Laboratory and Field Evaluation of Granite Aggregate as a Physical Barrier Against Subterranean Termites of the Genus *Coptotermes* spp. (Isoptera: Rhinotermitidae)

by

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ABSTRACT

The commercialization of a physical termite barrier using basaltic screenings in Hawaii has led to a reappraisal of physical barriers for termite control elsewhere. We briefly outline physical barriers involving the use of sand and crushed stone currently in use around the world and then describe laboratory and field tests undertaken in Australia to evaluate granite aggregate as a potential physical barrier against subterranean termites, in particular, termites of the genus *Coptotermes*. A granite aggregate has been accredited as a termite physical barrier in Australia and marketed under the trade name 'Granitgard'.

INTRODUCTION

In 1957, Ebeling and Pence reported on the relationship of particle size to the penetration by subterranean termites through barriers of sand or cinders. They described how subterranean termites progressed through sand material. The termites press the sand particles to either side, primarily with their heads and the exterior surfaces of the mandibles, although the entire body appears to be used to some extent for this purpose. The smaller sand particles are taken into the buccal cavity, then placed along the walls of the tunnel to make a smooth and tightly sealed surface. The sand particles are mixed with a gluey substance in the mouth of the termite, then pushed out by means of the large hypopharynx. This organ is greatly broadened anteriorly, evidently as an adaptation capable of pushing out soil or sand particles and spreading them over a relatively broad surface. When they carry subsoil to the surface in order to build their shelter tubes, the termites transport the smaller particles in their buccal cavities and grasp the larger ones with their mandibles. Although the span of the mandibles is only about 0.5 mm, by grasping the edge of a sand particle, termites can move particles of about 1.0 mm in length.

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At the time of this publication by Ebeling & Pence (1957) the notion of a physical barrier appeared to be only of academic interest, as chemical soil barriers, using cyclodiene insecticides became the "preferred treatment method" against subterranean termites.

In 1987, Tamashiro and his colleagues described what they claimed to be a safe, cost effective and permanent subterranean termite barrier that would stop termites without the use of termiticides. Development of the barrier was based on laboratory and field experiments, which demonstrated that the subterranean termite, *Coptotermes formosanus* Shiraki, had difficulty in penetrating certain substrates. Studies indicated that a substrate's ability to stop this type of termite from tunnelling or chewing its way through were functions of size, mass, hardness and smoothness of the particles making up the substrate. One of the many types of substrate examined by Tamashiro and his colleagues was basaltic gravel produced from crushing basaltic rock.

Laboratory and field tests indicated that *C. formosanus* were completely stopped by a substrate composed of basaltic particles with diameters in the range of 1.7-2.4 mm. Tamashiro *et al.* (1987) claimed that *C. formosanus* will never penetrate the barrier as the individual particles were too large and too heavy to be carried, too hard for the termites to chew, and the void between granite particles too small for termites to crawl through. No termites penetrated this substrate after four years in the laboratory and field (Tamashiro *et al.* 1991). There was no movement by the termites beyond the initial 10 mm maximum penetration, which was made in the first two of days of experimentation (Tamashiro, pers. com. 1989).

According to the specifications drawn up by Tamashiro and Ameron HC&D [the producer of the basalt screening in Hawaii (Yates *et al.* 2000)] the basaltic termite barrier should be placed beneath and around all new construction in a continuous 100 mm (4 inch) layer in all directions where subterranean termites could enter the structure. The barrier can be used underneath concrete slabs, around the perimeter of the slabs as backfill, inside hollow tile cells, around wooden posts, beneath and around foundations, and so forth. It may also be used around the perimeter of existing structures after trenching. There is provision to apply judicious amounts of termiticide, where appropriate, around the perimeter of buildings in conjunction with the basaltic gravel.

Laboratory evaluation on the size of the minimum foraging aperture for *C. formosanus* in Hawaii indicated that the termites can tunnel freely through apertures as small as 1.4 mm diameter, but activity is negligible at 1.2 mm, and no termites pass a 1.1 mm aperture (Ewart *et al.* 1991). We recorded similar dimensions using *Coptotermes acinaciformis* (Froggatt) in laboratory bioassays in Melbourne. In field bioassays in the Northern Territory of Australia an examination of the response of termites to cracks of different widths in concrete has recently been published. Lenz *et al.* (1997) reported the smallest penetrated crack width for *Mastotermes darwiniensis* (Froggatt) was 3.1 mm, for *C. acinaciformis* 1.5 mm, for *Schedorhinotermes intermedius breinli* (Hill) 1.4 mm, for *Heterotermes validus* Hill 1.5 mm and for *H. vagus* (Hill) 1.8 mm. The lower limit to allow entry through a circular opening for *C. acinaciformis* was given as 1.3 mm.

