as, Puche and Su (2001a) observed a systematic pattern of tunneling regardless of the presence or absence of a food source in foraging sites. Puche and Su (2001c) determined that both *Coptotermes formosanus* and *R. flavipes* could not detect wood in a test chamber and did not alter their tunneling to intercept the wood discs. Another study by Puche and Su (2001b) determined that population density of subterranean termites, *C. formosanus* and *R. flavipes*, had no effect on the overall complexity of the tunnel network and tunnels were generally straight. It has been shown that termite tunneling is influenced by guidelines and passageways (Pitts-Singer and Forschler 2000, Swoboda and Miller 2004). Because tunneling is a necessary component of finding new resources, termites tunneling beneath a concrete slab can use cracks as foraging guidelines. Therefore, it is essential to attempt to eliminate as many cracks as possible in structure foundations to ‘build out’ subterranean termites and prevent economic loss due to termite damage.

Table 3-1. Percentage of termite castes located on the bottom of the arena that passed through various crack widths and consumption of filter paper by termites in arena at 5 d.

Crack width (μm)	% \pm SE Termite castes located on the bottom			Mean \pm SE filter paper consumption (mg)	
	Workers	Larvae	Soldiers	Total (top and bottom)	Bottom
< 508	0.0 \pm 0.0d	0.0 \pm 0.0c	0.0 \pm 0.0b	39.8 \pm 0.0b	0.0 \pm 0.0b
610	0.0 \pm 0.0d	0.3 \pm 0.3c	0.0 \pm 0.0b	37.3 \pm 0.0b	0.0 \pm 0.0b
711	34.7 \pm 6.1c	38.0 \pm 8.1b	0.0 \pm 0.0b	61.5 \pm 0.0a	37.8 \pm 0.0a
813	53.9 \pm 3.6b	30.7 \pm 8.5b	11.1 \pm 8.5b	62.9 \pm 0.0a	39.2 \pm 0.0a
991	64.1 \pm 3.2a	67.8 \pm 4.8a	72.2 \pm 9.9a	64.4 \pm 0.0a	39.5 \pm 0.0a
5,000	73.4 \pm 5.4a	80.2 \pm 8.5a	69.4 \pm 8.7a	69.0 \pm 0.0a	39.6 \pm 0.0a

Means within a column followed by the same letter are not significantly different (Student-Neuman-Keuls, $P = 0.05$, SAS Institute 2001).

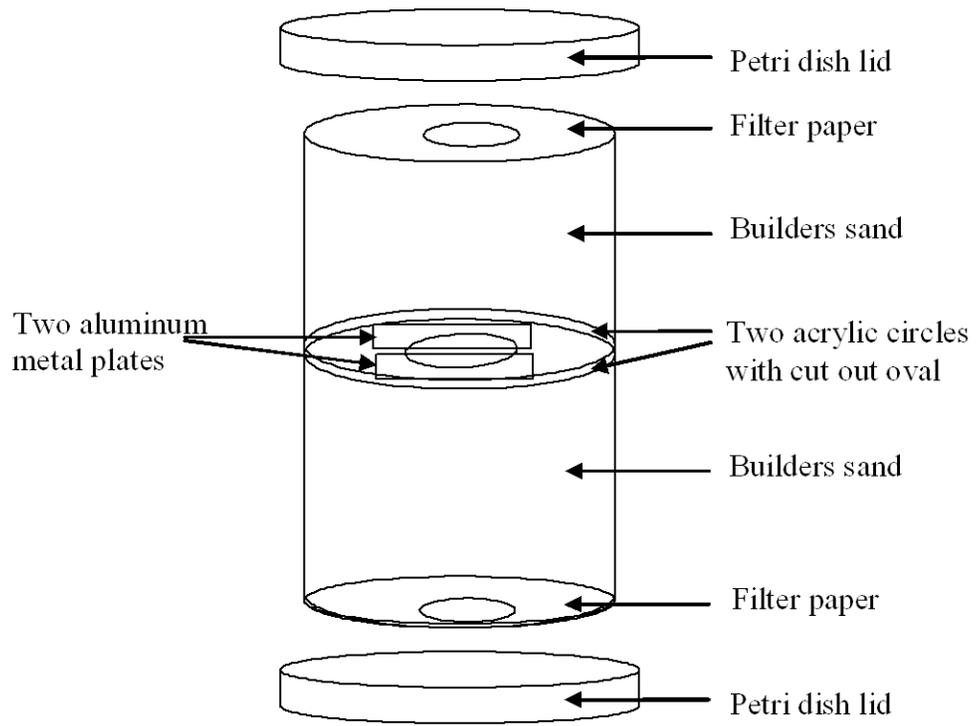


Figure 3-1. Termite caste location and consumption test arena.

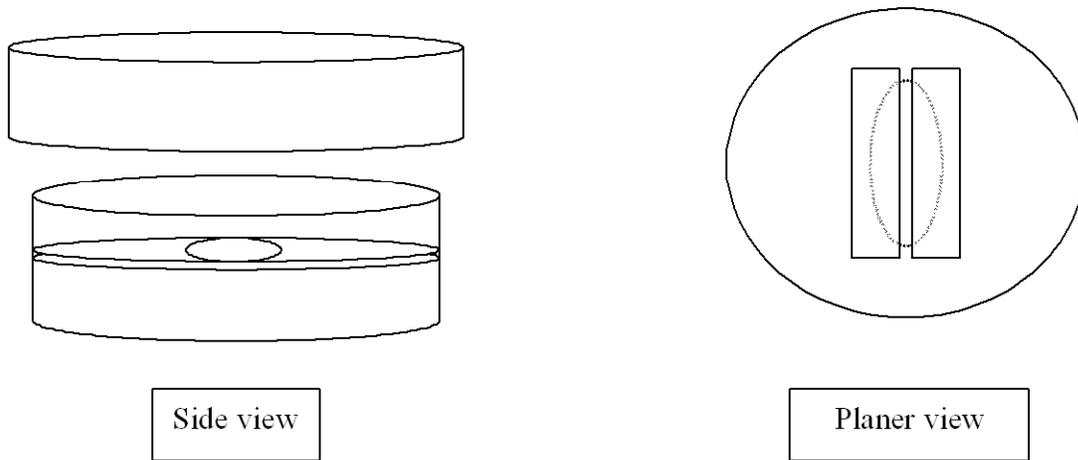


Figure 3-2. Head capsule Petri-dish test arena.

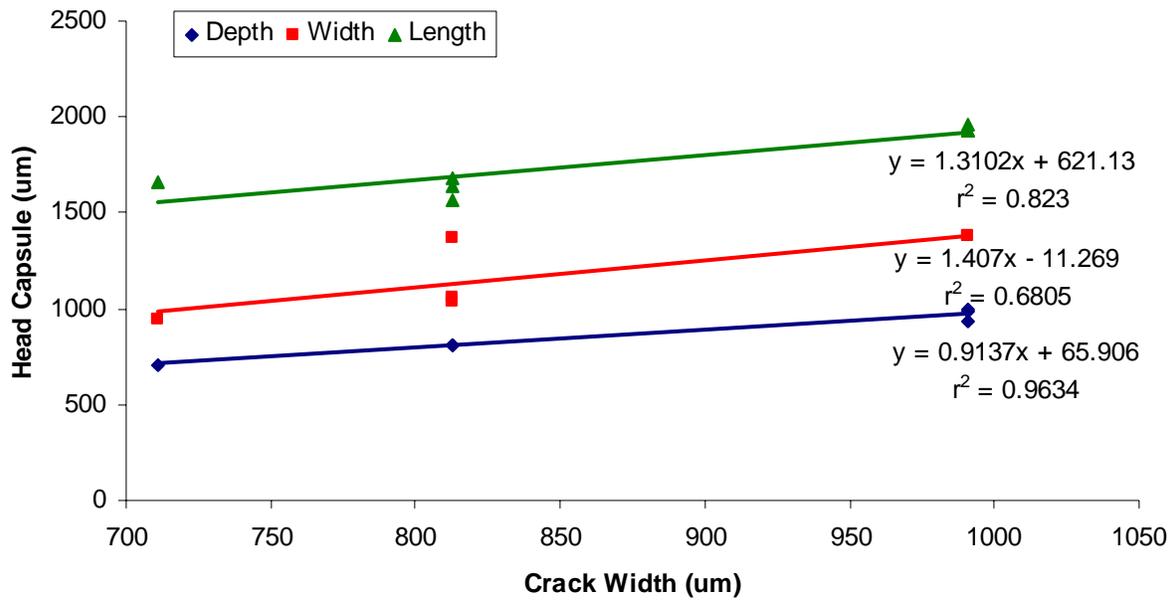


Figure 3-3. Linear regression comparing the maximum soldier head capsule measurements (length, width, and depth) able to pass through the three crack widths (711, 813, and 911 μm) for each of the three termite colonies.

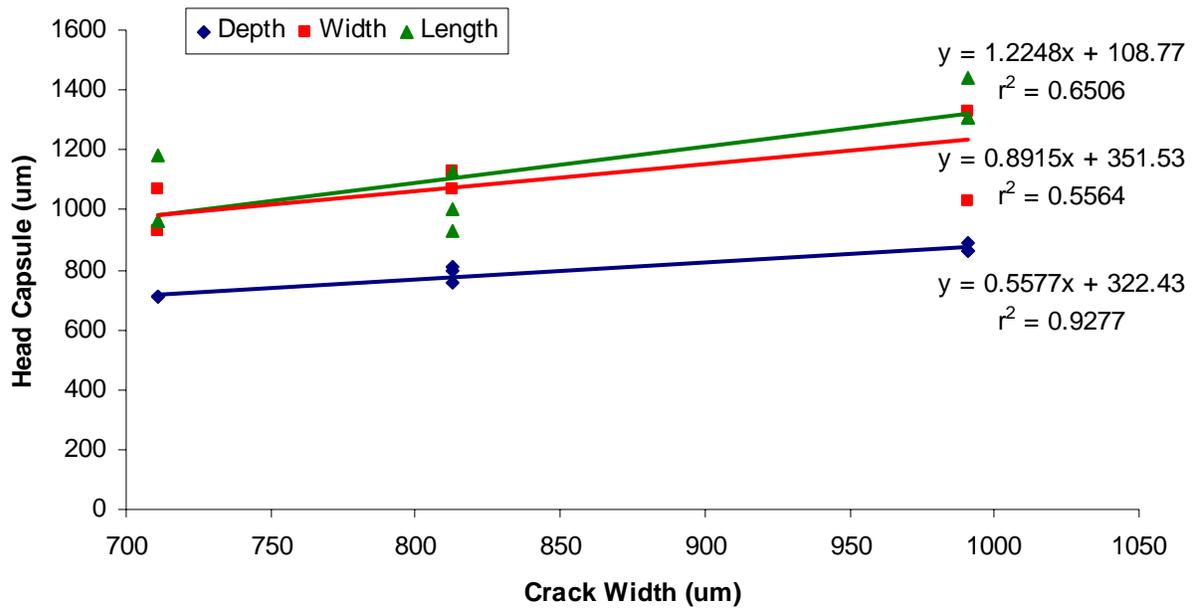
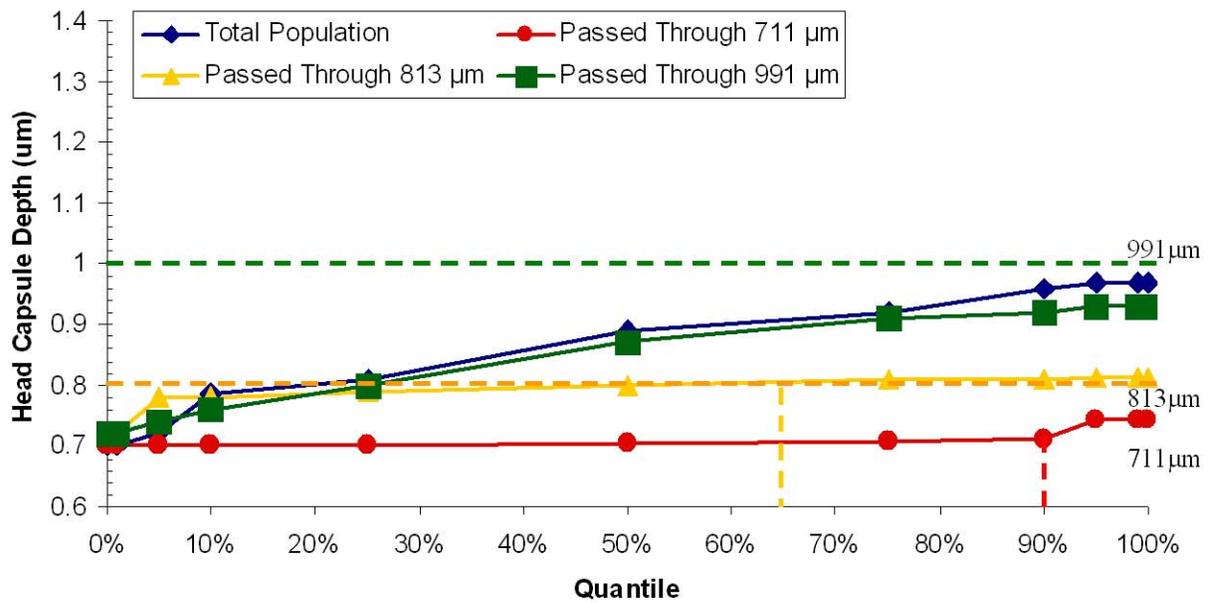


Figure 3-4. Linear regression comparing the maximum worker head capsule measurements (length, width, and depth) able to pass through the three crack widths (711, 813, and 911 μm) for each of the three termite colonies.

(A)



(B)

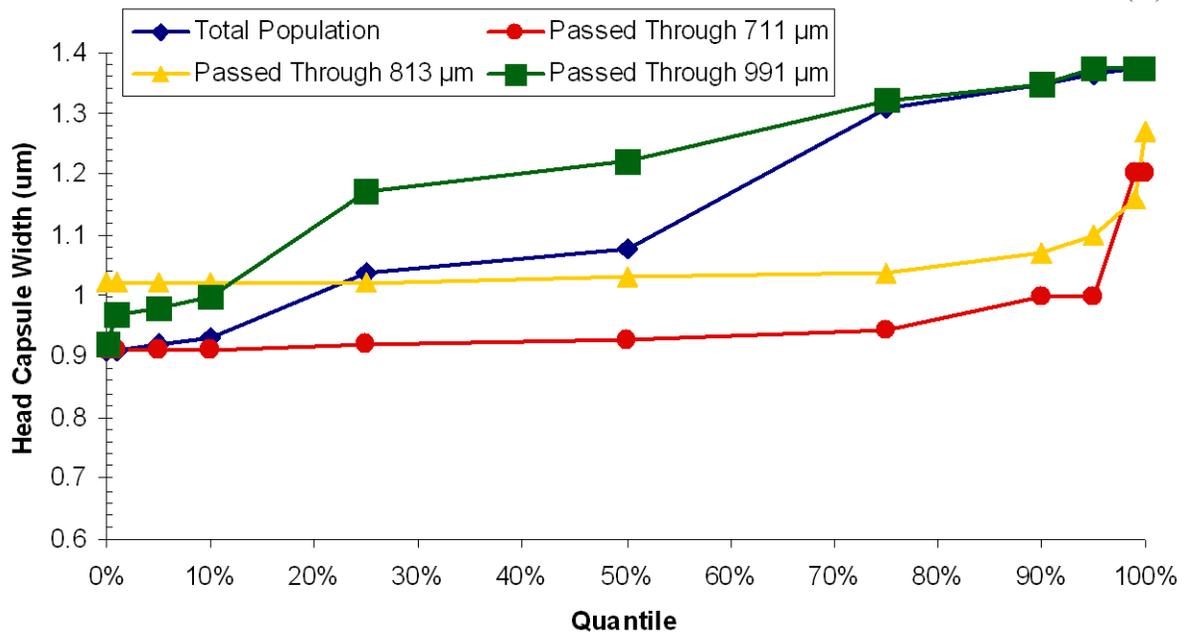


Figure 3-5. Quantiles of soldier head capsule width (A) and depth (B) measurements of the total population and the termites able to pass through the cracks of 711, 813, and 991 µm.

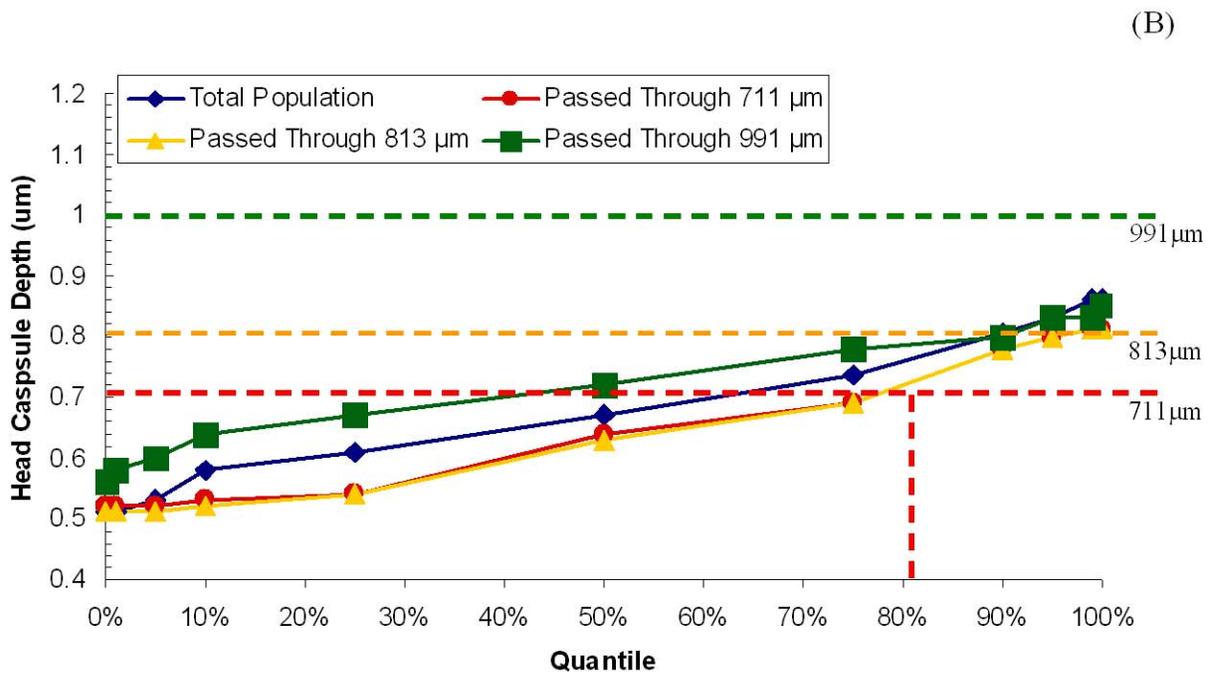
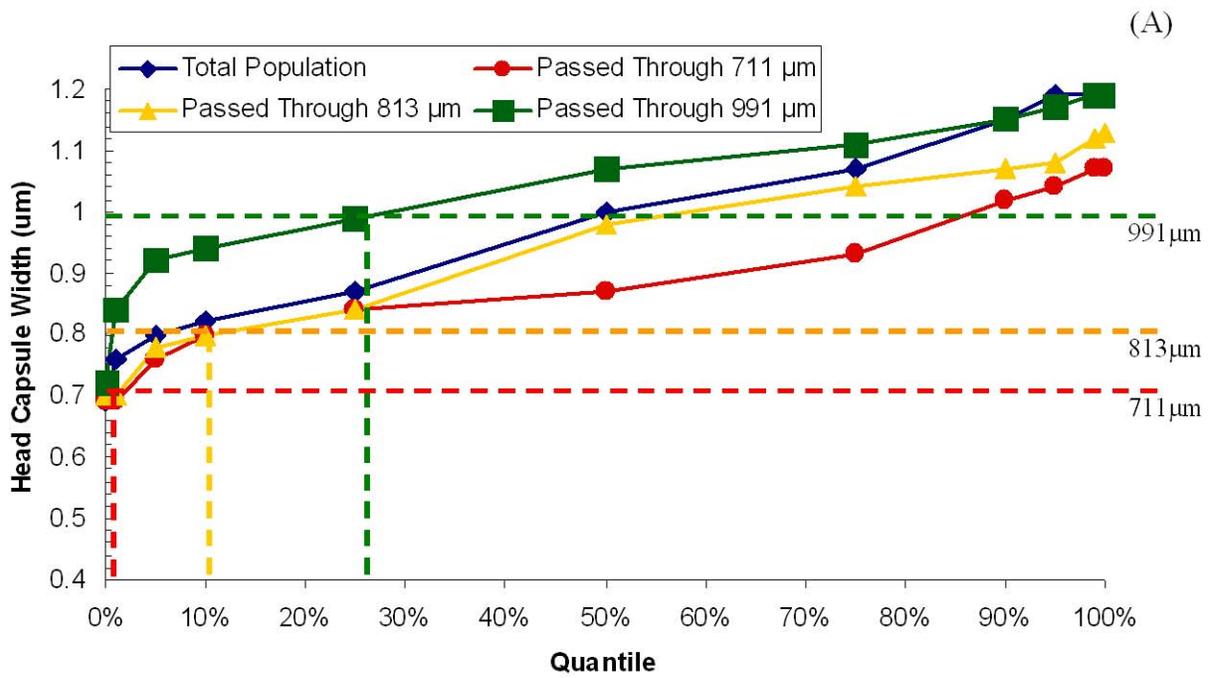


Figure 3-6. Quantiles of worker head capsule width (A) and depth (B) measurements of the total population and the termites able to pass through the cracks of 711, 813, and 991 μm .

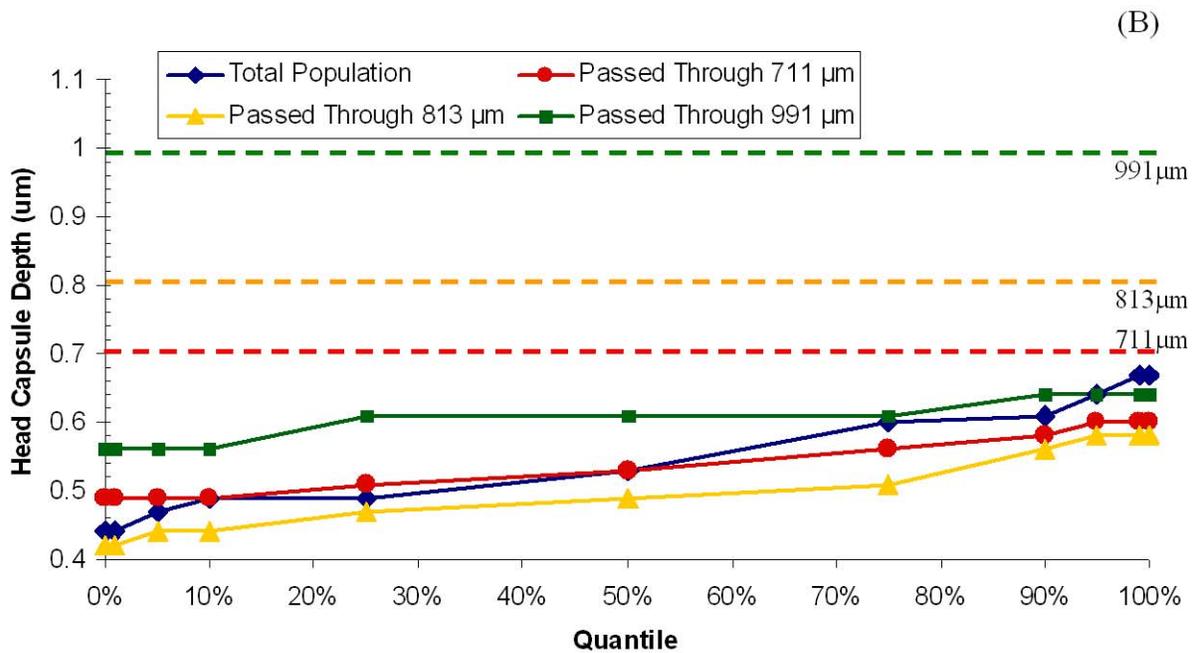
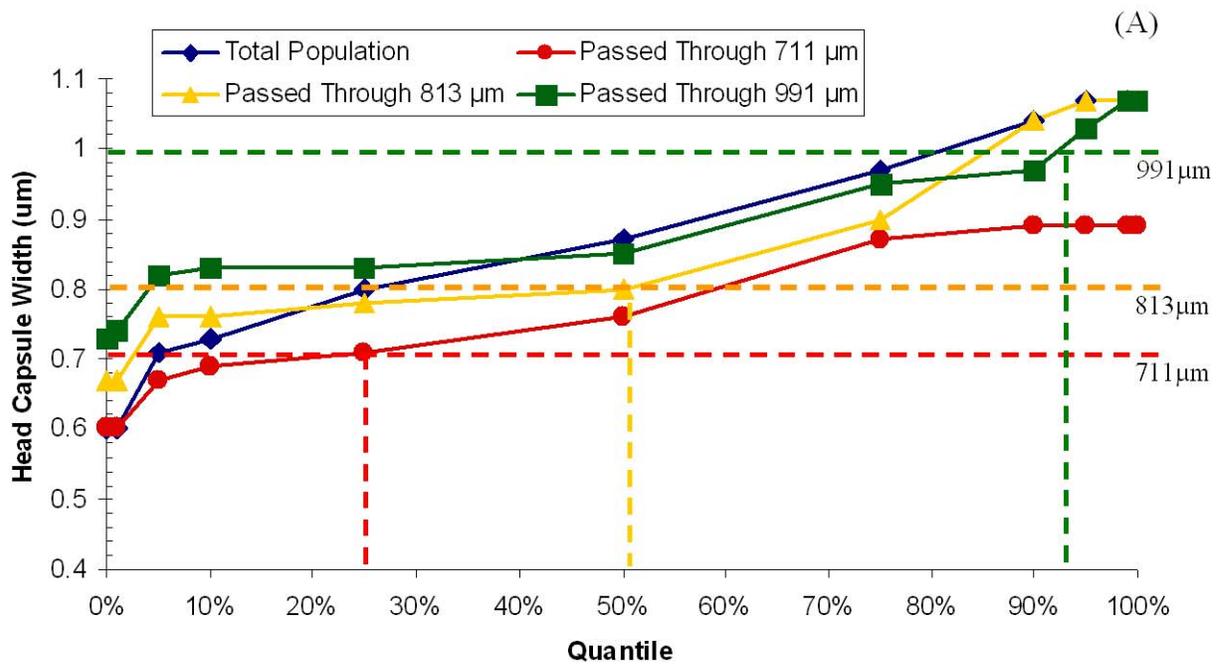


Figure 3-7. Quantiles of larval head capsule width (A) and depth (B) measurements of the total population and the termites able to pass through the cracks of 711, 813, and 991 μm .

CHAPTER 4
METHODS TO PREVENT PENETRATION OF CONCRETE-PIPE INTERFACES BY THE
EASTERN SUBTERRANEAN TERMITE

Introduction

Subterranean termites in North America typically nest in the ground and enter structures either around the foundation perimeter or next to pipe penetrations. Termites cannot penetrate concrete, so the foundation can act as a physical barrier to entry into the structure (Lentz et al. 1997) provided there are no cracks or other hidden termite entry points due to construction design. It has been shown that termite tunneling is influenced by guidelines and passageways (Pitts-Singer and Forschler 2000, Swoboda and Miller 2004). Therefore pipes beneath structures may guide termite movement into buildings through plumbing penetrations in the foundation.

Pipes for plumbing and utilities are placed during the initial construction phase before the slab is poured. An average slab-on-grade foundation has multiple pipe penetrations using several pipes typically composed of metal (copper) or plastics (chlorinated polyvinyl chloride [CPVC] and polyvinyl chloride [PVC]). Copper pipes are required by the current international building code (IBC 2006) to have pipe sleeving on pipe sections that penetrate and contact the slab to protect the pipe from corrosion and abrasion. Protective pipe sleeving is recommended by building codes (FBC 2004, IBC 2006) and the CPVC pipe manufacturer (Lubrizol 2007). No pipe sleeving is required or recommended for PVC pipe (IBC 2006).

The most common termiticide treatment for termite prevention at new construction is chemical treatment of the soil using a repellent or non-repellent termiticide. Chemical termiticide treatment around critical areas, such as plumbing, must extend 30 cm (1ft) below the sand-slab interface and is applied at a higher volume than elsewhere in the structure. Repellent termiticides can act as a chemical barrier (Tamashiro et al. 1987, Jones 1990, Smith and Rust 1990, Su and Scheffrahn 1990a, Grace 1991) provided there are no gaps in the treatment.

Lubrizol (2007) recommends that CPVC pipe sleeving extends at least 30 cm (1ft) below the slab, the same depth as the required termiticide treatment around critical areas. This could result in the soil around the bottom opening of the pipe sleeve containing relatively little or no termiticide. Termites foraging along the pipes could then enter the structure through the pipe sleeve, protected from any contact with the termiticide treatment. Termite infestations originating at gaps around pipe penetrations through the concrete slabs may go undetected long enough to result in significant damage to structures (AS 1995).

In addition to liquid termiticides, the US pest control industry currently has used two commercial products that may potentially prevent termite entry through gaps around pipe penetrations through slabs: Termimesh™ (Termimesh Australia Pty Ltd , Australia) and Impasse™ Termite Blocker (Syngenta Crop Protection, Inc., Greensboro, NC). Termimesh™, a stainless steel mesh with an aperture of 660 by 450 μm, has been documented to prevent termites from entering through gaps in slab over which the mesh is attached (ABSAC 1992, Lentz and Runko 1994). Impasse™ Termite Blocker, herein referred to as termite blocker, contains the repellent termiticide lambda-cyhalothrin sealed between two thick layers of construction-grade polymer, which prevents termites from chewing through the polymer (Su et al. 2004). Both products must be secured around pipes or other conduit before the concrete slab is poured, sealing the products into the foundation of the structure.

The purpose of this research was to evaluate the efficacy of physical and chemical products and their installation methods for preventing termite access along pipe penetrations to the upper surface of a concrete slab. The factors evaluated with typical plumbing were pipe sleeve length and composition in combination with soil termiticide treatment and termite blocker.

Materials and Methods

Termites

Eastern subterranean termites, *R. flavipes*, were field collected using traps from several locations in Gainesville, FL. A trap consisted of a 6-liter plastic bucket inserted below ground with its lid accessible above the soil surface. Each bucket was filled with 2-3 moistened corrugated cardboard rolls (15 cm long by 10 cm diam.; Gainesville Paper Co., Gainesville, FL). Termites accessed cardboard rolls through ~10 holes (4-cm diam.) on the sides and bottom of each bucket. Cardboard rolls containing termites were collected and returned to the lab. Termites were removed from the cardboard and reared at room temperature (~23°C) in plastic boxes (27 by 19 by 9.5 cm) with moistened cardboard for ≤ 2 wk before inclusion in the experimental arenas. The laboratory maintained termites used in the experiment were gently shaken from clean cardboard, weighed, and then inspected to confirm that there was approximately a 1:100 soldier:worker ratio.

Pipe Sleeve Experiment

Pipe Sleeve Treatments

Dry builders sand (0.04 m³) was treated with TalstarOne™ (Bifenthrin, FMC Corporation, Philadelphia, PA) diluted 8.7 ml in 5.6 L tap water to obtain the maximum label concentration of 0.12% a.i. The termiticide-treated sand was mixed in a cement mixer for 15 minutes, spread over a plastic tarp, and air-dried to allow termiticide to bind to the sand. A new termiticide mixture was prepared for each replicate. Untreated control sand was prepared in the same manner as the termiticide sand mixtures but using only tap water. All sand was remoistened (10% moisture wt:wt) immediately prior to use in the experiment.

Five treatment configurations of CPVC pipes (Flowguard®, Noveon, Inc., Cleveland, OH) (60 cm long, 2.2 cm OD [3/4 in.]) were evaluated. Pipes were installed without pipe sleeving or

wrapped in two lengths, 20 cm or 50 cm, of sleeving consisting of either foam (FosterKing, Thermwell Product Co., Inc., Mahwah, NJ) or polyethylene (Great Bay Productions, Inc. St. Petersburg, FL).

Pipe Sleeve Experimental Arena

The experimental arena (Figure 4-1) was constructed by capping a PVC tube (61 cm long x 15.3 cm diam.) and adding 5 cm of dry builders sand. A CPVC pipe (60 cm long, 2.2 cm OD [3/4 in.]), with or without pipe sleeving, was embedded in the sand. Concrete (Quickrete® concrete mix #1101, Atlanta, GA) poured on top of the sand around the CPVC pipe created a slab 15.3 cm diam. by 10 cm height. After the concrete dried, the PVC tube arena was inverted and the sand was removed. The CPVC pipe penetrated through the center of the slab, extending 5 cm above slab and 45 cm below the slab. Pipe sleeves were trimmed to be flush with the upper slab surface and to extend either 20 cm or 50 cm below the slab. Temporary wax paper wrappings were used to prevent contamination of non-treated arena surfaces and the space between the CPVC pipe and sleeve when treated sand was added. The wax paper was wrapped inside the lower 15 cm of the PVC tube distal to the concrete and around the bottom of the CPVC pipe and sleeves. Moistened sand treated with termiticide or water only was added to the PVC tube and extended ~30 cm below the concrete slab. This resulted in short pipe sleeves (20 cm) being contained within the termiticide treatment and the long pipe sleeves (50 cm) extending below the termiticide treatment. About 15 cm of untreated moistened builders sand was then added to fill the PVC tube. A pre-weighed, corrugated cardboard (8 cm²) was placed on the moistened untreated sand. Termites (10 g, ~2500 workers and 25 soldiers), were introduced on top of the cardboard. After termites tunneled into the sand, the bottom end of the tube was capped. Another pre-weighed corrugated cardboard disk (15.25 cm diam.) was placed around

the pipe on the top of the slab and the concrete-slab end was of the tube capped. The arenas were stored horizontally for 4 weeks at room temperature (~23°C and ~55% RH).

The ten treatments (5 CPVC pipe sleeve configurations x 2 sand treatments) were each replicated four times using a different termite colony for each replicate for a total of 40 experimental units and ~100,000 termites. The headspace above the concrete slab containing the cardboard disc in each arena was inspected for the presence of termites after 24 h and at weekly intervals thereafter. Arenas were disassembled after 4 weeks. All pre-weighed cardboard disks were removed, oven dried (40 °C for 24 h) and re-weighed to calculate consumption by termites. The sand and sleeves below the concrete slab of the arena were checked for presence of live termites.

Termite Blocker Experiment

Treatments

Termite blocker (1.9 cm [$\frac{3}{4}$ in.]) was installed according to manufacturer specifications around either CPVC or copper pipe (15.5 cm long, 2.2 cm OD [$\frac{3}{4}$ in.]) (Fig. 4-2). The pipes were sealed at both ends with pipe caps. The termite blocker consisted of a semi-rigid plastic collar (6.5 cm long) which fit snugly along the pipe shaft and completely encircled it. A 2.5-cm flange extended at a 90° angle completely around the middle of the collar. The flange was designed to extend into the concrete to block the gaps between the pipe and cement. The flanges were centered 7.75 cm from the ends of the pipe pieces and the collar secured with two cable-ties above the flange. Control CPVC and copper pipes were cut and capped for use without termite blockers.

After installation of the termite blockers, CPVC and copper pipe were wrapped with either foam sleeving (FosterKing, Thermwell Product Co., Inc., Mahwah, NJ) or polyethylene sleeving (Great Bay Productions, Inc. St. Petersburg, FL). The foam or polyethylene sleeves were cut in

two 7.25 cm lengths and installed above and below the termite blocker flange. For pipes without termite blocker, sleeves were 15.5 cm long. Because CPVC pipes can be used in construction without sleeving, CPVC pipes were also evaluated with no pipe sleeves and no termite blocker.

Termite Blocker Experimental Arena

The experimental arenas were designed to represent typical plumbing penetrations through the concrete slab and vapor barriers (Fig. 4-2). The arena was constructed by placing an open plastic container (240 ml; 7.4 cm height) in the center of a 6-liter plastic bucket (20 cm diam.; 19.5 cm height), then filling the bucket and plastic container with sand to 1.5 cm below the top opening of the plastic container. A 10 cm diameter plastic vapor barrier (6-mil), with a central cross-cut to allow the pipe penetration, was placed flush on top of the sand in the plastic container. The lip of the plastic container extended 1.5 cm above the vapor barrier. Pipe treatments with and without termite blocker were pushed into the sand through the cross cut in the vapor barrier, centered inside the plastic container so pipes would extend 2.75 cm into the sand. Concrete (Quickrete® concrete mix #1101, Atlanta, GA) was poured on top of the vapor barrier to a depth of 10 cm, embedding the termite blocker and lip of the plastic container and leaving 2.75 cm of the pipe exposed above the slab surface. For the five arenas with CPVC with no pipe sleeve and no termite blocker, a 20-cm long rod (1 by 4 mm) was installed adjacent to the pipe to simulate a temporary pipe support typically used during a concrete pour. The rod was removed before the concrete dried to leave an open channel adjacent to the CPVC pipe, a common occurrence in current construction practices. After the concrete dried, the bucket and supporting sand were removed from all treatments.

The arenas were temporally inverted and a 6-cm diam. hole was cut into the bottom of the plastic container. The dry sand in the plastic containers was replaced with 400 g builders sand (10% moisture), and cardboard (8 cm²) was added as a food source. Termites, (4.2 g, ~1000

workers:10 soldiers) collected from one location in Gainesville, FL, were introduced onto the cardboard. The hole was plugged and the arena was inverted. Wood blocks were placed under the concrete slabs extending outside the plastic container to stabilize the arenas in the upright position on the laboratory counter. Pipe sleeves were trimmed flush to the top of the concrete slab. An additional food source of a moistened, pre-weighed corrugated cardboard disk (10 cm diam.) was placed around the pipe on top of the concrete slab. To prevent moisture loss, a plastic container (240 ml; 7.4 cm height) was inverted over the pipe and cardboard on the concrete surface. The cardboard was moistened as needed throughout the experiment period.

The nine treatments (2 pipes x 2 pipe sleeves x 2 blocker + CPVC pipe only) were replicated five times. Arenas were checked daily for eight weeks to document the date that any termites were present above the slab. The arenas were disassembled after 8 wk. The pre-weighed cardboard disks on the concrete surface were removed, oven dried (40°C for 24 h), and re-weighed to calculate consumption by termites.

Data Analysis

In pipe sleeve length experiments, the number of experimental arenas where termites were able to access the moist cardboard above the concrete, and cardboard consumption (g), calculated from the dry cardboard weights before and after the assays, were analyzed with one-way analysis of variance (ANOVA) and were separated with Student-Newman Keuls (SNK), ($P = 0.05$; SAS 2001). In addition, a *t*-test compared termite slab penetration and cardboard consumption in treated and untreated sand for each combination of pipe sleeve length and composition (SAS 2001).

For the termite blocker experiment, the day of first appearance of termites above the slab and cardboard consumption were also analyzed with one-way analysis of variance (ANOVA) and were separated with Student-Newman Keuls (SNK), ($P = 0.05$; SAS 2001). A *t*-test

compared arenas having termite blocker and pipe treatments to arenas without termite blocker and the same pipe treatments (SAS 2001).

Results

Pipe Sleeve Experiment

On the bottom of the arena, termites consumed an average of 2 g (~83%) of the cardboard during the 28-day experimental period. There was no significant difference in consumption of the cardboard placed on the bottom in arenas treated with the repellent termiticide compared the untreated to arenas ($F = 2.29$; $df = 1$; $P = 0.1385$), or with different sleeve composition (no sleeve, foam, and polyethylene) and sleeve length (short [20 cm] and long [50 cm]) ($F = 0.84$; $df = 4$; $P = 0.5093$). Termites in the bottom of both termiticide treated and untreated arenas were active and healthy at the end of the 28-day experimental period.

The concrete poured in the experiments did not show any visible evidence of shrinkage or cracking around the pipe treatment penetrations on top of or below the slab after arenas were disassembled for inspection. The pipe treatments with sleeves were easily pulled from the concrete slab, however, the pipes without a sleeve were snugly fixed to the concrete.

At no time did the termites gain access the top of the concrete slab in arenas without pipe sleeves in either the termiticide-treated or untreated arenas. The sleeveless CPVC pipe was completely imbedded in the concrete slab with no gaps for termites to access the surface of the concrete. The termites were not able to access the surface of the concrete therefore they did not consume the cardboard on the surface (Table 4-1).

When termites were able to access the top of the concrete through the annular space between the pipe sleeve (foam and polyethylene) and pipe, they deposited frass, chewed cardboard, and sand on this surface and the adjacent PVC wall (Figs. 4-3A, B). Arenas in which

termites were unable to access the top of the concrete did not have frass and chewed cardboard on this surface (Figs. 4-3C, D).

Short (20-cm) foam or polyethylene pipe sleeves terminated within the termiticide-treated sand and were not damaged by termites (Figs. 4-4, 4-5). Termites were confined to the bottom of the arena below the treated sand due to the presence of the repellent termiticide and were unable to access or consume the cardboard on top of the concrete (Table 4-1). In the untreated arenas, termites were able to tunnel into the sand directly below the concrete, access and damage the 20-cm foam pipe sleeves (Fig. 4-4). The damage was concentrated in the upper part of the foam pipe sleeves at the concrete-pipe sleeve interface. Polyethylene sleeves, regardless of the termiticide treatment or length, were not damaged by termites (Fig. 4-5). In arenas with 20-cm sleeves in untreated sand, the termites tunneled into the annular space between the sleeve and pipe, and consumed the cardboard on the surface of the concrete in the first 24 h (Table 4-1). In arenas with 20-cm sleeves, there was significantly more cardboard consumed on the surface of the concrete in untreated sand compared with that of termiticide-treated sand (Table 4-1).

Long (50-cm) foam or polyethylene pipe sleeves passed through the termiticide-treated sand and terminated in the untreated sand (Figs. 4-4, 4-5). Termites were not able to tunnel into the termiticide-treated sand. Instead, termites tunneled in the annular space between the CPVC pipe and sleeve interface that terminated in the untreated sand, and thereby access and consume the cardboard on top of the concrete (Table 4-1). In both the termiticide-treated and untreated arenas, the damage to the 50-cm foam sleeve was concentrated in the upper part of the foam pipe sleeve at the concrete-pipe sleeve interface (Fig. 4-4). There was no damage to polyethylene sleeves (Fig. 4-5). Termites accessed and consumed the cardboard on the surface of the concrete in both termiticide-treated and untreated arenas in the first 24 h (Table 4-1). In arenas having 50-

cm sleeves, the consumption of cardboard on the surface of the concrete was not significantly different in termiticide-treated and untreated arenas (Table 4-1).

Termite Blocker Experiment

When termites were released into the moistened sand, they began to tunnel and explore the arenas. The cardboard squares at the bottom of the arena were not weighed; however, at the end of the experiment, part of this cardboard was consumed and the termites appeared to be healthy.

Termites reached the top of the concrete slab of the arenas on average between 2.2 and 3.6 days in all treatments having no termite blocker, whereas no termites reached the top of the slab in any termite blocker treatment ($F = 15.93$; $df = 8$; $P < 0.0001$). The difference in cardboard disk consumption in pipe sleeve treatments with and without termite blocker was significant (T-test; $T = 18.97$; $df = 38$; $P < 0.0001$). Termites consumed an average of 1.3 ± 0.1 g cardboard in all experimental arenas without termite blocker compared to no consumption of the cardboard disk in the termite blocker treatments (Fig. 4-6). There was no significant difference in cardboard disk consumed between treatments without termite blocker ($F = 0.5$; $df = 4$; $P = 0.7382$).

Termites caused observable damage to the foam insulation, tunneling into the foam pipe sleeves and removing foam. Termites also moved sand and fecal matter in their tunnels in the foam pipe sleeves. In arenas with foam pipe sleeves and termite blocker, damage to the foam pipe sleeve only occurred below the termite blocker flange. The termite blocker flange prevented passage of termites; therefore, termites were unable to damage the pipe sleeve above the flange. In arenas that had foam pipe sleeve treatments and no termite blocker, the foam pipe sleeve was extensively damaged by termite tunneling. Termites caused no damage to the polyethylene pipe sleeve material.

In arenas that had termite blocker, the flange imbedded in the concrete and the secure collar around the pipe prevented termites from accessing the slab surface. However, when the termite blocker was not installed, the termites constructed trails and shelter tubes in the annular space between the pipes and the sleeves that extended from the sand to the surface of the concrete. This tunneling behavior of lining the walls with sand and fecal matter was also observed in arenas with no termite blocker and no pipe sleeves, which had a hole created in the concrete with a rod.

The concrete poured in the experiments did not show any visible evidence of shrinkage or cracking around the pipe treatment penetrations on the top of the concrete slab. As in the previous experiment, the pipe treatments with sleeves could easily be pulled from the concrete slab, but the pipe treatments with termite blocker or without a sleeve were snugly fixed to the concrete.

Discussion

The pipe sleeve assays demonstrated that pipe sleeve length had a significant effect on termite movement through sand treated with a repellent termiticide and subsequent consumption of cardboard on the surface of the concrete. However, pipe sleeve composition and pipe type had no significant effect. Bifenthrin, a repellent termiticide, was effective in preventing termite passage through the slab, provided the pipe sleeve did not extend below the treated sand. If the pipe sleeve extended below the treated sand, the termiticide treatment was bypassed by the termites. This indicates that both foam and polyethylene sleeves are relatively impervious to termiticide, providing a protected route for termites to tunnel through and effectively avoid termiticide-treated sand.