Workers of *C. formosanus* and the eastern subterranean termite, *Reticulitermes flavipes* (Kollar) were tested for their abilities to penetrate barriers 50 mm thick of ground coral particles. Each barrier was composed of one of 13 particle sizes, ranging from 0.5 to 4.0 mm diameter. *C. formosanus* penetrated least through particles 1.70-2.36 mm in size, and a wider size range of particles (1.00-2.36 mm) prevented penetration by *R. flavipes*. When several size ranges were uniformly mixed, the resultant barriers composed of particles in the 1.18-2.80 mm size range effectively prevented penetration by both termite species (Su *et al.* 1991).

In Australia, the physical barrier standard for the protection of buildings against subterranean termites was published in 1974 (Anon 1974). The barriers comprised "termite caps", a square shaped metal plate designed to overlap the top of an isolated pier or post, and "termite strip shielding" - shaped lengths of sheet metal designed to overlap the edges of walls and their engaged piers. Termite caps and strip shielding were commonly used since the 1950's. An appropriately installed termite cap will not prevent termites from gaining access to a building. It will however cause termites to form a visible bridge over the cap, which can be readily detected upon inspection.

Between 1974 and the mid-1980's, virtually no research into physical barriers for "whole-of-house" protection was undertaken. However, in July 1990, following laboratory and field evaluations by Dr. J.R.J. French, CSIRO, on a crushed stone aggregate, accreditation was granted to the quarry company, E.B. Mawson & Sons, Pty Ltd., Cohuna, in the State of Victoria for this aggregate to be used in the protection of buildings against termite infestation (Anon 1990). In 1996 national accreditation was also granted to Mawson's for areas of continental Australia north of the Tropic of Capricorn for the installation of this granite barrier against *M. darwiniensis*. Mawson's market this granite barrier under the trade name 'Granitgard'.

Both Granitgard and Termi-mesh are now accredited termite physical barrier systems that are incorporated into the newly revised Australian

Standard – Protection of buildings from subterranean termites Part 1: New buildings (AS. 3660.1-2000).

This paper describes the laboratory and field evaluations undertaken to determine the suitability of granite screenings from Mawson's quarry in Cohuna by CSIRO as a physical termite barrier. The information obtained in this evaluation was instrumental in gaining national accreditation for this product as a physical termite barrier, and its inclusion in the Australian Standard (AS. 3660) in 1993.

MATERIALS AND METHODS

Laboratory bioassays

Test termite

The test subterranean termite ('termite') in all the laboratory bioassays was *C. acinaciformis*, collected from the Darwin area in the Northern Territory. This species is of the same genus as the Hawaiian termite, *C. formosanus*, and similar in size and activity. *C. acinaciformis* is the most economically important subterranean termite in Australia, with respect to damage to timber-in-service, and is widely distributed across the mainland (Gay & Calaby 1970). All laboratory bioassays were conducted under controlled conditions of 27°C and 75% relative humidity.

Substrate

Crushed granite aggregate was supplied by E.B. Mawson & Sons Pty Ltd. The screenings, produced from crushing parent granite rocks at the Mawson quarry in Cohuna had a specific gravity of 2.8. The screenings supplied were graded from 3.0 - 1.7 mm in diameter. The test material was clean granite only with 90% passing the 2.4 mm sieve and 0-6% passing the 1.7 mm sieves. The screenings were graded into several particle sizes, namely, (i) >2.4 mm, (ii) 2.4 - 1.7mm, (iii) <1.7 mm, and used in laboratory and field evaluations. The term 'substrate' used throughout this study refers to granite screenings.

Laboratory Experiment 1 - Substrate without fines

The aim of this experiment was to determine the ability of termites to penetrate cylinders (150 mm in length) packed with granite substrate at the dimensions mentioned above. The 150 mm depth was selected to be representative of the depth of packing sand normally recommended in Australia as a base layer for concrete slab-on-ground construction.