Su et al. (1990a and 1993b) and Gahlhoff and Koehler (2001) found that subterranean termites were unable to tunnel through sand treated with bifenthrin in laboratory tube tests.

Powell (2000) determined that termites were able to detect sand treated with repellent termiticides and avoided the treated zone and access a food source through gaps in termiticide treatment in the sand. In our study, termites were also able to avoid the termiticide-treated sand and utilized the pipe as a guideline and the pipe sleeve as protection from the termiticide-treated sand. The protected environment within the pipe sleeve gave termites access to the surface when the pipe sleeve extended below the termiticide-treated sand.

Critical areas within a structure that are hidden from termite inspections include any pipe penetrations through a slab with pipe sleeving that may extend below termiticide-treated sand. Our study identified two commonly used pipe sleeves (foam and polyethylene) that allowed termite access to the surface of the slab when the pipe sleeves extended beyond the termiticide-treated sand. When the pipe sleeves terminated within the termiticide-treated sand, the termites were unable to access the surface of the slab.

Termites are known to follow natural guidelines in the soil, tunneling along objects like tree roots in search of food (Pitts-Singer and Forschler 2000, Campora and Grace 2001). This behavior may easily be adapted to pipes and pipe sleeves, so a longer pipe sleeve penetrating into untreated sand can give termites a guide to follow into the structure.

The termite blocker prevented termites from accessing the surface of the slab in all arenas in our experiments. When installed properly, termite blocker is embedded into the concrete and secured to the pipes, like Termimesh, to prevent termite access. In a field study, it was determined that *Heterotermes spp.*, a small species of subterranean termite, was able to squeeze through the screen openings of Termimesh™ (Lentz and Runko 1994). In contrast, Impasse™ Termite Blocker is a solid 2-layer membrane impregnated with lambda-cyhalothrin which is completely impenetrable to termites of any size (Su et al. 2004). Our study also showed that the

presence of termite blocker, regardless of pipe and sleeve type, prevents slab penetration by termites and subsequent above-slab consumption of cardboard.

Protective measures are important for preventing termite entry into structures via pipe slab penetrations. A properly installed pipe sleeve that does not extend below the termiticide-treated sand or termite blocker embedded in the concrete around the pipe both provides reliable protection. Current construction codes should be modified to require that pipe sleeves do not extend more than 20-cm below the slab and must terminate in the termiticide-treated zone. This would prevent termites tunneling inside sleeves to bypass the termiticide treatments. In addition, termite blocker could be used as a beneficial supplemental treatment when sand surrounding plumbing penetrations is not treated with a soil termiticide.

Table 4-1. Effect of pipe sleeve composition and length and termiticide treatment on Mean consumption (g) of cardboard (\pm SE) on top of the concrete slab by termites.

Composition	Sleeve		Termiticide-treated ^a		Untreated ^b		<i>t</i>	df	<i>P</i>
	Length ^c	Termites ^d	Consumption (g) \pm SE	Termites ^d	Consumption (g) \pm SE				
--	no sleeve	-	0.00 \pm 0.00b	-	0.00 \pm 0.00b	-	6	-	
foam	short	-	0.00 \pm 0.00b	+	2.54 \pm 0.26a	9.60	6	< 0.0001	
	long	+	2.40 \pm 0.25a	+	2.48 \pm 0.27a	0.20	6	0.8462	
polyethylene	short	-	0.00 \pm 0.00b	+	2.39 \pm 0.41a	5.86	6	0.0011	
	long	+	2.75 \pm 0.21a	+	2.58 \pm 0.50a	-0.27	6	0.7974	

Consumption is in g. Means within a column followed by the same letter are not significantly different. (Student-Neuman-Keuls Means Separation, $P = 0.05$, SAS Institute 2001). A *t*-test compared data within a row. $n = 4$ replicates. ^a Termiticide-treated sand prepared with TalstarOne, SNK termiticide-treated; $F = 91.11$, $df = 4$, $P = <0.0001$, ^b Untreated sand prepared with tap water, , SNK untreated; $F = 11.29$, $df = 4$, $P = 0.0002$, ^c Short = 20 cm; long = 50 cm, ^d Termites able to access concrete surface.

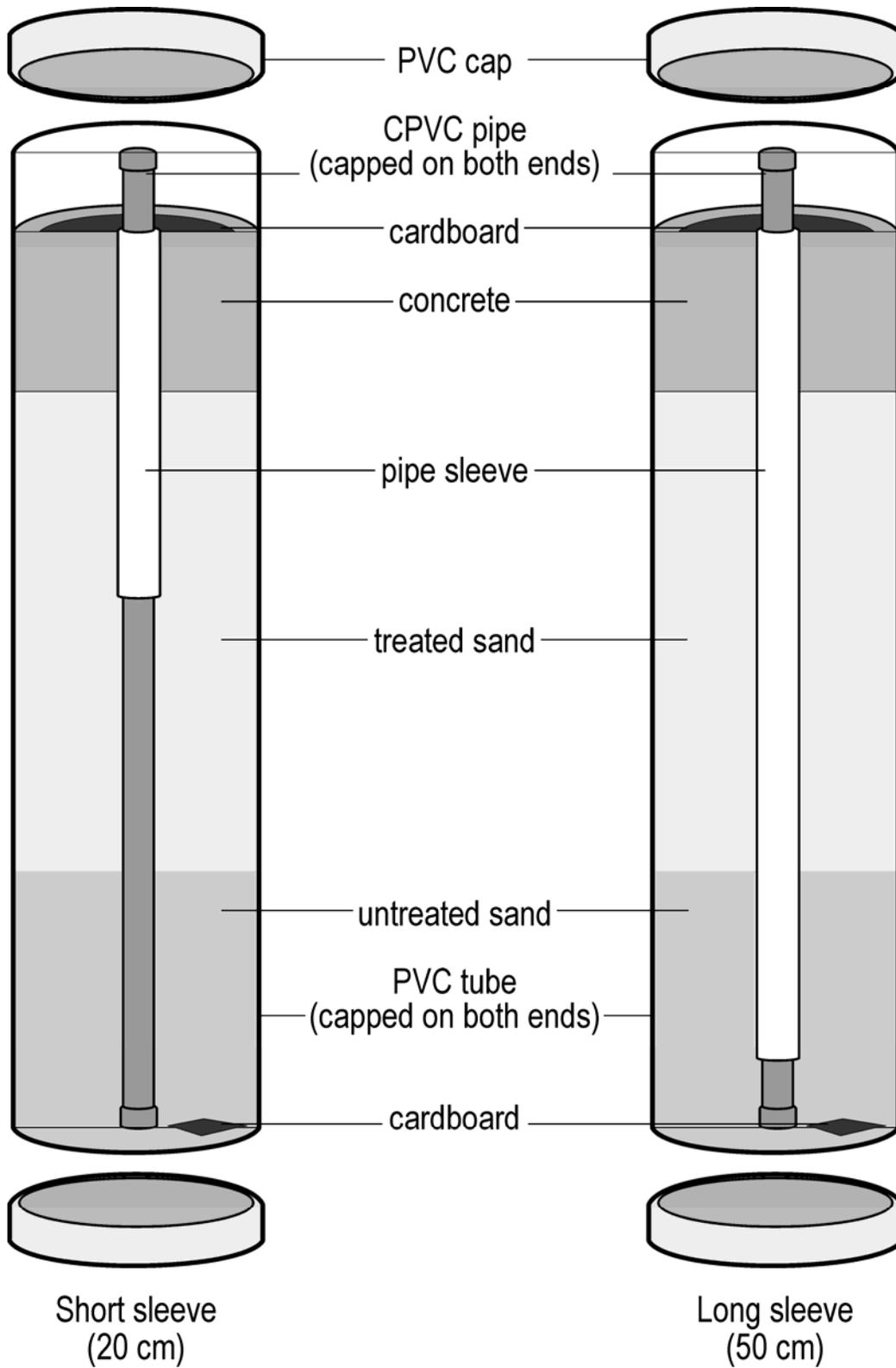


Figure 4-1. Pipe sleeve experimental arena.

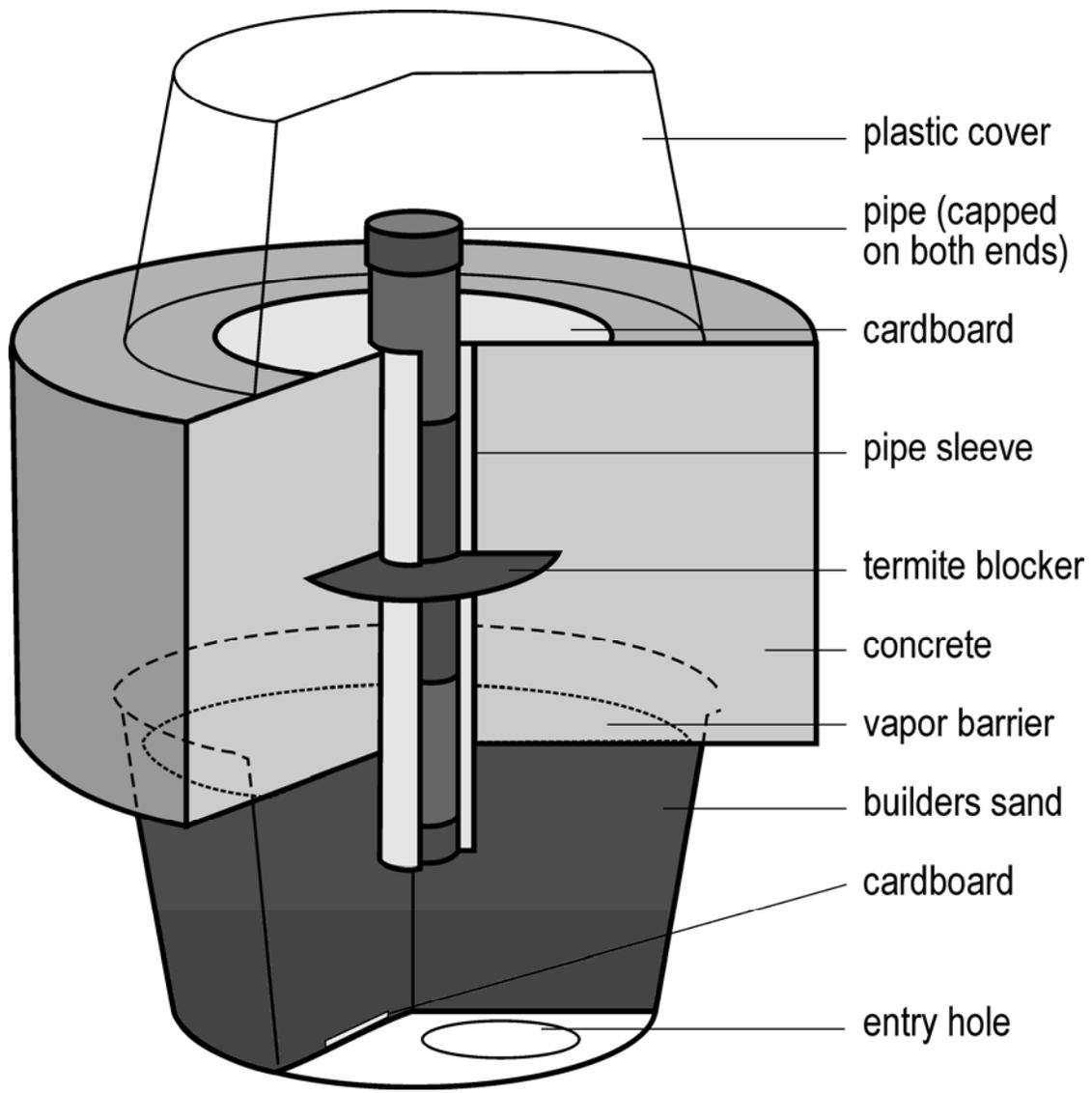


Figure 4-2. Termite blocker experimental arena.



Figure 4-3. Top view of typical pipe sleeve experiment arenas at 28 d. A) and B) are representative arenas where termites reached the top of the concrete. C) and D) are representative arenas where termites could not access the top of the concrete.

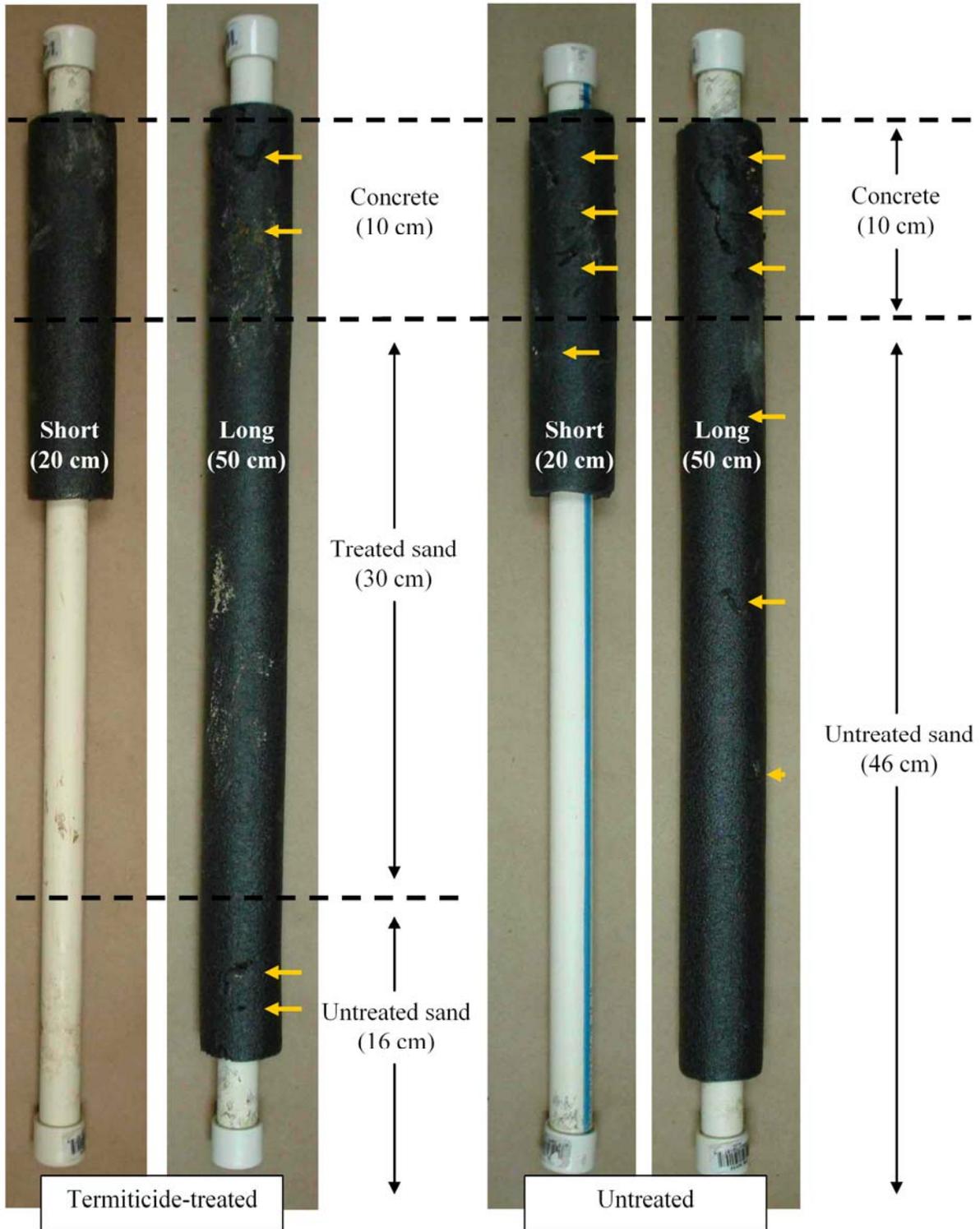


Figure 4-4. Foam pipe sleeves exposed to eastern subterranean termites for 28 d in termiticide-treated and untreated arenas. Arrows indicate location of termite surface damage.

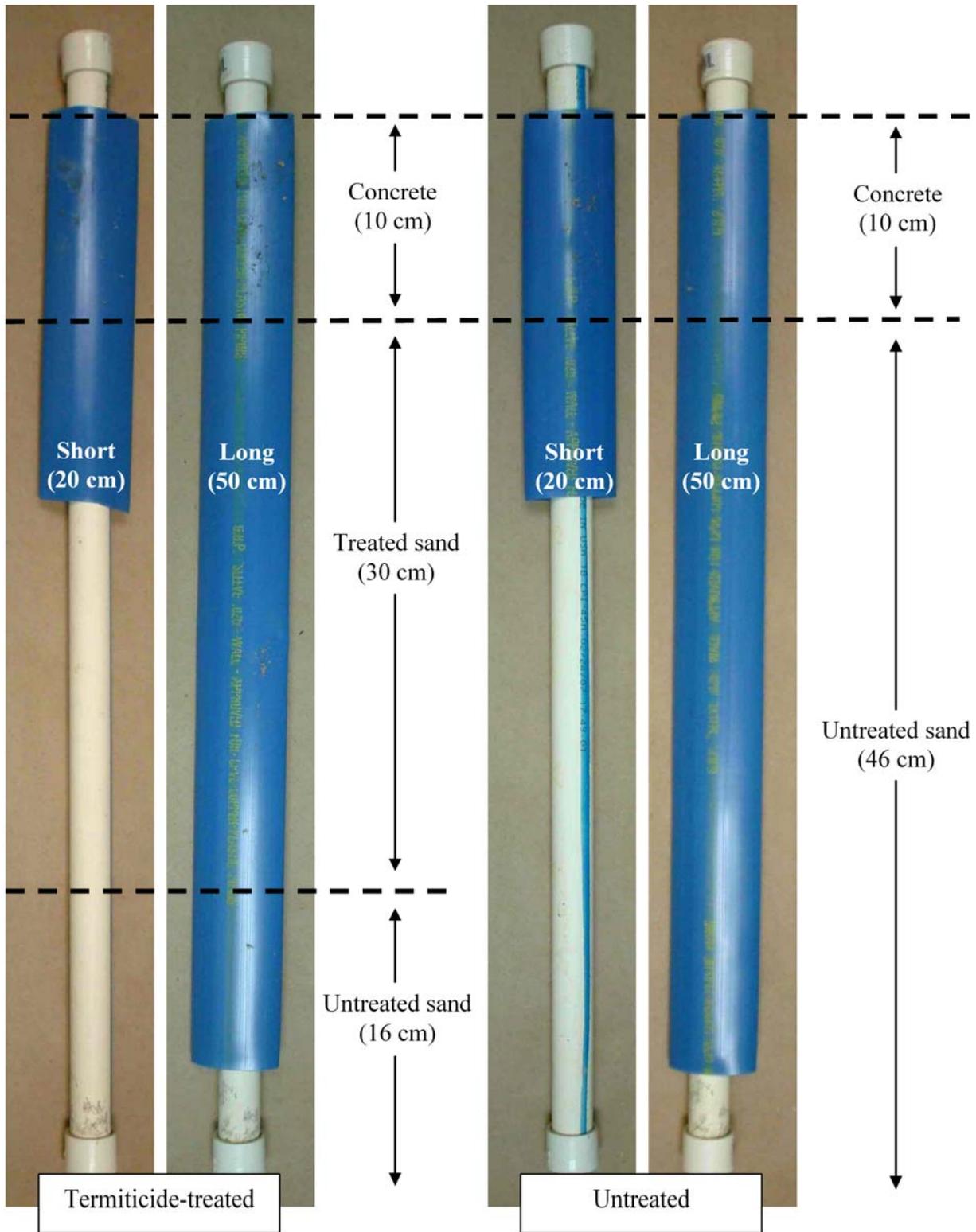


Figure 4-5. Polyethylene pipe sleeves exposed to eastern subterranean termites for 28 d in termiticide-treated and untreated arenas.

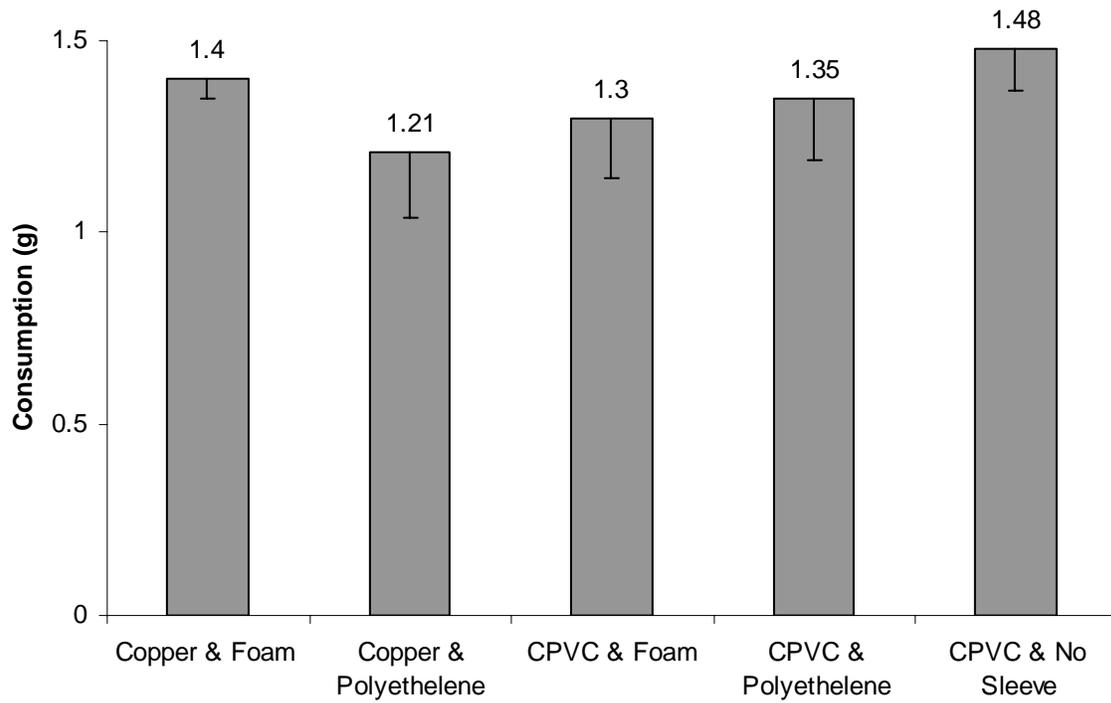


Figure 4-6. Mean cardboard consumption (g) (\pm SE) after 8 wk by termites in arenas without termite blocker around copper and CPVC pipes, with or without foam or polyethylene sleeves.

CHAPTER 5
DEVELOPMENT OF A METHOD TO EVALUATE THE EFFECTS OF EASTERN
SUBTERRANEAN TERMITE DAMAGE TO THE THERMAL PROPERTIES OF BUILDING
CONSTRUCTION MATERIALS

Introduction

Reticulitermes flavipes (Kollar) is a species of subterranean termite well known in North America for the damage it causes to homes and other buildings. The damage is most commonly thought of in terms of weakening a structure, making infested areas prone to collapse (Harris 1965, Johnston et al. 1979). Water damage is also associated with these termites, as they bring moisture from the soil into their galleries within the structure (Hickin 1971, Grube and Rudolph 1999b).

One aspect of damage that has been overlooked is the change in the thermal properties of a structure after infestation by subterranean termites. This is a concern in any structure built in a climate that varies from the comfortable human range of ca. 20-25°C. Materials damaged by subterranean termites are typically filled with galleries or, in the case of wood, laminar spaces where spring wood has been eaten away (Forschler 1999b). These spaces may facilitate the transfer of heat through a material, compromising the material's capacity for insulation. If material in an exterior wall is compromised, it will cost more to maintain a comfortable temperature range within the structure. In this way, termite damage can be even more costly than is generally believed.

In most American homes, exterior walls of structures are often made up of cellulosic materials, such as the structural lumber (e.g., 2x4) and siding material (e.g., 5-ply plywood). These two building materials are the most common exterior wall components in use that termites are capable of consuming. Another class of building material highly relevant to thermal transfer is insulation (e.g., rigid foam board). While most types of insulation are composed of plastics or

fiberglass, and thus cannot constitute a food source for termites, the soft texture found in many types of insulation makes them easy for the termites to tunnel through (Bultman et al. 1972 missing from ref cited; Hickin 1971, NPCA 1993). In fact, the physical qualities of insulation materials confer an appreciable amount of internal temperature stability, making them an almost ideal habitat for termites. While termites may not be able to effectively consume most types of insulation, they can still tunnel into and cause significant damage to insulation (Guyette 1994, Smith and Zungoli 1995ab, Ogg, 1997).

The first objective of this experiment was to determine the relative damage by subterranean termites to each building material. The second objective was to determine differences in the rate of heat transfer and, consequently, temperature change between damaged and undamaged samples of each building material.

Materials and Methods

Termites.

Five colonies of *R. flavipes*, separated by more than 1.5 km in Gainesville, FL, were field collected in 6-liter plastic buckets inserted below ground with their lids accessible above the soil surface. Each bucket was filled with 2-3 moistened corrugated cardboard rolls (15 cm long by 10 cm diam.; Gainesville Paper Co., Gainesville, FL). Termites accessed cardboard rolls through ~10 holes (4-cm diam.) in the sides and bottom of each bucket. Cardboard rolls containing termites were collected and returned to the lab in Ziploc bags (3.8-L). Termites were removed from the cardboard by gently separating the corrugated cardboard and allowing the termites to fall into a 20-L plastic bucket. The termites were then placed on moistened corrugated cardboard and reared at room temperature (~23°C) in plastic boxes (27 by 19 by 9.5 cm) with moistened cardboard for ≤1 wk before inclusion in experimental arenas. Worker termites of at least 3rd

instar were aspirated into groups of 300 workers with a 1% soldier population for use in the experiments.

Termite Damage to Construction Materials.

Three building construction materials were tested: pine 2x4s, 5-ply plywood, and rigid foam board insulation. The 2x4s were cut across the grain to a thickness of 1.27 cm [$\frac{1}{2}$ inch]. Five-ply plywood and rigid foam insulation had a thickness of 1.2 cm [$\frac{15}{32}$ inch] and 1.9 cm [$\frac{3}{4}$ inch], respectively. Each material was cut into square samples (4 x 4 cm) for exposure to termites. The building materials were oven-dried at 40°C for 24 h and pre-weighed.

Moistened sand (10% water content) was evenly distributed inside a 0.74 L plastic container (GladWare®; Glad Products Co., Oakland, CA). A sample of building material was placed on a linoleum square (7.5 x 7.5 cm) on the surface of the sand. The linoleum provided a barrier between the moistened sand and the building material. Termites were placed on the moistened sand next to the linoleum and the building material. Lids were placed on the containers, which were stored in the laboratory at ~23°C. Control arenas containing no termites were prepared in the same manner.

The arenas were opened 8 wk after setup. Sand and termites were brushed off the surface of the building materials and galleries. Building materials were then oven dried at 40°C for 24 h and re-weighed to calculate termite damage. A digital image of each building material sample was taken to record the visible damage caused by termites.

An experimental unit was defined as a plastic arena with a building material, sand, linoleum, and 300 termites. Each building material (n=3) was evaluated using five termite colonies with five replications per colony. The experiment had an equal number of control units with no termites, resulting in a total of 150 experimental units tested.

Thermal Imaging.

The cleaned and oven dried building materials were photographed using an infrared (IR) thermal imaging camera (FlexCam®; Fluke Corporation. Everett, WA). A tripod held the thermal camera in place ~53 cm above a building material. An enamel container filled with dry sand (2000 g builders sand) was placed on a hot plate and heated to 52°C. The building materials were tightly fitted to a pre-cut hole in rigid foam insulation square (10 x 10 cm) to minimize the edge effect of heat radiating from the sand and hot plate. The building material, with the rigid foam insulation surrounding it, was placed on the heated builders sand and thermal images were taken at 0.5, 5, 10, and 15 min. During initial testing, the surface temperature reached equilibrium for the samples during the 15 minutes period. The digital file associated with the image included a thermal map of surface temperatures for the building material and a record of the minimum, maximum, and average surface temperatures.

Data Analysis.

Percent damage from pre- and post-exposure weights of each sample of building material was calculated, arcsine square root transformed, analyzed by one-way analysis of variance, and means separated with SNK ($P = 0.05$; SAS Institute 2003). The initial temperature and the maximum temperature reached during 15 min of heating for each building material was recorded, and the mean temperature increase for the upper surface of the building material was calculated. Significant differences in temperature for damaged and undamaged building materials were determined with Student's *t*-test ($P = 0.01$). The percentage increase in temperature of a damaged sample in relation to the temperature of the same material not damaged by termites was calculated.

Results

All three building construction materials were damaged by termites. Termites tunneled into the insulation, removed the plastic, and caused significantly more damage, based on weight loss, by tunneling in the insulation than by consuming either the wooden 2x4 or plywood samples (Table 5-1). Plywood samples had significantly less damage than did the other building materials.

2x4s.

The rings of lighter, spring wood and darker, summer wood were obvious in the visible spectrum images (Fig. 5-1A). However, the rings were not noticeable in the thermal images (Fig. 5-1C) indicating no noticeable difference in heat transfer between spring and summer wood. The thermal images of undamaged 2x4 samples showed uniform heat transfer through the wood at 0.5, 5, 10, and 15 min with the average surface temperature increasing only 0.5°C, from 23.9 to 24.4°C in the representative sample (Fig. 5-1C). After 15 min of heating, the undamaged 2x4 sample had a narrow range of temperatures (23.8 to 25.2°C) across the surface.

Termites ate a mean of 6.7% of each exposed 2x4 sample, causing characteristic damage in the form of distinct lamellar tunnels excavated in the annular rings of the spring wood (Table 5-1)(Fig. 5-1A). The thermal images of damaged 2x4 samples showed a greater overall heat transfer compared with undamaged samples. There were distinct localized hot spots in the images of the damaged 2x4s, where heat passed through more rapidly, that coincided with the location of termite tunnels (Fig. 5-1B). After 15 min of heating, the representative damaged 2x4 sample had a wide range of surface temperatures (24.5 to 30.6°C), typical of the samples tested.

The mean temperature for all 2x4 samples was $\sim 24^{\circ}\text{C}$ at 0.5 min (Table 5-1). After 15 min exposure, the average maximum surface temperature reached was 35% greater and significantly more for termite damaged samples (31.0°C) compared to undamaged samples (28.8°C).

Plywood.

Samples of plywood showed fairly wide bands of spring and summer wood in the upper layer, indicating a fairly oblique, longitudinal cut across the wood rings (Fig. 5-2A). Thermal images of the undamaged samples showed almost uniform heat transfer, indicating no noticeable difference in heat transfer for spring and summer wood areas of the plywood samples. The images showed little rise in temperature through 15 min of heating from 23.4 to 23.8°C in the representative sample (Fig.5-2C), indicating plywood is a good insulating material. After 15 min of heating, the undamaged representative plywood sample had a narrow range of temperatures (23.3 to 25.2°C) across the surface.

Termites ate a mean of $\sim 3\%$ of each plywood sample (Table 5-1) (Fig. 5-2A). Rather than excavating tunnels in spring wood as seen in the 2x4 sample (Fig. 5-1A), the termites tunneled between plywood layers and consumed portions of the spring wood bands in each layer. The thermal images of damaged plywood showed a greater overall heat transfer compared with undamaged samples. The damage was demarcated by increased heat transfer and localized hot spots in the thermal images (Fig. 5-2B). After 15 min of heating, the representative damaged plywood sample had a wider range of temperatures (24.0 to 27.2°C) across the surface compared to that of the undamaged sample.

For all the plywood samples, the mean temperature at 0.5 min was $\sim 24^{\circ}\text{C}$ (Table 5-1). After 15 min of heating, the average maximum temperature was 25.7°C for undamaged plywood

and 27.5°C for termite damaged plywood. The increase in temperature for termite damaged plywood was 74% greater and significantly more than that for undamaged plywood.

Rigid Foam Board Insulation.

Undamaged samples of rigid foam board insulation were very homogenous in appearance. The insulation material of foam was covered by a radiant barrier composed of kraft paper covered by a thin layer of aluminum. The undamaged sample of rigid foam insulation showed low heat transfer and temperatures were very uniform across the entire surface, as observed in the representative sample (Figure 5-3C). The thermal images of the representative undamaged insulation sample showed an average surface temperature increase of only 0.4°C, from 23.4 to 23.8°C, after 15 min of heating, which was typical of samples tested.

Termite-damaged rigid foam insulation was riddled with extensive termite tunnels (Fig. 5-3A), lined with soil and fecal material. The tunnels were more extensive than those seen in the 2x4 or plywood samples, most likely due to the soft nature of the insulation. The radiant barrier had been largely eaten away, exposing the scarified, pitted foam. The thermal pictures of damaged insulation samples showed a greater degree of temperature variability across the surface of the insulation. The hotspots coincided with areas where termites had tunneled and removed the insulation material (Fig. 5-3B). After 15 min of heating, the representative damaged rigid foam insulation had a wide range of surface temperatures (24.2 to 30.0°C)

Heat transfer in damaged rigid foam insulation samples was greatly increased within the extensive tunnel system (Table 5-1). For all the insulation samples, the mean temperature was ~23°C at 0.5 min. After 15 min of heating, the average maximum surface temperature was 27.4°C for undamaged samples and 28.7°C for damaged samples. The temperature increase was ~27% greater and significantly more for damaged insulation compared to undamaged insulation.

Discussion

All building materials tested were damaged by termites. There was very little correlation between the percentage damage (% weight loss) of the building material and the percentage increase in surface temperature caused by termite damage. It appeared that intrinsic thermal properties of the construction material and configuration of termite tunneling were important in determining the increase of thermal conductivity in relation of weight loss. Plywood samples had the lowest percentage damage caused by termites and the greatest percentage increase in surface temperature of damaged versus undamaged samples. The temperature increase in damaged and undamaged plywood was the lowest of all the materials tested. This indicates that of the undamaged materials tested, plywood was the most resistant to heat flow through it; however, once eaten by termites, plywood was the most thermally damaged. This may be due to the laminar structure of the plywood. Termites tunneled with the grain and between the layers of plywood; however, some tunnels cut through the plywood layers allowing heat to flow through the material. Consequently, the impact of termite tunneling through the layers was more thermally significant than expected by the amount of wood damage.

Not surprisingly, rigid foam insulation was the second-most heat resistant material tested in its undamaged state. Nonetheless, rigid foam had greatest weight loss of all the building materials and the termite damage created a network of tunnels allowing heat transfer. Termites tunneled throughout the rigid foam board, leaving multiple routes of rapid heat transfer between surfaces of the sample.

The significantly greater temperature increase seen in 2x4 materials in comparison to plywood was due to the cross-sectional nature of 2x4 samples. Plywood had wood fibers mostly perpendicular to the direction of heat flow; whereas the 2x4 cross-sections had the wood fibers mostly parallel to the direction of heat transfer assayed. Termites mainly tunneled along the

fibers and within the softer spring wood. These tunnels penetrated the sample allowing heat to flow unobstructed through the sample. As a result, small termite wood damage of only 6-7% was responsible for 35% greater increase in temperature in damaged samples compared to undamaged samples.

With the increasing cost of energy, houses are being built to be more energy efficient using foam insulation as well as wooden components. The impact of termites on the thermal properties of these building materials has been virtually overlooked. Our research documented that termites can significantly negatively impact the thermal properties of building construction materials designed to be energy efficient. Our research demonstrates the importance of termite control for home energy conservation.

Table 5-1. Percent damage and surface temperature increase for building materials heated for 15-min. Damaged materials were exposed to eastern subterranean termites (n=300) for 8 wk.

Material	Damaged/ undamaged	% damage	Initial temp	Mean highest surface temp	Temp increase ^a	% temp increase ^b
2x4	Undamaged	-	24.2 ± 0.25	28.8 ± 0.12	4.5 ± 0.24	-
	Damaged	6.7 ± 0.75b	24.9 ± 0.24	31.0 ± 0.15*	6.1 ± 0.28*	34.8
Plywood	Undamaged	-	24.1 ± 0.23	25.7 ± 0.15	1.6 ± 0.20	-
	Damaged	3.1 ± 0.33c	24.8 ± 0.24	27.5 ± 0.11*	2.7 ± 0.29*	74.0
Insulation	Undamaged	-	23.4 ± 0.04	27.4 ± 0.08	4.0 ± 0.10	-
	Damaged	12.1 ± 1.10a	23.6 ± 0.10	28.7 ± 0.14*	5.1 ± 0.19*	27.1

* significant difference between damaged and undamaged ($P = 0.01$, Students t -test). ^a Mean temperature increase at the upper surface of the building material (4 x 4 cm) when lower surface was exposed to hot plate at 52°C for 15 min, ^b % temperature increase = ((damaged [temp increase] – undamaged [temp increase])/undamaged [temp increase]).

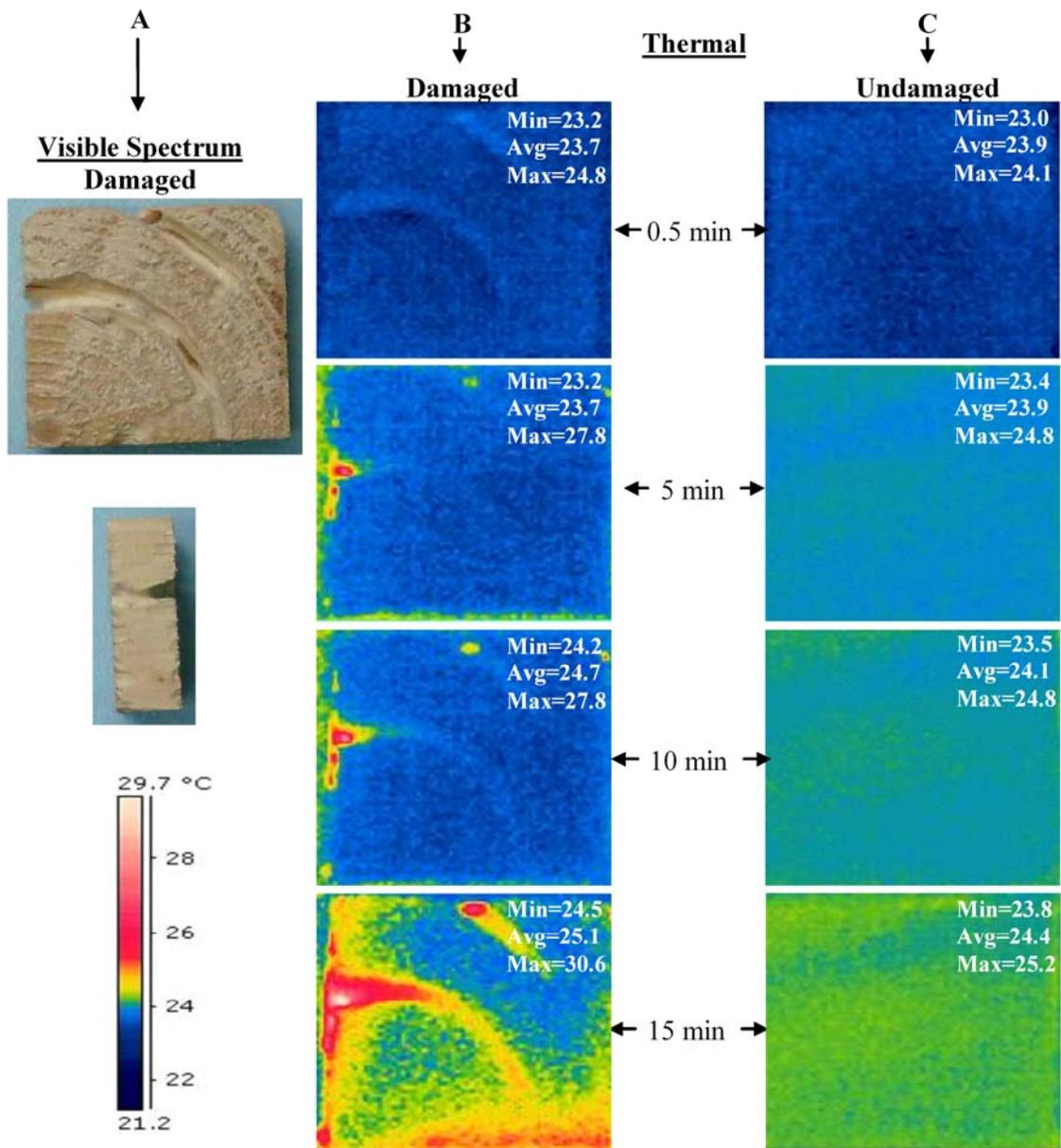


Figure 5-1. Images of a 2x4 sample after exposure to 300 termites for 8 wk. A. Visible spectrum images of a damaged 2x4 sample. B. Thermal images of a damaged 2x4 sample heated over 15 min. C. Thermal images of an undamaged 2x4 sample heated over 15 min.

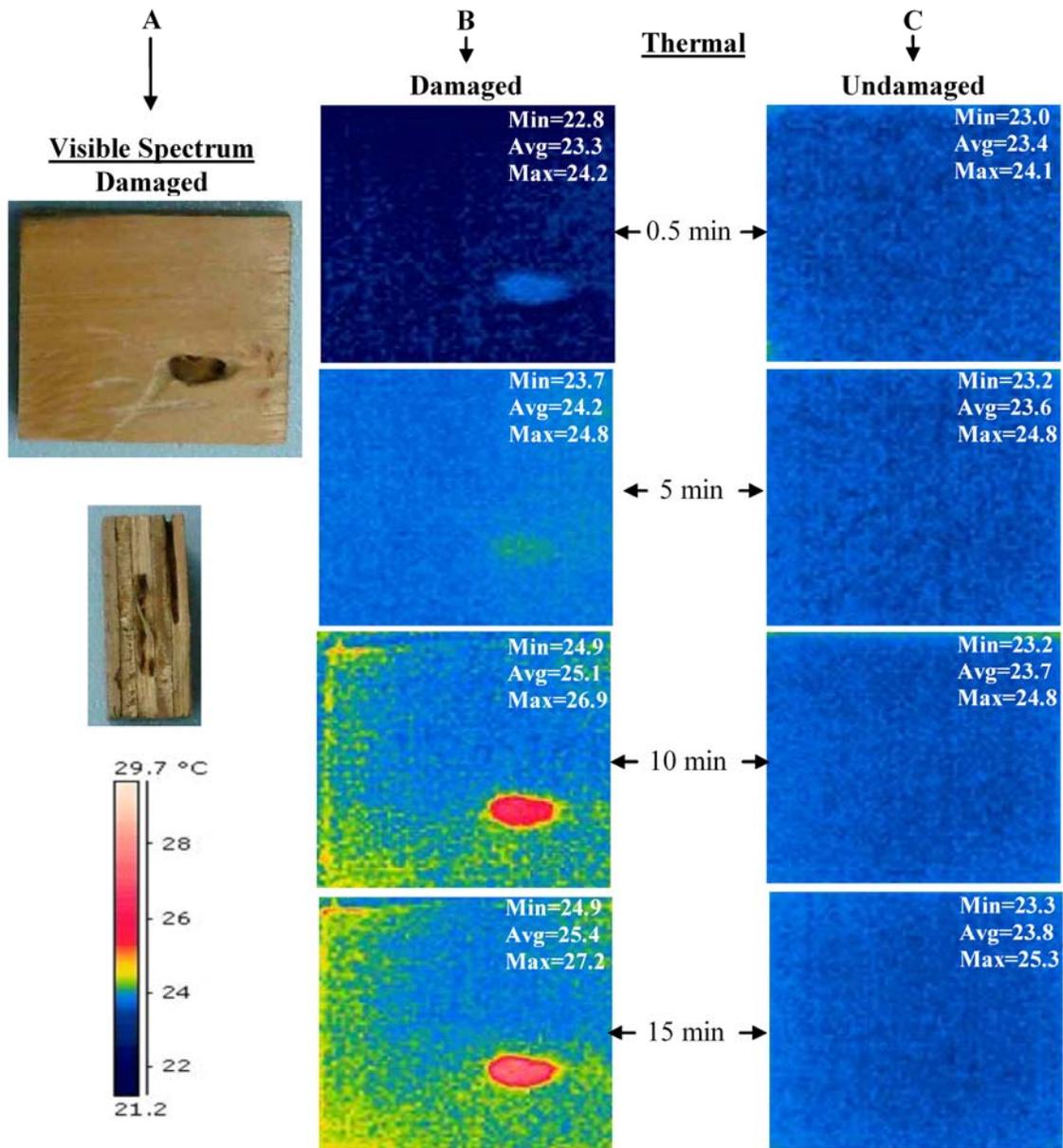


Figure 5-2. Images of a plywood sample after exposure to 300 termites for 8 wk. A. Visible spectrum images of damaged plywood samples. B. Thermal images of a damaged plywood sample heated over 15 min. C. Thermal images of an undamaged plywood sample heated over 15 min.