Each experimental unit consisted of a plastic container (ca. 380 mm^3 volume) into which 20 g of damp (100% moisture content) washed river sand was added. A clear plastic cylinder (150 mm long) was placed vertically in the centre of the sand on top of a coupling (Fig. 1). Granite substrate of the various sizes (viz. >2.4 mm, 2.4 - 1.7 mm, and <1.7 mm) were prepared to examine both upward or downward tunnelling by termites. Five replicates of each substrate and orientation were prepared and the experiment repeated twice. The duration of each tunnelling test was two weeks.

At the distal ends of the cylinders small cork blocks were set in agar. If the termites were able to penetrate the substrate and feed on the cork, the barrier was considered "breached", and thus failed.

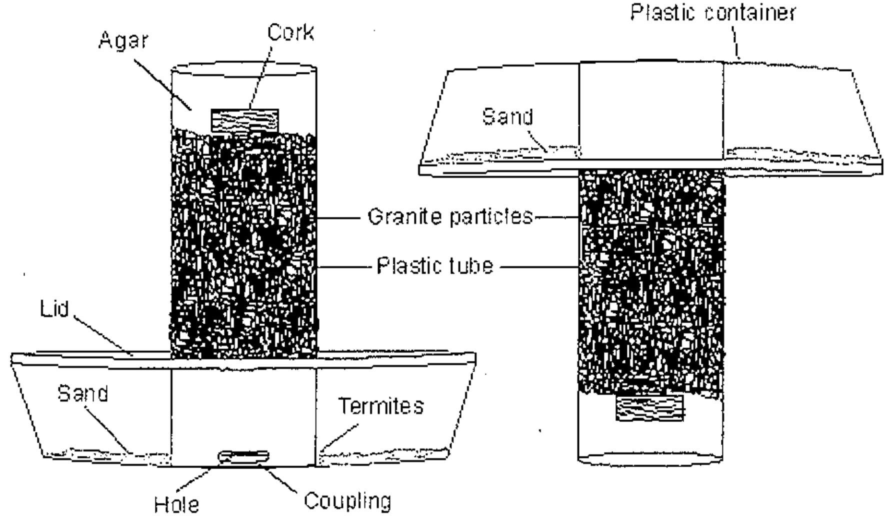

Fig. 1. Diagrammatic representation of the experimental layout in Experiment 1 to evaluate upward and downward tunnelling through crushed granite by termites.

Laboratory Experiment 2 - Horizontal tunnelling–substrate without fines.

Cylinders of experimental units as described in Experiment 1, were arranged horizontally, rather than vertically. Five replicates of each particle size were tested in the horizontal cylinders, and repeated twice.

Laboratory Experiment 3 - Blending substrates with fines

Preliminary bioassays had shown that termites could penetrate the blended granite substrate if the material was sieved when damp or wet. Termites were able to penetrate this moist substrate which had fine particles adhering to the solid substrate. Experiment 3 was designed to examine the ability of the termites to penetrate a "blended" substrate, sieved dry and composed of medium substrate and fines in various proportions. The experimental units were as for Experiment 1, and the duration of each bioassay was two weeks.

Laboratory Experiment 4 - Untamped substrate with no agar plugs

A similar experimental layout to Experiment 2 (horizontal tunnelling) was used, except that no agar plugs were placed at either end of the 150 mm long clear plastic cylinders holding the substrate. Five replicates of the clean material in the range 2.4 - 1.7 mm were used, and the duration of the test was two weeks.

Experiment 5 - Tamped substrate with no fines and no agar plugs

There was no measurable penetration of the substrate in the cylinders during the two-week test period. Laboratory Experiment 5 - Tamped substrate with no agar plugs. Experiment 5 was carried out as for Experiment 4 above, except that the clean substrate (1.7 – 2.4 mm) was compacted or tamped down in the clear plastic cylinder (150 mm long).

Field Bioassays

Boola Boola State Forest, Erica, Victoria.

Field Experiment 1 - Conduits in mounds

Several live, above-ground mounds of *Coptotermes lacteus* (Froggatt) were utilized in the field in 1990 at the Boola Boola State Forest near Erica in Victoria (38 00' S., 146° 30'E.). This termite species is similar to *C. acinaciformis* in size, shape, and biological characteristics. The most southerly aboveground *C. acinaciformis* mounds occur north of Brisbane (27.28 S; 153.02 E). The main reason for utilizing live mound colonies was to place test materials in the highest termite hazard possible. Thus, five mounds of *C. lacteus* were selected, and into each mound were inserted plastic conduits containing the various granite screening sizes, namely, (a) >2.4 mm, (b) 2.4 - 1.7 mm, and (c) < 1.7 mm after the method of French & Robinson (1985).