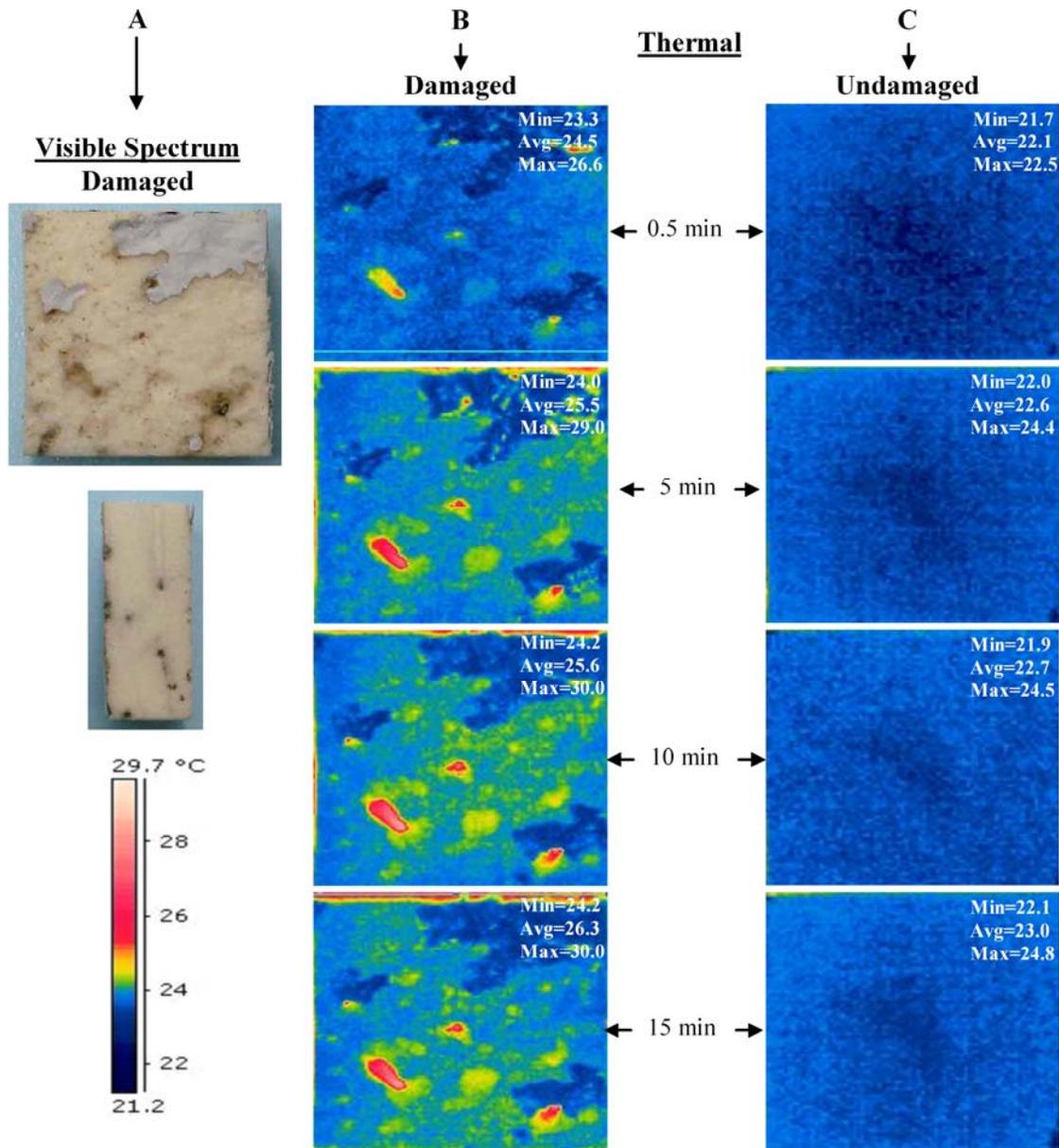


Figure 5-3. Images of a rigid foam insulation sample after exposure to 300 termites for 8 wk. A. Visible spectrum images of a damaged rigid foam insulation sample. B. Thermal images of a damaged rigid foam insulation sample heated over 15 min. C. Thermal images of an undamaged rigid foam insulation sample heated over 15 min.

CHAPTER 6
EFFECTS OF EASTERN SUBTERRANEAN TERMITE DAMAGE ON THE THERMAL
PROPERTIES OF COMMON BUILDING MATERIALS

Introduction

Reticulitermes flavipes (Kollar) is a species of subterranean termite well known in North America for the damage it causes to homes and other buildings. The damage is most commonly thought of in terms of weakening the materials of the structure, making potentially costly repairs and renovations necessary. Water damage can also result from termite infestation. Termites, *R. santanensis* De Feytaud, use their labial glands to move water into structures they infest to maintain humidity and temperature in their gallery system, increasing the moisture content of the building construction materials (Grube and Rudolph 1999ab).

One aspect of termite damage that is often overlooked is the change in the thermal properties of a structure. This is a concern in any structure built in a climate that varies from the comfortable human range of ca. 20-25°C (ASHRAE 2005). Solid materials damaged by subterranean termites are typically filled with galleries that may facilitate the transfer of heat through an object, compromising the material's capacity for insulation. If an exterior wall of a structure is compromised by termites, it may cost more to maintain a comfortable temperature range within the structure. Therefore, termite damage to the thermal conductivity of a building can be more costly than previously known and precede damage that compromises the structural integrity or appearance of a building.

Exterior walls of structures are made up of structural lumber, siding materials, insulation, and other internal components. Typical structural lumber is 2x4 or 2x6 cut from either Southern yellow pine or Douglas fir trees, depending on the region. Common siding materials of plywood (5 ply) or T1-11 siding (T1-11) are constructed from uniform layers or veneers of wood. The uniform layers cut from logs are stacked so that the wood fibers of each layer are perpendicular

to each other, compressed and bonded together with glue. Another common siding material is oriented strand board (OSB), formed by layering fragments of wood (2.5 by 15 cm) in specific orientations. The surface of the OSB is rough with wood fragments positioned unevenly across each other. The rectangular wooden fragments are compressed and bonded together with wax and resin adhesives. The five types of building materials referenced above are common exterior wall components composed of wood that termites are capable of consuming

Another class of building material important in thermal transfer is insulation. While most types of insulation are created from synthetic materials and cannot constitute a food source for termites, the soft texture found in many types of insulation makes it easy for the termites to tunnel through (NPCA 1993). In fact, the physical qualities of insulation materials confer internal temperature stability, making them a suitable habitat for termites. Even though termites may not be able to effectively digest most types of insulation, they can still severely damage the product (Guyette 1994, Smith and Zungoli 1995ab, Ogg 1997).

Energy efficiency codes for building construction require structures to meet minimum insulation prescriptive standards. The United States is divided into eight climate zones (Briggs et al. 2002). Exterior wood frame walls are required to have an R-value that ranges from 13 to 25, depending on the climate zone in which the structure is built (IECC 2006). Each component that comprises the building envelope has distinct physical properties which include an assigned R-value. The building envelope consisting of a typical exterior wall has many components, including interior paint, plasterboard, insulation, wood studs, exterior sheathing, vapor barrier, exterior cladding, and exterior paint. The R-values of all these components are added together to derive an R-value for the completed wall.

The first objective of this experiment was to determine termite survivorship on seven building materials, providing some indication of each material's suitability as a diet for termites. The second objective was to determine the relative damage of each of the seven building materials by subterranean termites. The final objective was to determine differences in the rate of heat transfer between damaged and sound samples of each building material.

Materials and Methods

Termites

Five colonies of *R. flavipes* in Gainesville, FL, each separated by more than 1.5 km, were field collected in 6-liter plastic buckets inserted below ground with their lids accessible above the soil surface. Each bucket was filled with 2-3 moistened corrugated cardboard rolls (15 cm long by 10 cm diam.; Gainesville Paper Co., Gainesville, FL). Termites accessed cardboard rolls through ~10 holes (4-cm diam.) in the sides and bottom of each bucket. Cardboard rolls containing termites were collected and returned to the lab in Ziploc® bags (3.8-L). Termites were removed from the cardboard by gently separating the corrugated cardboard and allowed the termites to fall into a 20-L plastic bucket. The termites were then placed on moistened corrugated cardboard and maintained at room temperature (~23°C) in plastic boxes (27 by 19 by 9.5 cm) with moistened cardboard for ≤1 wk before inclusion in experimental arenas. Prior to the test, worker termites of at least 3rd instar were randomly aspirated into groups of 300 workers with a 1% soldier population.

Test Arena

The test arenas used to evaluate damage of wood and insulation materials consisted of a sand base with linoleum on the surface on which a building material sample was placed. Seven building construction materials were evaluated; 2x4, 2x6, oriented strand board (OSB), T1-11

plywood (T1-11), 5-ply plywood (5-ply), extruded polystyrene (EXP), and polyisocyanurate insulation (ISO).

Builders sand was oven-dried at $\sim 177^{\circ}\text{C}$ for 24 h, sifted through a 1.18 mm mesh soil sieve to remove debris, and moistened by mixing 50 ml of distilled water in 500 g sand. Moistened sand was evenly distributed into a 0.74 L plastic container (GladWare®; Glad Products Co., Oakland, CA). A linoleum square (56 cm^2) was placed on the surface of the moistened sand. The linoleum provided a barrier between the moistened sand and the building materials. The building materials dimensions were cut to the following sizes. The 2x4 and 2x6 materials were purchased in 2.4 m [8 foot] lengths and were cut across the grain to a thickness of 1.27 cm [$\frac{1}{2}$ inch]. Because the nominal thickness of the two materials is fixed, the material had the following dimensions $3.7 \times 4.4\text{ cm}$ ($\sim 16.3\text{ cm}^2$). The remaining building materials were purchased in sheets 1.2 by 2.4 m [4 by 8 feet] at a local building supply store and were cut into squares $4 \times 4\text{ cm}$ (16 cm^2). Sample thickness varied by building material; OSB was 1.2 cm [$\frac{15}{32}$ inch] thick, 5-ply plywood 1.8 cm [$\frac{23}{32}$ inch], T1-11 plywood 1.5 cm [$\frac{19}{32}$ inch], EXP 1.27 cm [$\frac{1}{2}$ inch] and ISO 1.9 cm [$\frac{3}{4}$ inch]. The building materials were oven-dried at 40°C for 24 h and weighed.

The termites were placed on the moistened sand next to the linoleum and the building materials. Lids were placed on the plastic arenas, which were stored in the laboratory at $\sim 23^{\circ}\text{C}$. Control arenas containing no termites were prepared in the same manner. The arenas were opened eight wk after setup and live termites were counted. The pre-weighed building materials were then brushed off, oven dried at 40°C for 24 h and re-weighed to calculate termite damage. Digital images of the building materials were taken to record visible damage caused by termites.

An experimental unit was defined as a plastic arena containing sand, linoleum, a building material and 300 termites. Each building material (n=7) was evaluated using five termite colonies with five replications per colony. The experiment had an equal number of control units with no termites, resulting in a total of 350 units tested.

Thermal Imaging Setup

All of the cleaned and oven dried building materials were photographed using a thermal imaging camera (FlexCam®; Fluke Corporation. Everett, WA). A tripod held the thermal camera in place ~53 cm above a building material. An enamel container filled with dry sand (2000 g builders sand) was placed on a hot plate and heated to 52°C. A square hole (~16 cm²) was cut into rigid board insulation (10 by 10 cm) minimize the edge effect of heat radiating from the sand and hot plate. The building material imbedded in the rigid board insulation was placed on the heated builders sand and a thermal image was taken after 0.5, 5, 10, and 15 min.

Data Analysis

All analyses were conducted using SAS (SAS 2001). Mean termite survivorship was calculated and converted to percent survivorship. Percent survivorship was arcsine square root transformed and analyzed using one-way analysis of variance (ANOVA) with material as the main effect and was separated with Student-Newman Keuls (SNK), ($P = 0.05$; SAS 2001).

Damage (g of material lost) was calculated for each material tested and analyzed using one-way analysis of variance (ANOVA) with material as the main effect and was separated with Student-Newman Keuls (SNK), ($P = 0.05$; SAS 2001). Damage for each material was converted to percent damage, arcsine square root transformed, and analyzed using one-way analysis of variance (ANOVA) with material as the main effect and were separated with Student-Newman Keuls (SNK), ($P = 0.05$; SAS 2001).

A heat transfer index was derived from Fourier's Law in one dimension (Healy and Flynn 2002) and calculated for each sample using the following equation:

$$HTI = (k)(t)(A)(\Delta T)/L$$

where: *HTI* = heat transfer index, *k* = thermal conductivity (W/m * °C), *t* = time (min), *A* = area (m²) for the corresponding control after 5 min reaction, ΔT = the change in temperature (°C), and *L* = thickness (m).

Heat transfer indices (HTIs) were calculated for damaged and undamaged samples of each material. Percent increase in HTI from undamaged to damaged samples was calculated for each material and analyzed using one-way analysis of variance (ANOVA) with material as the main effect and were separated with Student-Newman Keuls (SNK), ($P = 0.05$; SAS 2001). HTIs for damaged and undamaged samples were compared for each material using a two-tailed *t*-test ($\alpha = 0.05$; SAS 2001).

Surface temperatures for damaged and undamaged samples of each material at 0.5, 5, 10, and 15 min were plotted and subjected to natural logarithmic regression. The coefficients of the natural log (ln) for each equation were compared between damaged and undamaged samples for each material. The 95% confidence limits (CL) were calculated and non-overlap of the CL determined significant differences in slopes.

Results

All seven building construction materials evaluated were damaged by termites. Termite damage of solid wood and wood products was characteristic in that the damage was mostly to the soft spring wood and followed the grain. The insulation, which had no nutritional value to termites, was extensively excavated. Termites damaged EXP by creating long tunnels under the clear plastic barrier which were randomly oriented throughout the sample. In contrast, damage

to the ISO was concentrated at the surface where termites pitted and scarified the material under the craft paper, which they consumed.

Structural Lumber

Undamaged samples of the 2x4 and 2x6 building material had rings of lighter spring wood and darker summer wood that were obvious in the visible spectrum (Figs. 6-2A, 6-4A, respectively). However, the rings were absent in the thermal images of the undamaged 2x4 and 2x6 samples (Figs. 6-2B, 6-4B, respectively) indicating no noticeable difference in heat transfer by spring and summer woods. In addition, the thermal image of undamaged samples showed uniform heat transfer through the wood after 15 min of heating. The representative undamaged 2x4 and 2x6 samples had a narrow range of temperatures ($< 3^{\circ}\text{C}$) across the surface.

The survivorship of termites in the 2x4 and 2x6 samples was $>83\%$ after 8 wk (Table 6-1). During that time, termites consumed significantly more 2x6 (0.33 g) than 2x4 (0.25 g; Table 6-1). Damage in the 2x4 samples took the form of distinct lamellar tunnels excavated in the wood annular rings (Fig. 6-2C). Damage in the 2x6s similar to the 2x4s, but tunnels were excavated within the wider rings of less dense spring wood and the galleries extended the full thickness of the sample (Fig. 6-4C). A thermal image of a representative damaged 2x4 sample (Fig. 6-2D) and 2x6 sample (Fig. 6-4D) showed higher maximum temperatures by nearly 4°C in damaged wood due to greater overall heat transfer compared to that in undamaged wood. There were distinct hot spots in the images of the damaged samples that coincided with the location of termite tunnels, indicating that these tunnels allowed more rapid heat transfer than the surrounding wood. After 15 min of heating, the damaged 2x4 and 2x6 samples had a wider range of surface temperatures in the representative samples than in undamaged samples.

Southern yellow pine 2x4s have an assigned thermal conductivity value (k) of approximately $0.12 \text{ W/m}^{\circ}\text{C}$ (Table 6-1) which is an inherent physical property of this material.

Using the *k*-value of the material, the calculated heat transfer index (HTI) for undamaged 2x4 samples was 1.063 (Fig. 6-1). This indicated that 2x4 was the most thermally conductive of the undamaged materials. The HTI for termite damaged 2x4 samples was significantly greater and 30% higher than for undamaged samples, indicating that termite damage increases heat transfer through damaged samples.

The HTI for undamaged 2x6 samples was 0.926, indicating it was the second most thermally conductive of the undamaged building materials (Fig. 6-1). The HTI for the termite damaged 2x6s was significantly greater and ~51% higher than the HTI for undamaged samples, indicating higher heat transfer through damaged samples. The percent HTI increase for damaged 2x6 samples was also significantly greater than that for damaged 2x4 samples (Table 6-1).

Differences in the mean surface temperatures of individual 2x4 and 2x6 samples steadily increased through time (Figs. 6-3 and 6-5). Regression analysis of temperature and time (ln) indicated that the rate of temperature increase for damaged samples were significantly greater than the rate of temperature increase for undamaged samples for 2x4 and 2x6 substrates.

Wood Based Siding

Representative undamaged OSB samples had thin overlapping wood fragments that were generally long and narrow and were obvious in the visible spectrum image (Fig. 6-6A). The pattern of wood fragments was slightly noticeable in the thermal image of the undamaged OSB sample after 15 min of heating (Fig. 6-6B), indicating a slight difference in heat transfer between the fragments of wood based on color difference (green and yellow). The representative undamaged OSB sample had a narrow range of temperatures across the surface, ranging from 30.9 - 32.9°C.

Like structural lumber, undamaged samples of T1-11 (Fig. 6-8A) and 5-ply (Fig. 6-10A) showed wide bands of spring and summer wood in the visible image, which were not visible in

the thermal image (Figs. 6-8B and 6-10B, respectively). The lack of thermal variation in the undamaged T1-11 may be partially attributed to the perpendicular layering of the material. The thermal images of undamaged T1-11 and 5-ply representative samples showed uniform heat transfer through the wood after 15 min of heating, with temperatures across the surfaces varying less than 1.5°C.

Termite survivorship after feeding 8 wk was significantly lower (~59%) on T1-11 samples than that of OSB (~67%), 5-ply (~79%), and the other materials tested (Table 6-1). Although survival of termites feeding on 5-ply was good, this substrate had significantly lower wood consumption and damage than any other substrate, including T1-11 and OSB. Wood consumption and damage were not significantly different between T1-11 and OSB.

Visual damage to wood sidings varied based on wood fiber orientation. Damage in the T1-11 and 5-ply samples was similar to that seen in structural lumber in that the termites tunneled into the spring wood. Termites preferentially consumed bands of spring wood in T1-11 (Fig. 6-8C) and 5-ply (Fig. 6-10C); however, the termite damage formed longitudinal pockets on the surface rather than the rings seen in the structural lumber. There were distinct localized hot spots in the thermal image of the damaged T1-11 (Fig. 6-8D) and 5-ply (Fig. 6-10D) coinciding with the removal of the bands of spring wood, allowing heat to pass through more rapidly. The hot spot across the top of the thermal image of the representative T1-11 was due to termite damage of an interior layer not visible in the visible spectrum image.

In contrast, damage in the OSB took the form scarifying of the surface and short tunnels and holes in spring wood, largely between the thin wood fragments, visible as dark breaks in the surface (Fig. 6-6C). A thermal image of a representative damaged OSB sample (Fig. 6-6D) showed distinct localized hot spots that coincided with the location of termite tunnels and

scarification of the wood fragments, again showing that termite damage allowed more rapid local heat transfer.

After 15 min of heating, all the damaged wood siding samples had higher maximum temperatures than undamaged samples, with OSB having the greatest difference between damaged and undamaged samples (Fig. 6-6B, D). The maximum temperatures were associated with termite damage. Damaged samples of T1-11 (Fig. 6-8D) and OSB (Fig. 6-6D) typically had greater range in temperatures ($>4.5^{\circ}\text{C}$) than did damaged samples of 5-ply (Fig. 6-10D). 5-ply also had the least difference between maximum temperatures of damaged and undamaged samples (Fig. 6-10 B, D).

The calculated HTI for undamaged OSB samples was 0.706, indicating it was the most thermally conductive of the wood based siding materials tested (Fig. 6-1). There were no significant differences in HTI between the damaged and undamaged OSB, although the HTI for the damaged OSB was 12% higher than the HTI for undamaged OSB (Table 6-1).

In contrast, the calculated HTI's for undamaged samples of 5-ply and T1-11 were 0.213 and 0.502, respectively, indicating these were the most thermally resistant wood-based materials tested (Fig. 6-1). The HTI for termite damaged samples was significantly greater for undamaged samples for both these sidings, indicating a higher rate of heat transfer through damaged samples (Fig. 6-1). The HTI of damaged 5-ply samples was $\sim 73\%$ higher than undamaged samples, a difference that was significantly greater than those documented for all other materials tested (Table 6-1).

Mean surface temperatures of individual samples steadily increased through time for OSB (Fig. 6-7), T1-11 (Fig. 6-9) and 5-ply (Fig. 6-11). Regression analysis of temperature and time (ln) indicated that the rate of temperature increase for damaged samples was not significantly

greater for damaged samples than for undamaged samples for all three siding materials.

However, the rate of heat transfer for T1-11 and 5-ply was greater for the damaged than for the undamaged samples tested, as shown by the non-overlap of 95% confidence intervals through time.

Foam Insulation

The undamaged insulation samples were very homogenous in the visible spectrum images. EXP appeared light blue in color and faced with clear plastic (Fig. 6-12A). ISO had a reflective metallic appearance due to a coating of aluminum foil (Fig. 6-14A). The thermal image of the undamaged EXP (Fig. 6-12B) indicated no noticeable difference in heat transfer within the material, showing uniform heat transfer through the material after 15 min of heating. In contrast, the thermal image of the undamaged ISO sample (Fig. 6-14B) indicated small differences in heat transfer through the material. The representative undamaged EXP and ISO samples had a narrow range ($<1^{\circ}\text{C}$) of temperatures across their surfaces.

Termite survivorship in arenas with EXP samples was ~69% for 8 wk was significantly lower than ISO, which had the highest survivorship (~92%) of all materials tested (Table 6-1). EXP contains no cellulose, unlike the other six building materials tested. Termites removed 0.24 g of plastic resulting in ~6% damage, similar to 2x4, OSB, and T1-11 (Table 6-1). Termites tunneled extensively into the EXP plastic insulation and along the clear plastic facing. The tunnels were lined with fecal deposits and sand (Fig. 6-12C). Consumption and percent damage of ISO was higher than that of all other materials tested. Termites tunneled under the craft paper facing and into the plastic insulation. Most of the kraft paper was consumed, and the surface of the ISO insulation below was pitted and scarified, coated with a layer of tan fecal deposits and sand (Fig. 6-14C). Thermal images of a representative damaged EXP (Fig. 6-12D) and ISO (Fig. 6-14D) showed a greater overall heat transfer compared with undamaged samples.

Approximately 20% of the thermal image was covered with localized hot spots in the damaged EXP that coincided with the location of termite tunnels and removal of plastic. There were several distinct localized hot spots in the image of the damaged ISO that coincided with the location of termite tunnels and the removal of aluminum foil coated craft paper. Both the kraft paper removal and the tunnels in the insulation below allowed heat to pass through the sample more rapidly. The minimum temperatures for the damaged and undamaged samples were the same for each foam type. The maximum temperature for damaged samples compared to undamaged samples was $\sim 6^{\circ}\text{C}$ higher for EXP and $\sim 10^{\circ}\text{C}$ higher for ISO. Higher temperatures were associated with termite damage.

The calculated HTIs for undamaged samples was 0.164 for EXP and 0.109 for ISO, indicating these were the most thermally resistant of the tested materials (Fig. 6-1), which would be expected for materials developed to insulate buildings. The HTIs for the termite damaged EXP and ISO was significantly greater those for undamaged insulation, indicating a greater heat transfer through damaged samples (Fig. 6-1). The HTI of damaged EXP samples was $\sim 38\%$ higher than undamaged samples, and the % HTI increase was greater than that seen on ISO (Table 6-1).