A length of conduit (100 mm long and 25 mm diam.) was inserted horizontally 80 mm into each mound. At the distal end of the conduit a plastic elbow (90°) was added, plus a coupling to allow for a vertical conduit to be attached (170 mm long, 32 mm diameter). A plug of agar at the base of the vertical conduit held the granite particles in position, while at the top of the conduit, a small (60 x 40 x 10 mm) piece of cork was embedded in agar. The top of this unit was covered with aluminium foil. Corrugated cardboard inserts were placed within the conduits giving access to the substrate by termites foraging actively from the mound (French and Robinson, 1985). Two replicates of each grade of granite {viz. fine (<1.7 mm), medium (2.4 - 1.7 mm) and coarse (>2.4 mm)} and a single control replicate (corrugated cardboard only in the column) were inserted into each of five active mounds. The control was introduced to confirm active termite foraging from the mound. Inspections were made after one and two months.

Field experiment 2 - Substrate with fines in mound

A large (2 m high, 4.5 m in circumference at ground level), live, *C. lacteus* mound was used in this preliminary experiment to examine the ability of the termites to walk across and penetrate the substrates (>2.4, 2.4 - 1.7, <1.7 mm) containing fines (>10%). Eighteen rectangular plastic containers (215 x 140 x 70 mm) were connected separately into the mound by plastic conduit (25 mm diam.) (Fig.2.). Half the containers had the conduit entering along the length of the base and half had the conduit entering at the top of the container. Four small holes (8 mm diam.) were drilled in the conduit within the container giving termites ready access. Six containers were filled with coarse (>2.4 mm) substrate, where three containers that had the conduit glued to the base of the container and were filled to the brim with substrate, while the other three with conduit near the top of the container had the substrate level with the small holes drilled in the conduit so that termites might exit directly at the surface. The medium and fine substrate were similarly arranged within the remaining twelve containers. On the surface of each substrate were placed two small blocks of cork (100 x 20 x 20 mm) and lids sealed all the units. Inspections were made after two, four and six months.

Field Experiment 3 - Trenches outside the mounds using baits on the surface of the substrate.

This experiment was designed to simulate a natural situation in which actively foraging termites outside the nest colony are encouraged to aggregate into four small trenches (260 mm deep, 200 mm^2) dug about 160 mm from the edge of each of four mounds (Fig. 3). Granite screenings in three diameter size ranges, namely, >2.4, 2.4 - 1.7, and <1.7 mm, were selected at random and deposited into one of each of three trenches at each mound, while in the fourth trench (= the untreated control), was added some loose soil. Cork baits were placed on the surface of each substrate layer (see diagrammatic layout in Fig. 3). Inspections were made after two, four and six months.

Field Experiment 4 - Trenches outside *C. lacteus* mound using baits in and on the substrate.

Granite substrate within the 2.4 to 1.7 mm diameter range was used. Baits of cork and small blocks of slash pine (*Pinus elliottii* Engelm.) were positioned in the centre and on the surface of the substrate in each of four trenches (Fig. 4). One trench contained the untreated control (i.e., baits placed into the soil at the base of the trench without any substrate being added), and two trenches contained the 2.4-1.7 mm diameter substrate. Inspections were made after two, four and six months.