Mean surface temperatures of individual samples of EXP (Figure 6-13) and ISO (Fig. 6-15) steadily increased through time. Regression analysis of temperature and time (ln) indicated that the rate of temperature increase for damaged samples was significantly greater than for undamaged samples for both EXP and ISO.

Discussion

The resin in manufactured wood products appeared to decrease termite survivorship. Our study determined that termite survivorship was significantly lower on resin based, engineered wood (OSB, T1-11, and 5 ply) than 2x4 and 2x6. OSB contains phenol-formaldehyde resin as a

bonding agent. Other researchers have documented that Formosan termites had substantial mortality after consuming resinous building materials; ~55% mortality after 3 wk consuming OSB (Ayrilmis et al. 2005) and 53% mortality after 5 wk consuming plywood (Tsunoda 2001).

Termites caused an intermediate percent damage to the OSB samples compared to other building materials. The other sidings (T1-11 and 5-ply) compared to OSB had lower mean percent damage. This difference may be due several reasons; the laminar structure of the T1-11 and 5-ply, laminations are typically cut from older trees that have denser wood or a different resin from used in OSB used to adhere the laminations.

The wood materials that had a malleable consistency had the greatest termite damage. The 2x6 material had significantly higher percent damage than the 2x4 material, in spite of similar composition and a lack of significant difference in mean termite survivorship. The difference in damage was not due to wood species, since 2x4 and 2x6 samples were made from southern yellow pine. However, 2x4 lumbers are typically cut from younger, faster-growing trees than 2x6 lumbers. One effect of this is that the 2x6 lumbers have wider layers of soft spring wood bordered with denser summer wood. Because *R. flavipes* termites feed preferentially on less dense wood (Behr et al. 1972) this difference between 2x4 and 2x6 densities could easily cause significant differences in wood consumption, and resulting damage and heat transfer.

Structural lumber such as 2x4 and 2x6 must be strong, in both tension and compression, to withstand structural loads. Damage due to notching and drilling may reduce structural integrity. Notched wood should have a maximum depth of 25% of the width and bored holes should be no larger than 40% in an exterior wall (Miller et al. 2004). In this study, the 2x4 and 2x6 samples tested were not damaged by termites to this extent due to short duration of exposure and relatively small number of termites.

The major component of the two insulation materials tested was plastic. EXP insulation composed of plastic foam and a clear plastic barrier does not provide any nutritional value to termites, so in the absence of suitable food source, termites began to starve in these trials. This effect was not seen on ISO samples because this insulation was faced with a radiant barrier composed of kraft paper covered with a thin layer of aluminum foil. The cellulose content of this kraft paper provided adequate sustenance to significantly improve termite survivorship.

Termites extensively damaged the soft insulation materials. Su et al. (2003) described insulation (molded bead-board) damaged by termites as having patches where the surface was severely excavated and had several tunneling holes. Our study found that the damaged insulation described by Su et al. (2003) was similar to the ISO; however, the damage to the EXP took the form of a network of tunnels excavated under the clear plastic barrier. The ISO foam insulation had significantly greater damage and percent damage than the EXP foam insulation. In the ISO samples, termites stayed near to the food source (kraft paper), so most of the damage to the underlying foam took the form of scarification rather than complete tunneling. The EXP insulation had no kraft paper, and so the termites tunneled throughout the soft plastic material, leaving multiple routes and extensive galleries.

The significantly greater heat transfer seen in 2x4 and 2x6 materials in comparison to siding materials was due to the cross-sectional nature of the structural lumbers. Heat transfer probably flowed more easily with the grain of the wood fibers in the 2x4 and 2x6 samples. The siding materials were laminar or semi-laminar, with wood fibers mostly perpendicular to the direction of heat transfer assayed. In contrast, the structural lumber cross-sections had the wood fibers mostly parallel to the direction of heat transfer assayed.

OSB samples, compared to the other building materials, had no significant change in heat transfer index between damaged and undamaged samples. This indicates that OSB is the most resistant to thermal damage by termites of the materials tested. This may be due to the fact that termites tunneled between fragments. In contrast to OSB, 5-ply samples had the lowest mean percent damage, but had the greatest percent increase in heat transfer index with termite damage. This indicates that 5-ply is the least resistant to thermal damage by termites of the materials tested. This may be due to the laminar structure of the 5-ply. It was relatively easy for the termites to tunnel between layers of this material. As soon as all five layers were penetrated, the heat could flow readily through the 5-ply. This same effect was seen to a lesser extent in T1-11 siding, presumably because the thinner layers. The relatively low heat transfer in 5-ply may be largely due to its thickness, which was greater than that of the other siding materials tested.

Not surprisingly, the insulation materials had the lowest heat transfer of all materials tested in their undamaged state. The EXP insulation had a higher mean percent increase in heat transfer index comparing undamaged to damaged samples. In ISO, the layer of kraft paper influenced the termites' tunneling behavior, resulting in tunnels near the surface. In contrast, the EXP insulation had no surface food source, so the termites tunneled through the foam, leaving multiple routes of rapid heat transfer. While the percent damage to the EXP compared to ISO was less, it took the form of a network of conduits for heat transfer, causing a greater overall change in heat transfer index than that documented in the scarified ISO.

Houses are being built to be more energy efficient and new structures are required to meet minimum energy standards. The impact of subterranean termite damage on thermal properties of building materials has been virtually overlooked. Our research with termites and common building construction materials demonstrates that termite damage need not be structural to affect

the thermal properties of the building materials. Our research demonstrates the importance of termite control for home energy conservation and indicates further research is needed to identify and develop building materials which resist termite damage and the minimize loss of thermal properties if damage occurs.

Table 6-1. Mean \pm SE percent termite survivorship, damage (g), percent damage, and percent increase in heat transfer index (HTI) between undamaged and building material damaged by subterranean termites (n=300) and after 8 wk.

Building material	Material	% survivorship ^a	Damage (g)	% damage	<i>k</i> -value ^b	% HTI ^c increase
Structural lumber	2x4	83.64 \pm 1.75bc	0.25 \pm 0.03b	6.72 \pm 0.75b	0.12	29.95 \pm 2.80cd
	2x6	88.65 \pm 1.35ab	0.33 \pm 0.03a	11.25 \pm 1.16a	0.12	51.15 \pm 8.19b
Wood-based siding	OSB	66.71 \pm 3.65d	0.28 \pm 0.03b	8.44 \pm 0.99b	0.13	12.23 \pm 1.51d
	T1-11	59.00 \pm 2.83e	0.23 \pm 0.03b	5.73 \pm 0.61b	0.13	26.58 \pm 8.45cd
	5-ply	78.61 \pm 3.08c	0.17 \pm 0.03c	3.05 \pm 0.33c	0.13	72.90 \pm 8.49a
Foam insulation	EXP	68.88 \pm 3.34d	0.24 \pm 0.01b	5.71 \pm 0.33b	0.03	37.51 \pm 5.73bc
	ISO	92.45 \pm 0.96a	0.35 \pm 0.03a	12.07 \pm 1.10a	0.02	20.96 \pm 1.81cd

Means within a column followed by the same letter are not significantly different (Student-Neuman-Keuls Means Separation, $P = 0.05$, SAS Institute 2001), $n = 25$ replicates. ^a $n = 300$ termites per arena, ^b W/m * °C, (ASHRAE 2005, Miller et al. 1999, NIST 2000), ^c HTI = Heat transfer index.

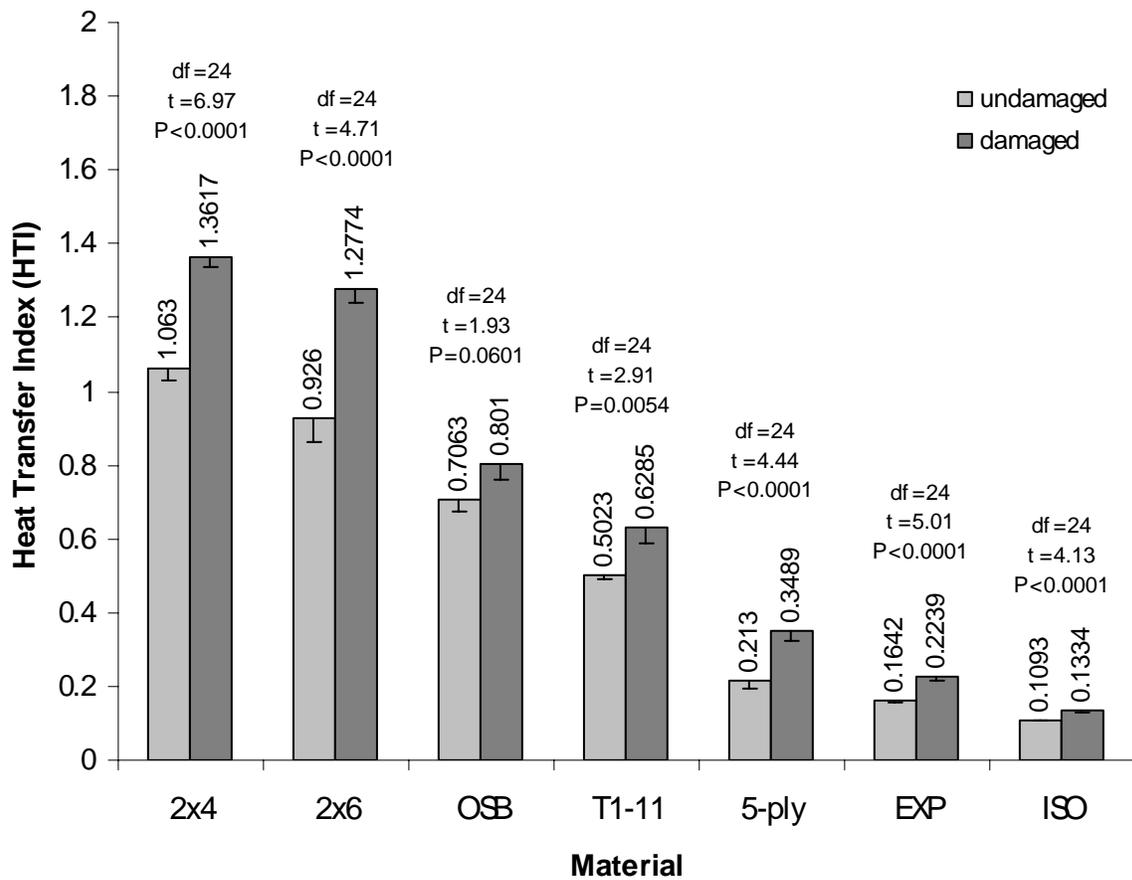


Figure 6-1. Differences in heat transfer index between undamaged materials and materials damaged by subterranean termites after an 8 wk period.

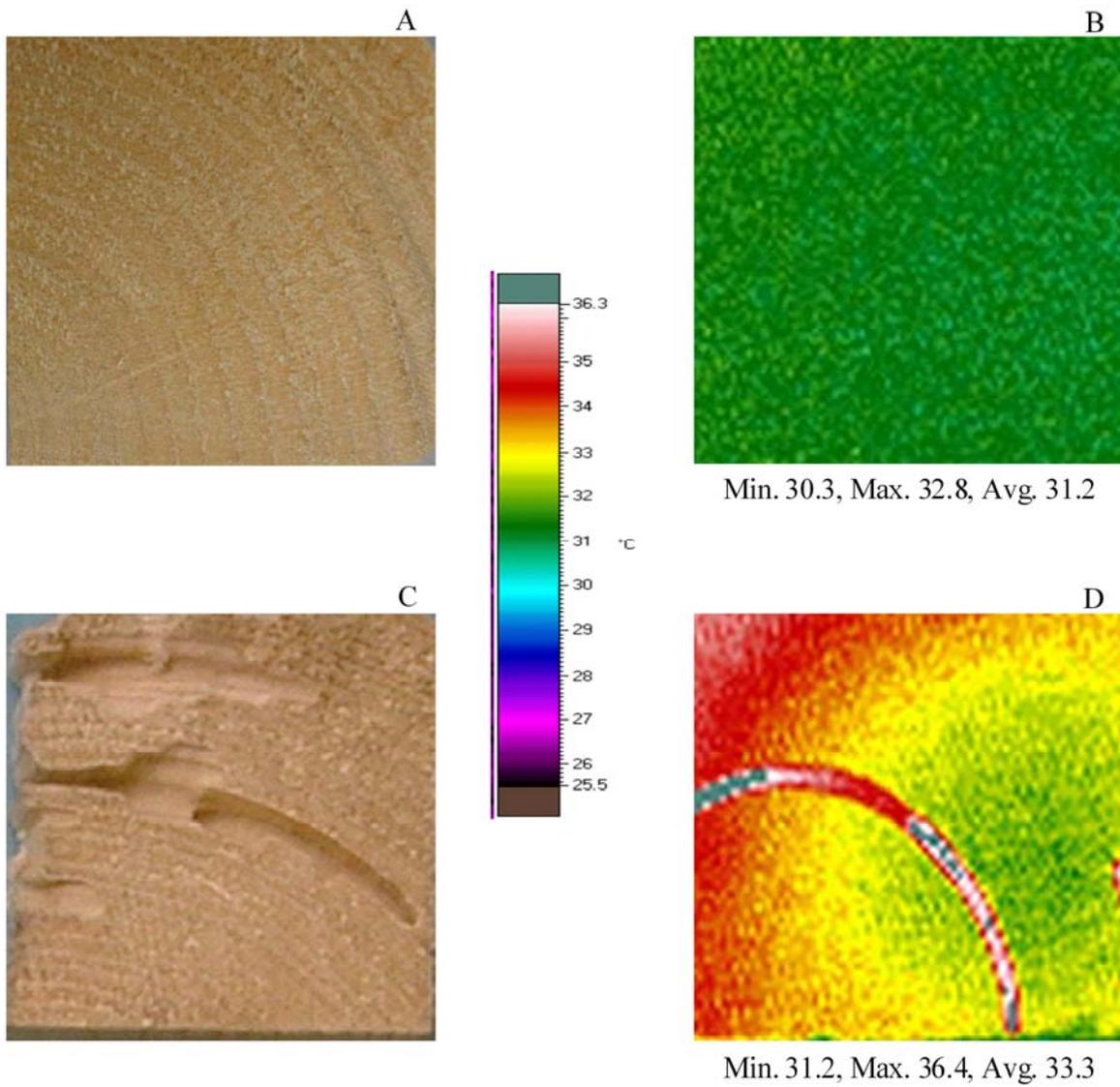


Figure 6-2. The 2x4 samples. Representative visible spectrum images (A, C) and thermal images (B, D) of undamaged (A, B) and termite-damaged (C, D) 2x4 samples after being heated (52°C) for 15 min.

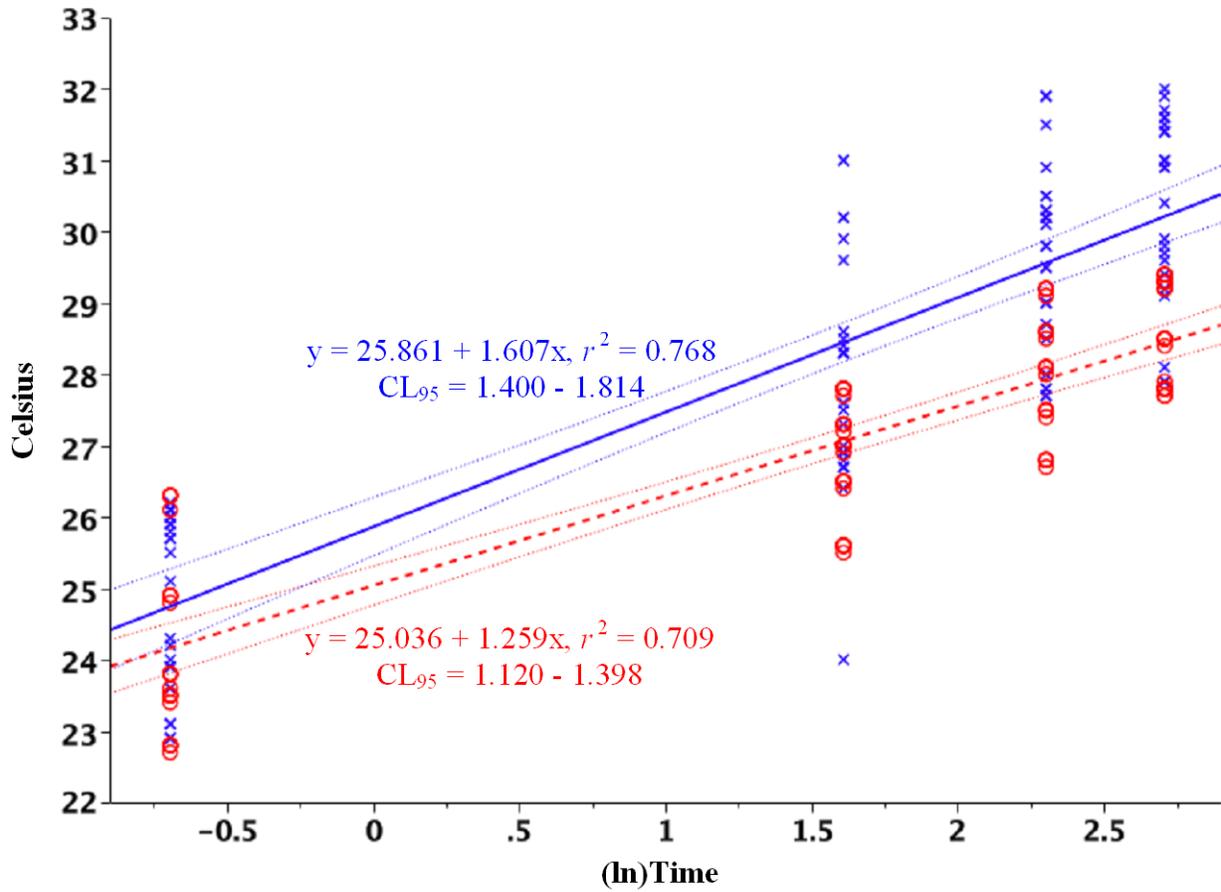


Figure 6-3. Natural log linear regression of 2x4 samples, termite damaged (red lines) and undamaged (blue lines), comparing temperature change (C°) recorded at ~0, 5, 10 and 15 m time intervals. Confidence intervals (95%) are represented by fine line around the regression lines and confidence limits (95%) of the slopes are given.

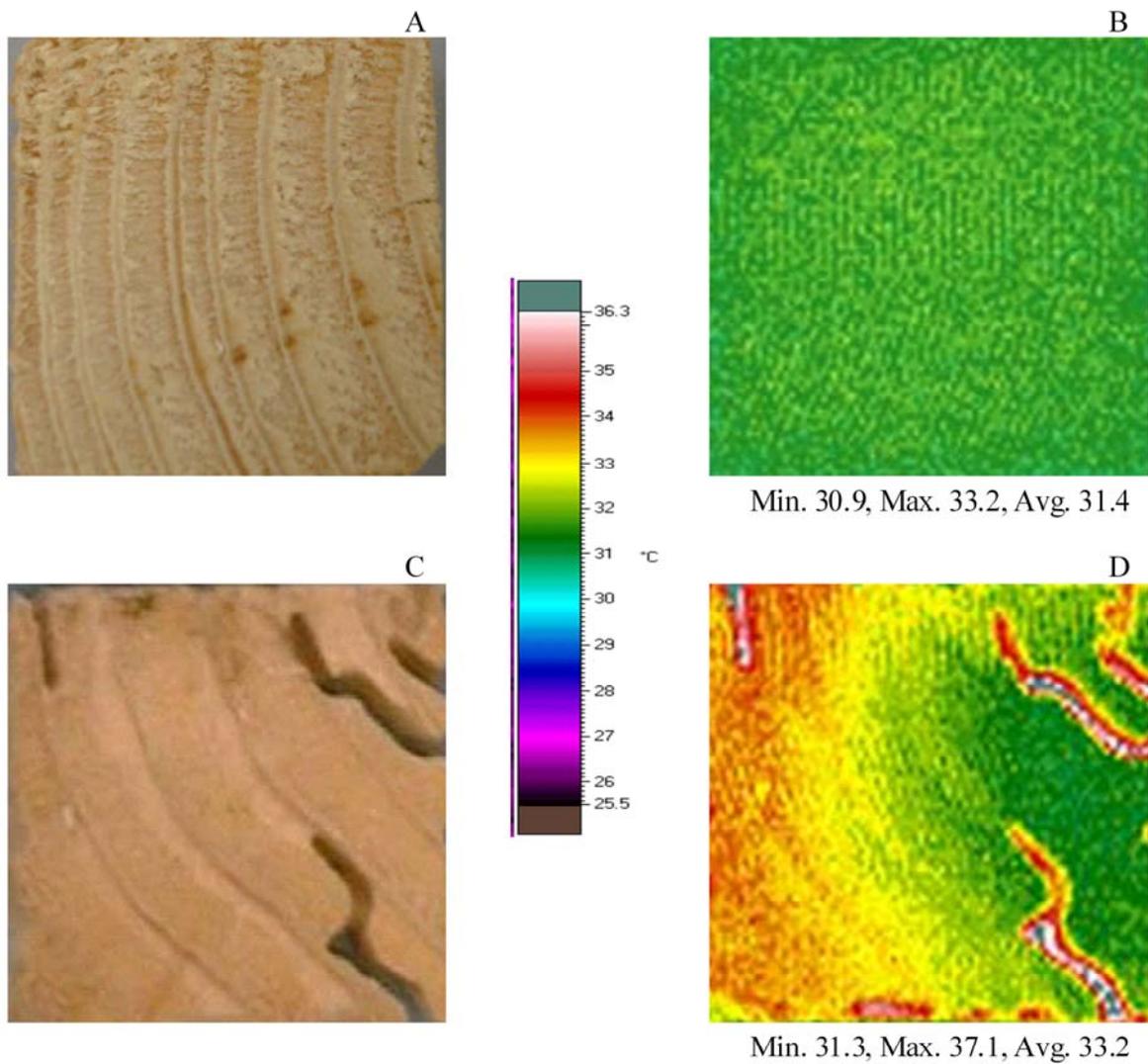


Figure 6-4. The 2x6 samples. Representative visible spectrum images (A, C) and thermal images (B, D) of undamaged (A, B) and termite-damaged (C, D) 2x6 samples after being heated (52°C) for 15 min.