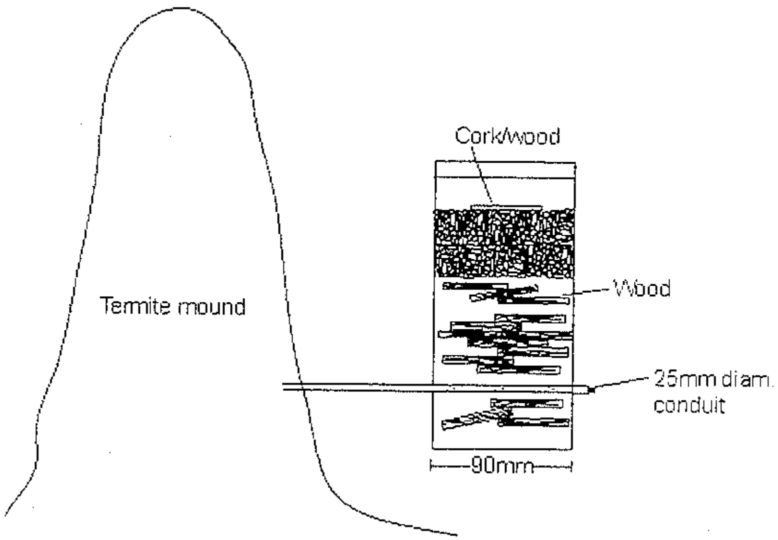

Fig. 2. Diagrammatic representation of the vertical plastic conduit bait-trap (200 mm long; 90 mm diam.) inserted in an active above-ground mounds of *C. lacteus* (Boola Boola State Forest, Victoria) and *C. acinaciformis* (Townsville, Queensland).

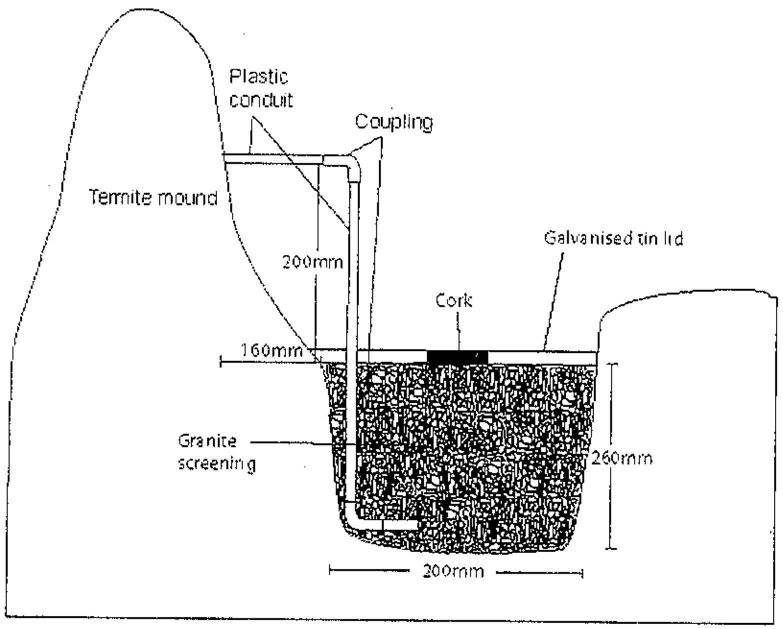

Fig. 3. Diagrammatic layout of field experiment 3 of the cork baits on the surface of the granite screenings within each adjacent to *C. lacteus* mound.

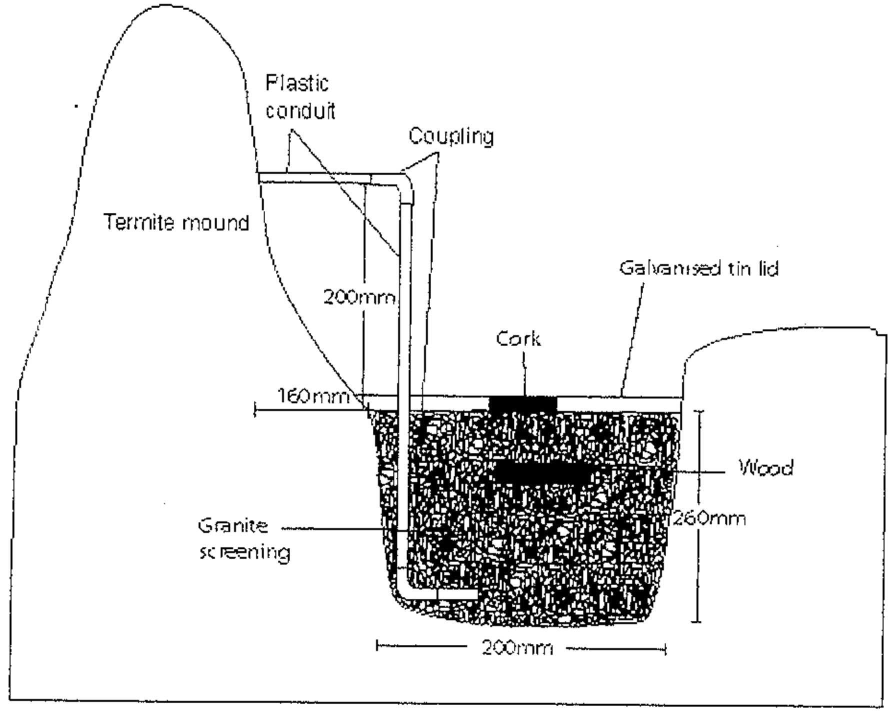

Fig. 4. Diagrammatic layout of field experiment 4 of cork and wood baits in and on the substrate on each trench adjacent to *C. lacteus* mound.

Field Experiment 5 - Trenches outside mounds with boric acid

A similar experimental layout as described in Experiment 4 above was used, except that 0.5 % boric acid solution (300 ml) was poured into the interfaces between the granite substrates and the sides of the trenches. The intention was to discourage termites from crossing such a chemical barrier. Leaching was not considered a major problem, as the experimental assembly was covered with a galvanized tin sheet. Inspections were made at 2,4,6 and 12 months exposure.

Townsville, Queensland

Field Experiment 6 - Substrate with fines in mounds

Ten live, above-ground mounds of *C. acinaciformis* were selected at Lansdown Park, about 40 km southwest of Townsville in Queensland (19.13 S; 146.48 E). Four rectangular plastic containers (250 x 120 x 90 mm) were connected into live mounds by a separate conduit that was glued into each container. The conduit (400 mm long, 16 mm diam) was glued into the base at the center of the longest side of each container so that it protruded about 200 mm out from the container. Four small holes (8 mm diam) were drilled in the conduit within the container giving termites access into the container via the conduit. Each container was filled with a substrate of fine (<1.7 mm diam), medium (2.4 - 1.7 mm diam.), coarse (>2.4 mm diam.) granite screenings and an untreated control with no screening, respectively. On the surface of each substrate were placed two small blocks of *P. elliottii* (100 x 20 x 20 mm) and the lid sealed the unit (see Fig. 5). The medium and coarse substrates contained a small proportion (> 10%) of the fine material, hence the emphasis on 'substrate with fines' in this experiment. Inspections were made at two, four and six months.

Field Experiment 7 - Substrate without fines in mounds

A similar layout was used as in Experiment 6 above, except that the substrate was without fines within the containers in each mound. Inspections were made at two, four and six months.

RESULTS

Laboratory bioassays

Experiment 1 - Substrates without fines

After two weeks the tunnelling success of the termites was recorded as shown in Table 1.

Termites penetrated the vertical granite substrates up to 2.4 mm and less than 1.7mm, but virtually no penetration occurred in the substrates ranging from 2.4 – 1.7mm diameter.

Experiment 2 - Horizontal tunnelling-substrates without fines

In both bioassays, results after two weeks indicated no penetration by any termite caste (i.e., soldier or worker termite) of substrate in the range 2.4 to 1.7 mm diam. All the other particle sizes were breached within two weeks.

Experiment 3 - Blending substrates and fines

Results of termite activity through the blended substrate are shown in Table 2, and represent the mean value of five replicates in each treatment group. The size of the material with less than 5% fines was within the range 2.4 to 1.7 mm diam. This material without fines is termed 'solids' in this section.

The results indicated that the termites could not fully penetrate the 150 mm substrate column with a ratio of coarse/fine of up to 8 percent fines incorporated into the blend. Although termites were seen to penetrate the blend with 8% fines to 62.5 mm after the seventh day of test, there was no further activity after 14 days. Termites were found