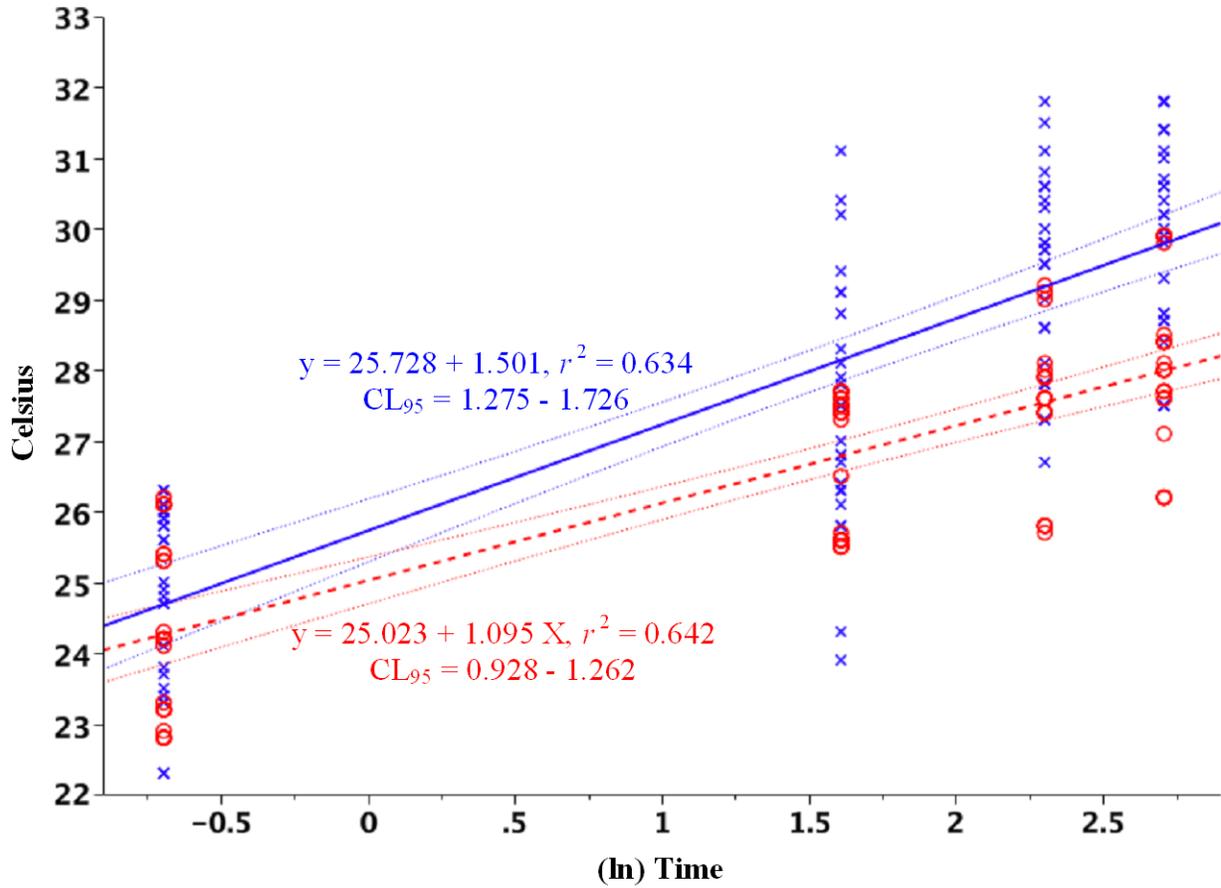


Figure 6-5. Natural log linear regression of 2x6 samples, termite damaged (red lines) and undamaged (blue lines), comparing temperature change (C°) recorded at ~0, 5, 10 and 15 m time intervals. Confidence intervals (95%) are represented by fine line around the regression lines and confidence limits (95%) of the slopes are given.

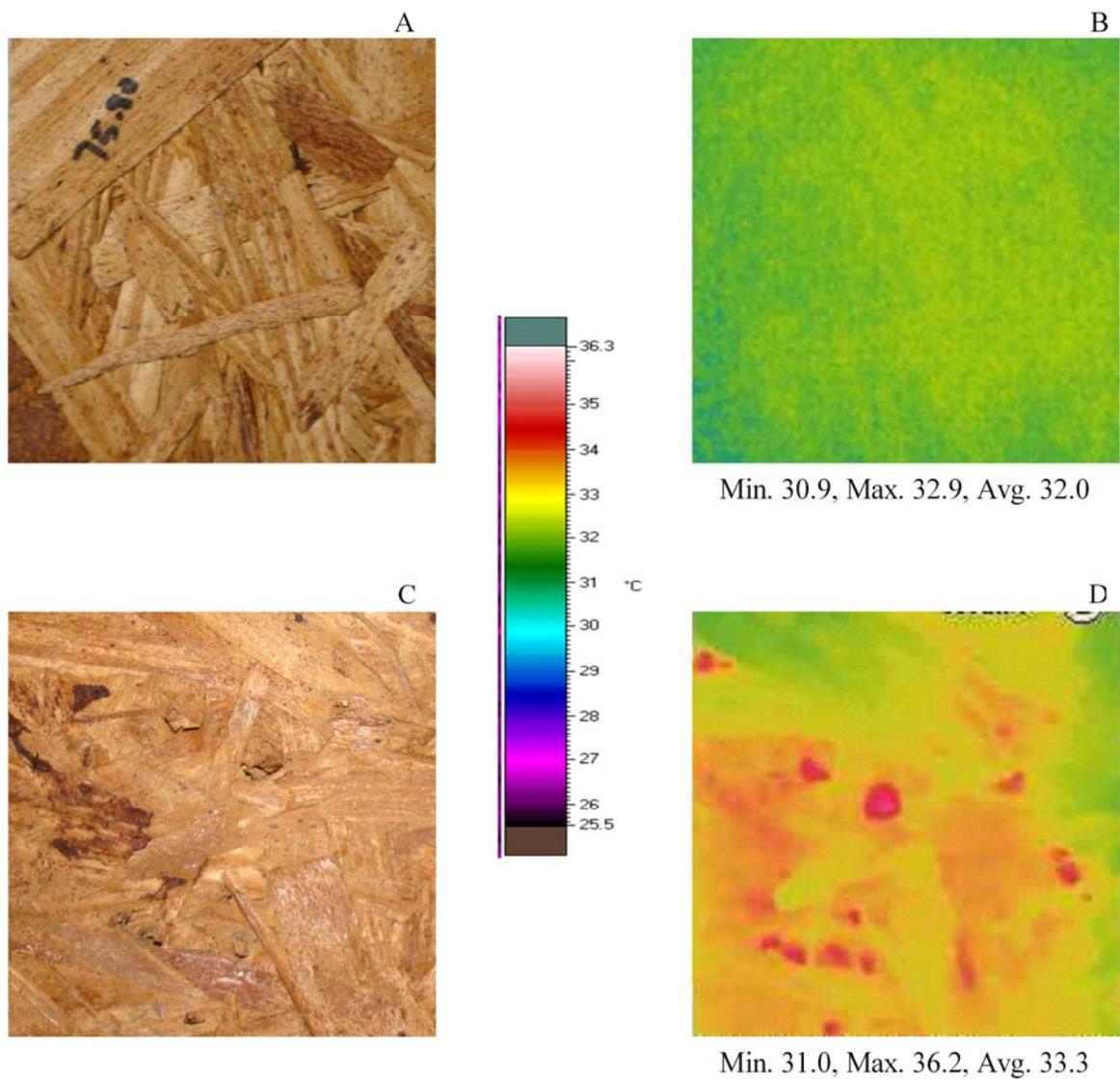


Figure 6-6. The OSB samples. Representative visible spectrum images (A, C) and thermal images (B, D) of undamaged (A, B) and termite-damaged (C, D) OSB samples after being heated (52°C) for 15 min.

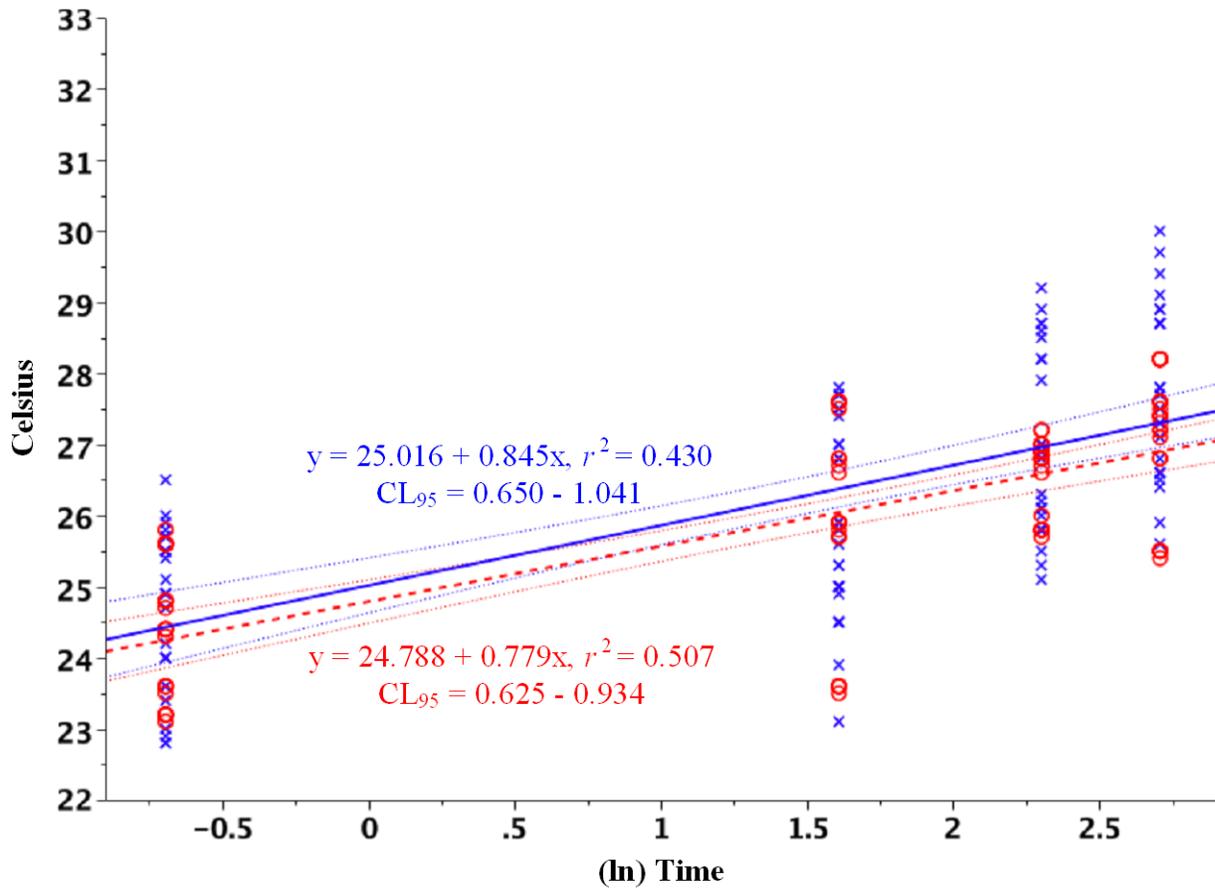


Figure 6-7. Natural log linear regression of OSB samples, termite damaged (red lines) and undamaged (blue lines) comparing temperature change (C°) recorded at ~0, 5, 10 and 15 m time intervals. Confidence intervals (95%) are represented by fine line around the regression lines and confidence limits (95%) of the slopes are given.

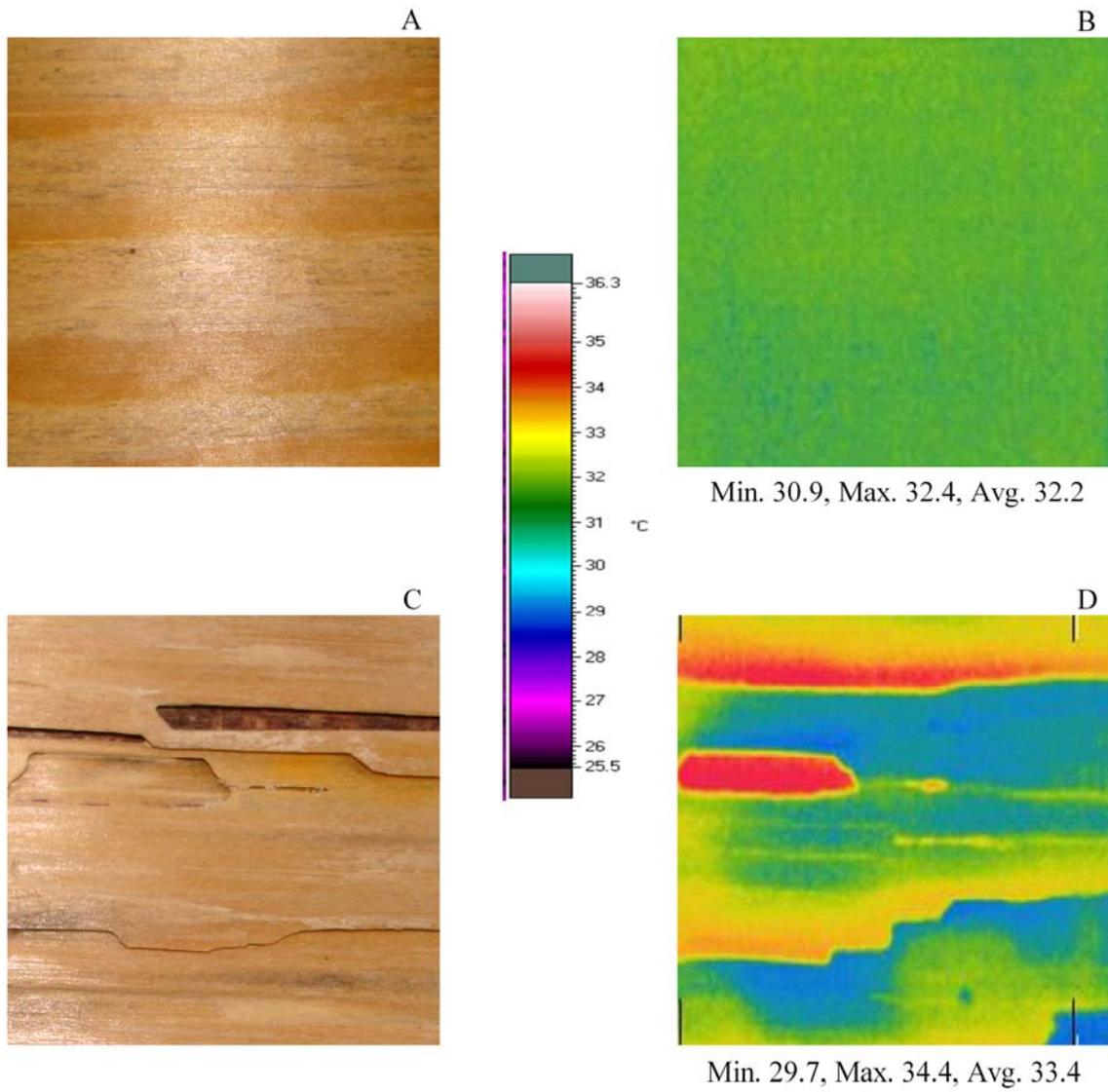


Figure 6-8. The T1-11 samples. Representative visible spectrum images (A, C) and thermal images (B, D) of undamaged (A, B) and termite-damaged (C, D) T1-11 samples after being heated (52°C) for 15 min.

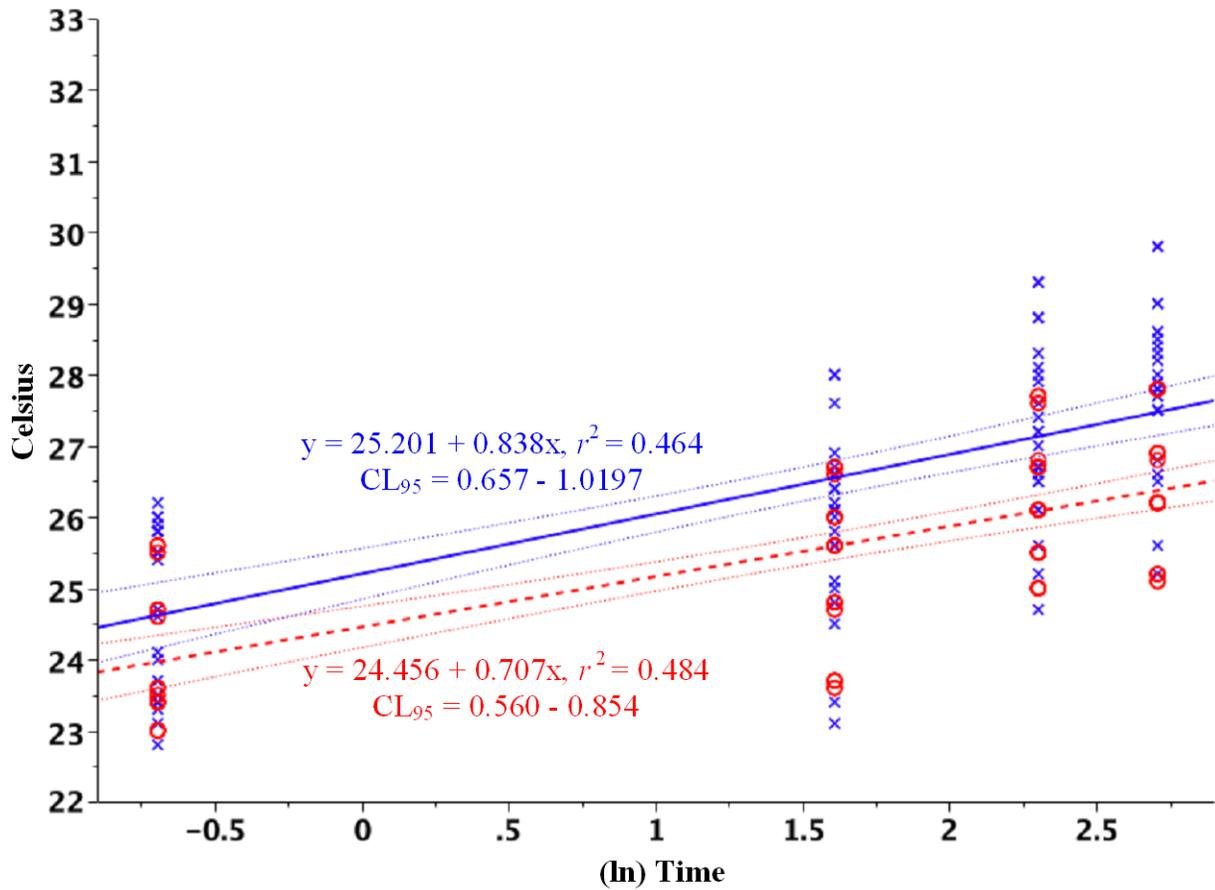


Figure 6-9. Natural log linear regression of T1-11 samples, termite damaged (red lines) and undamaged (blue lines), comparing temperature change (C°) recorded at ~0, 5, 10 and 15 m time intervals. Confidence intervals (95%) are represented by fine line around the regression lines and confidence limits (95%) of the slopes are given.

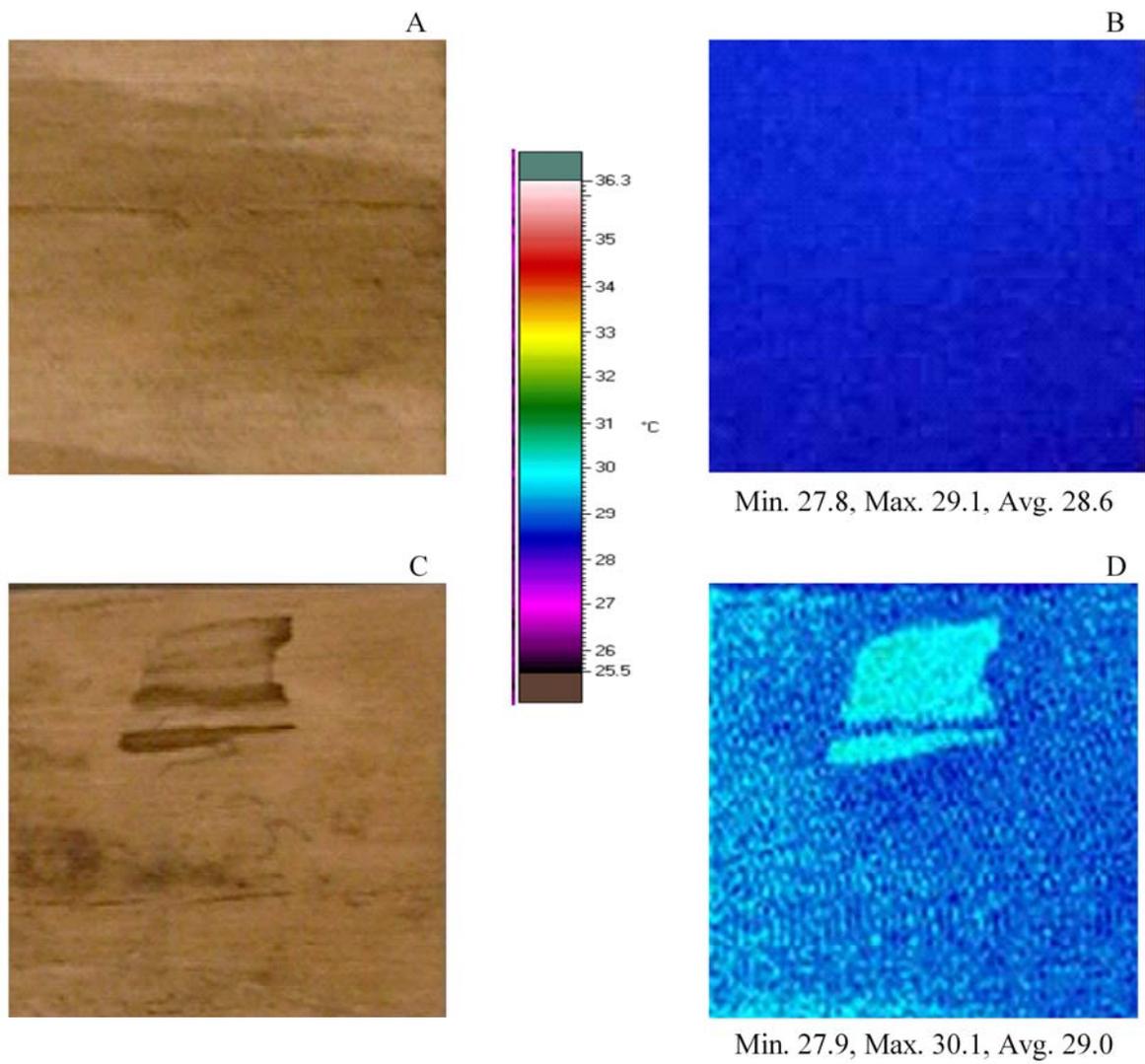


Figure 6-10. The 5-ply samples. Representative visible spectrum images (A, C) and thermal images (B, D) of undamaged (A, B) and termite-damaged (C, D) 5-ply samples after being heated (52°C) for 15 min.

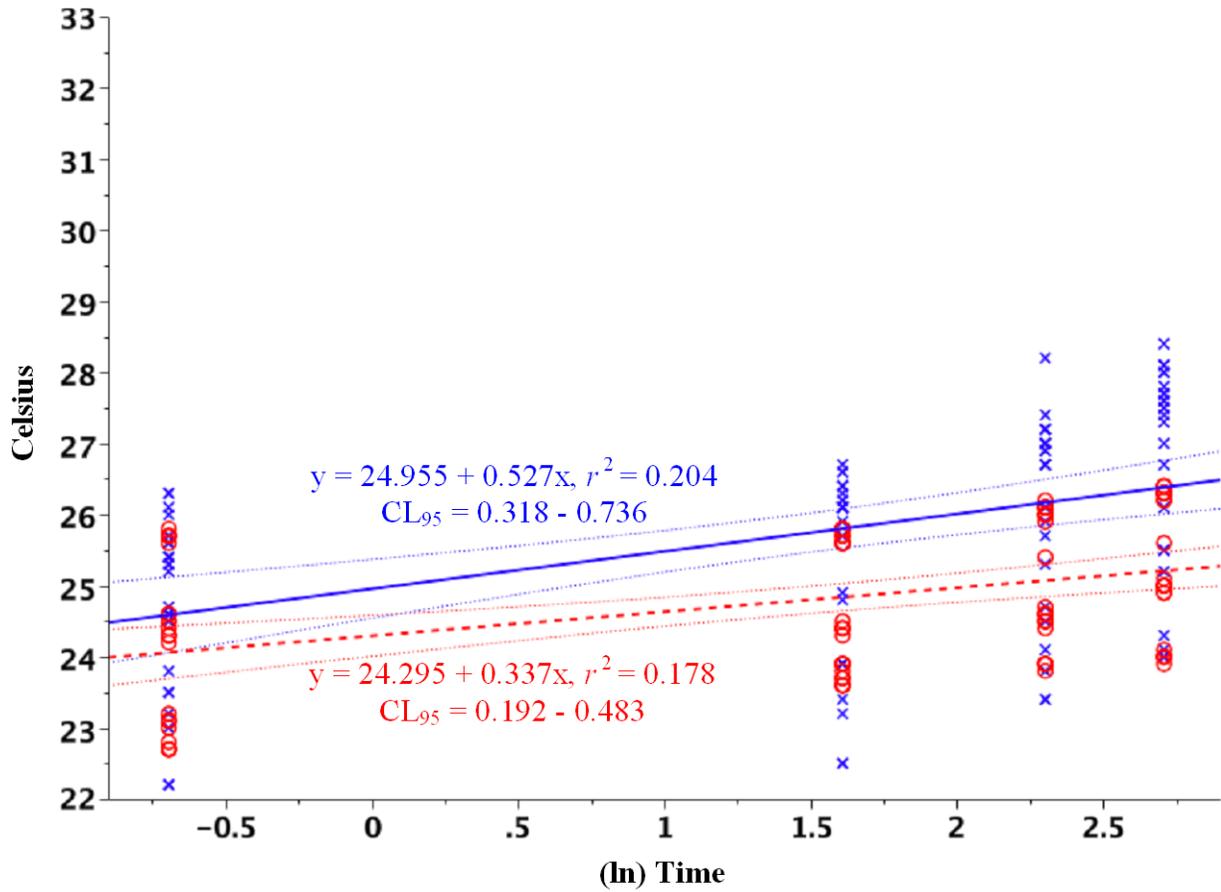


Figure 6-11. Natural log linear regression of 5-ply samples, termite damaged (red lines) and undamaged (blue lines), comparing temperature change (C°) recorded at ~0, 5, 10 and 15 m time intervals. Confidence intervals (95%) are represented by fine line around the regression lines and confidence limits (95%) of the slopes are given.

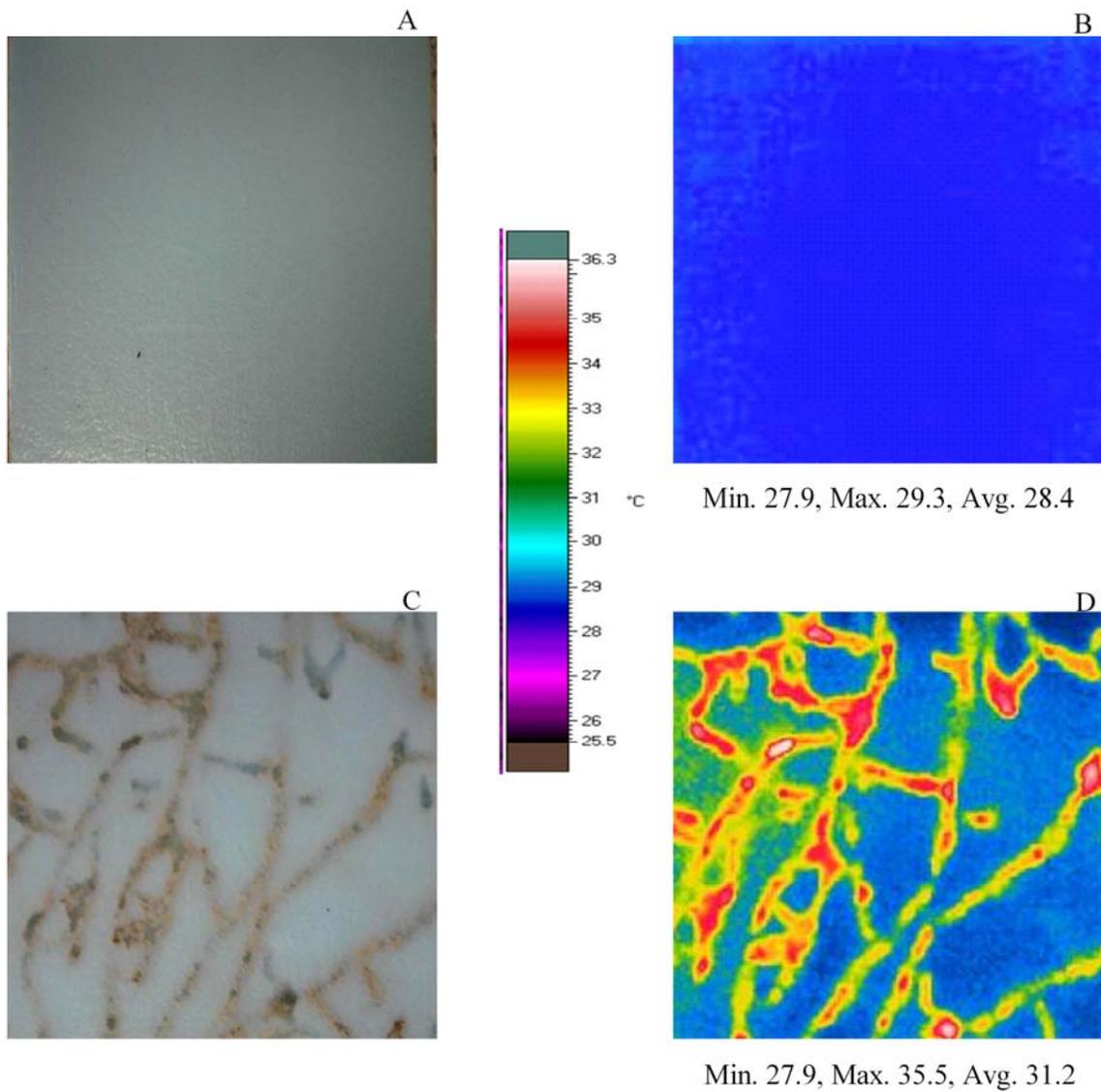


Figure 6-12. The EXP samples. Representative visible spectrum images (A, C) and thermal images (B, D) of undamaged (A, B) and termite-damaged (C, D) EXP samples after being heated (52°C) for 15 min.

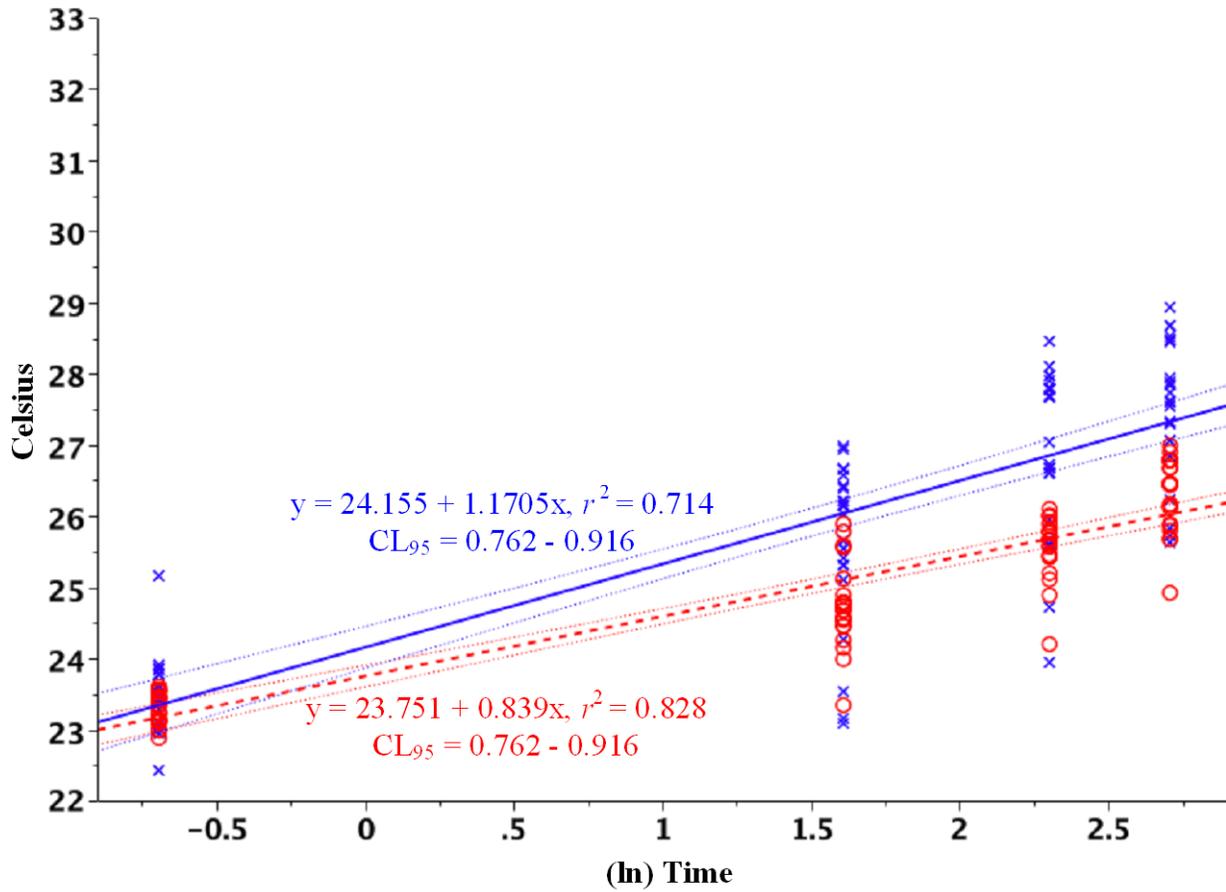


Figure 6-13. Natural log linear regression of EXP samples, termite damaged (red lines) and undamaged (blue lines), comparing temperature change (C°) recorded at ~0, 5, 10 and 15 m time intervals. Confidence intervals (95%) are represented by fine line around the regression lines and confidence limits (95%) of the slopes are given.

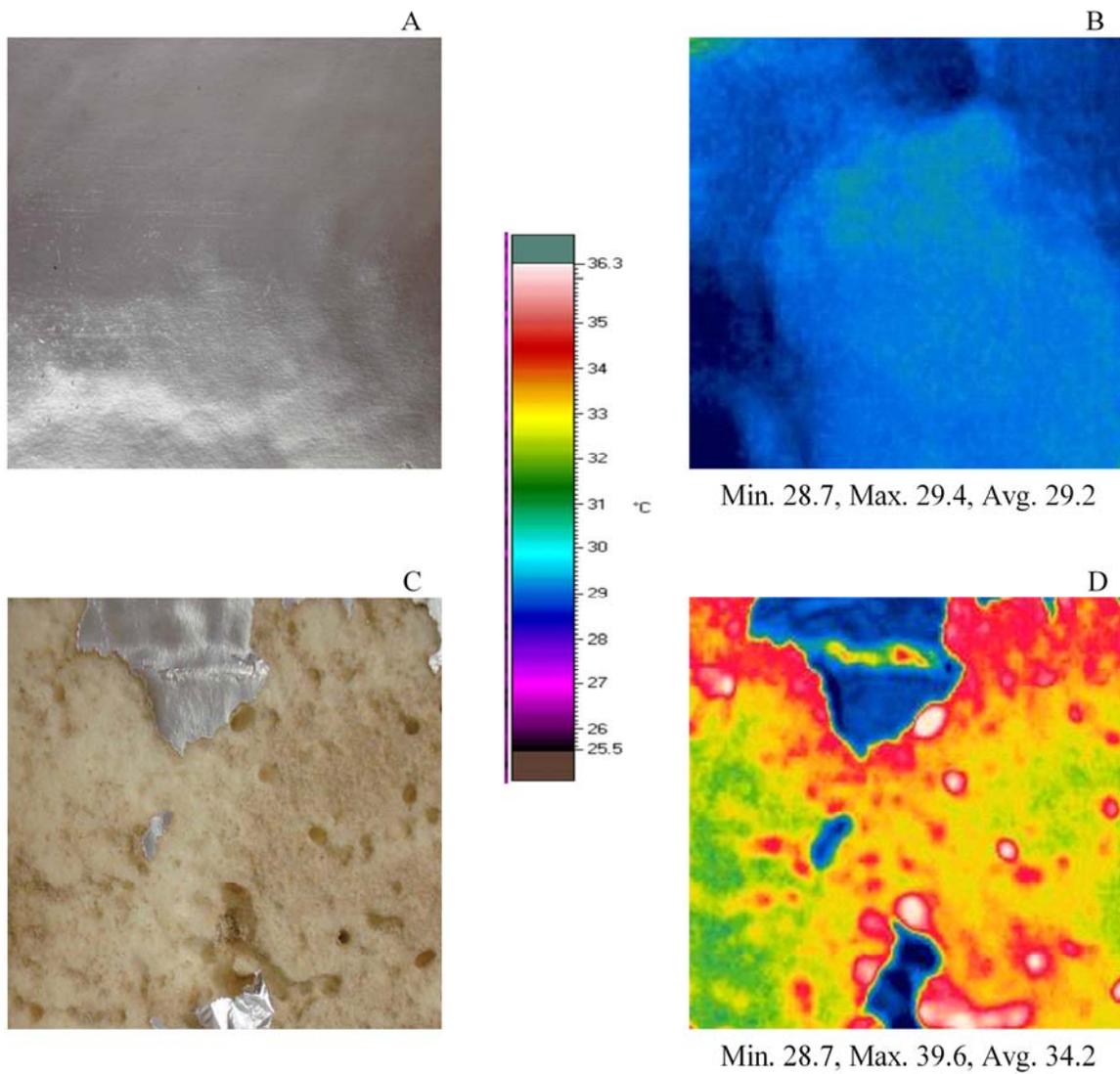


Figure 6-14. The ISO samples. Representative visible spectrum images (A, C) and thermal images (B, D) of undamaged (A, B) and termite-damaged (C, D) ISO samples after being heated (52°C) for 15 min.

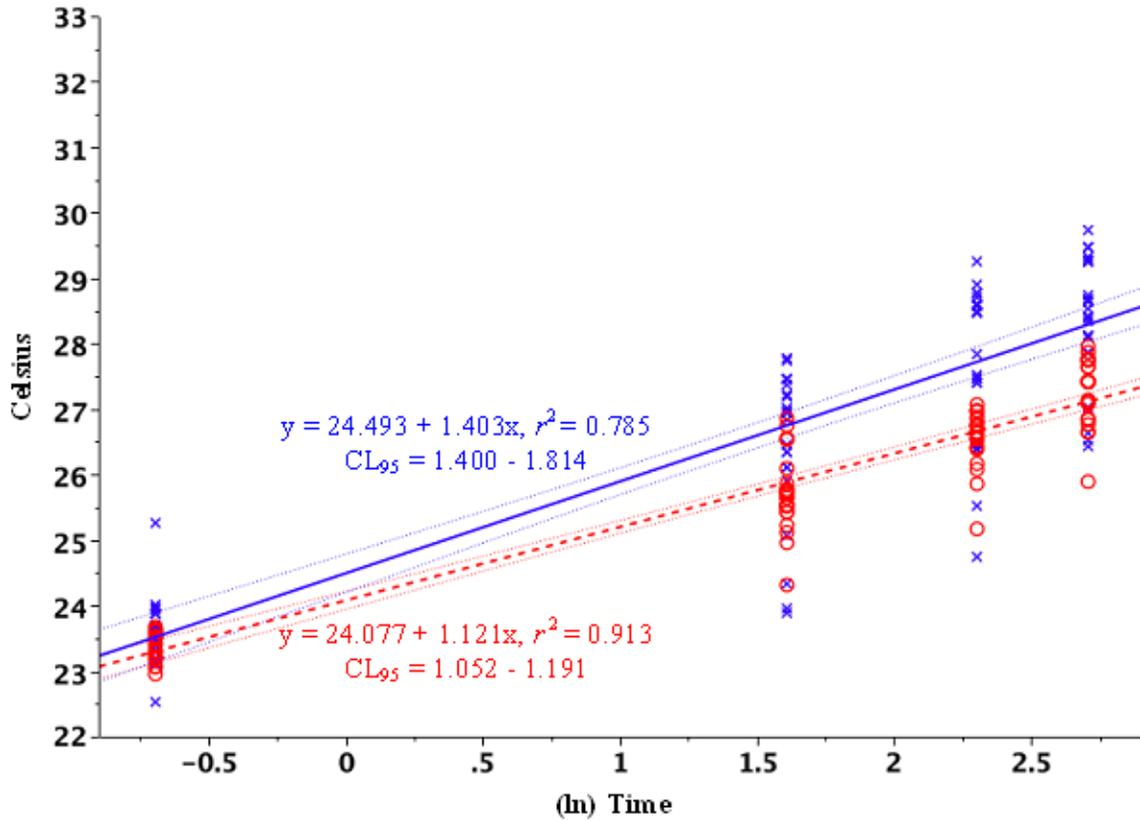


Figure 6-15. Natural log linear regression of ISO samples, termite damaged (red lines) and undamaged (blue lines), comparing temperature change (C°) recorded at ~0, 5, 10 and 15 m time intervals. Confidence intervals (95%) are represented by fine line around the regression lines and confidence limits (95%) of the slopes are given.

CHAPTER 7 CONCLUSION

Termite crack size assays showed a minimum crack width of ~0.7 mm is necessary for *R. flavipes* worker termites to travel through a crack. Assays further showed that *R. flavipes* soldier termites require a minimum crack width of ~1 mm to pass through a crack.

Pipe sleeve assays indicated that both foam and polyethylene pipe sleeves allowed termite access through a concrete slab if the sleeves extend below the termiticide-treated sand. However, termites were not able to access pipe sleeves that terminated within the termiticide-treated sand. Based upon these findings, it is important that protective measures are taken to prevent termite entry into structures via pipe and conduit slab penetrations. A properly installed pipe sleeve that does not extend below the termiticide-treated sand appeared to provide reliable protection. Care must be taken with soil treatment to ensure that it extends below the sleeve, if present.

Termite blocker assays showed that the presence of Impasse™ Termite Blocker, with or without sleeves or termiticide treatment, was sufficient to prevent slab penetration for at least 8 wk. Termite blocker properly installed and embedded in the concrete around the pipe should provide reliable protection from termites.

A method was developed to determine heat transfer using a hot plate to heat termite damaged and undamaged materials and document the surface temperature change through time with a thermal camera. The building construction materials (2x4s, 5-ply plywood, and rigid foam board insulation) were exposed to termites for 8 wk. Termites tunneled into and damaged all the building materials. When 2x4s were heated the surface temperature (°C) was ~35% higher in damaged compared to undamaged samples. Plywood damaged by termites was the

most thermally damaged with a temperature increase of 74% (damaged vs. undamaged samples) and insulation had a temperature increase of ~27% (damaged vs. undamaged samples).

A heat transfer index was developed to compare heat transfer through termite damaged building construction materials (2x4 and 2x6 pine lumber, 5 ply plywood, T1-11 siding, oriented strandboard, extruded polystyrene, and polyisocyanurate insulation). Termite damaged materials had higher heat transfer indices than undamaged materials. The heat transfer index of damaged 2x4 and 2x6 lumber was 37% higher than damaged 5 ply plywood and T1-11 siding; therefore the siding materials were more thermally resistant. As would be expected the insulation materials had lower heat transfer index values than the wood materials. Termite damaged polyisocyanurate was 68% more conductive than the damaged expanded polystyrene insulation.

In conclusion, the most likely routes for termite entry into structures are cracks and gaps in the foundation wider than 0.7 mm and unprotected pipe sleeves extending below soil treatments. The former of these routes can be remedied with adequate termiticide treatment below the slab. The latter can be remedied with termite blocker installed at construction and/or pipe sleeves cut short enough to not extend below termiticide-treated soil. If a structure is to be built in a hot or cold climate with concerns about termite damage and thermal transfer, OSB is a logical choice for wood-based siding while ISO foam is a preferable form of insulation. If all of these factors are taken into consideration while building a structure, it will be far more difficult for subterranean termites to invade, and the termites will cost the owner less money in increased heating and/or air conditioning bills if they do enter the structure.

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BIOGRAPHICAL SKETCH

Cynthia Linton Tucker, daughter of George and Gail Gross, was born in 1964, in Miami Florida. She graduated from Miami Killian High School (Miami, Florida) in 1982. She first attended Miami Dade Community College in Miami and then transferred to Santa Fe Community College in Gainesville, resulting in the completion of both Associate of Arts and Associate of Science-Medical Emergency degrees. She also attended Ocala Fire College where she received hazardous materials training and became a certified Fire Fighter. During the years of 1986-1998 she worked as a baker/manager at Bageland. Also between the years 1990 and 1996, she worked as an EMT/Paramedic/ Fire Fighter for Alachua County Fire Rescue and then for the City of Gainesville Fire Rescue. In 1999 Cynthia completed the requirements for the Bachelor of Science degree in entomology from the University of Florida (UF). Cynthia entered the graduate entomology program at UF in winter 2000 and completed her Master of Science in August 2002. Also in August 2002 Cynthia chose to continue her studies working with termites in the urban laboratory of UFs' entomology program. Additionally, Cynthia is also taking classes in the College of Building Construction and is working on completing a second master's degree. In 2006 Cynthia commissioned as a 1st Lieutenant with the United States Army Reserve and is currently the commander of the 342nd Preventative Medicine Detachment in Gainesville, Florida. Cynthia plans to continue serving in the United Stated Army, switching to active duty as soon as she completes her degree requirements.