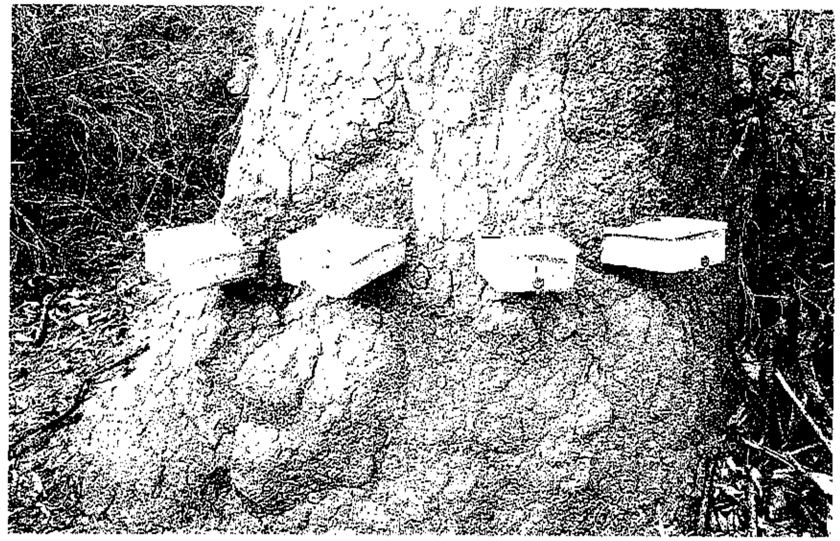

Fig. 5. The experimental layout of plastic containers (Experiment 6) in a live mound of *C. acinaciformis* near Townsville.

Table 1. Mean of five replicates in two bioassays indicating the ability of *C. acinaciformis* to vertically penetrate 150 mm cylinders of the granite substrate without fines after two weeks.

Substratesize (mm. diam)	Penetration Depth After Two Weeks			
	Upwards		Downwards	
	mm	%	mm	%
>2.4	150 (0.0)	100	150	100
2.4 - 1.7	5 (2.1)	3	3 (1.3)	2
<1.7	150 (0.0)	100	150	100

Key: Numbers in parenthesis are standard error of mean.

dead in the tunnels at this blended physical barrier treatment. However, at 16 percent fines, termites were found penetrating over 113 mm after 14 days. This suggests that the ratio of coarse/fine at 92/8 adequately prevented penetration.

Experiment 4 - Substrate with no fines and no agar plugs

Results of tunnelling in untamped substrate with no fines and no agar plugs by *C. acinaciformis* after two weeks are shown in Table 3. Within three days termite workers in Units # 1 and 5 had penetrated 4 and 22 mm respectively through the 2.4 - 1.7 mm diameter substrate. However, by the end of the first week, the leading termite worker at the end of each tunnel was dead, and no further tunnelling was observed. The dead termites were not eaten, removed, by-passed, nor replaced by other

Table 2. The ability of *C. acinaciformis* to penetrate 150 mm cylinders of untamped, solid granite substrate with fines positioned vertically for up to two weeks. Mean of five cylinders.

Ratio of coarse/fine%	Performance (mm)					
	After 7 days			After 14 days		
	Mean	Max.	Proprotion*	Mean	Max.	Proportion*
**100	0	0	0/5	0	0	0/5
98/2	8.3 (5.6)	27	2/5	8.3 (5.6)	27	0/5
96/4	39.2 (11.6)	71	4/5	39.2 (11.6)	71	4/5
92/8	62.5 (5.0)	77	5/5	62.5 (5.0)	77	5/5
84/16	62.0 (9.7)	81	5/5	113.2 (12.9)	142	5/5
68/32	81.0 (10)	117	5/5	134.4 (6.7)	150	5/5
52/48	109.8 (17.8)	150	5/5	141.2 (6.8)	150	5/5

Key: **Solids in the range 2.4 - 1.7 mm diam.; Numbers in parenthesis are standard error of the mean. *Proportion = Proportion of cylinders with termite activity; Max. = Maximum

Table 3. Indicating the maximum penetration by C. acinaciformis through 150 mm of granite substrate with no fines (2.4 - 1.7 mm diam) and with no agar plugs after two weeks. Mean of five replicates.

Experimental Unit # (mm. diam)	Maximum penetration			
	After 7 days		After 14 days	
	mm	Termite activity	mm	Termite activity
1	4	TA	4	NA
2	20	TA	20	NA
3	0	NA	0	NA
4	6	TA	6	NA
5	22	TA	22	NA

Key: NA = No termite activity. TA = Termite activity.

active termites in the tunnel systems. Thus, the results after two weeks indicated that the maximum penetration of the 150 mm thick barrier was 22 mm.

Field Bioassays

Boola Boola State Forest

Field experiment 1 - Conduits in mounds

After 4 weeks the termites had penetrated only to the top of the control columns, as indicated by the termite activity at the cork baits. Whereas in the cylinders with the various sizes of substrate with fines, no termite activity was observed at the cork baits, indicating that the termites had not penetrated through any of the columns.

On inspection at 8 weeks, two cylinders containing coarse substrate had been breached, as had three cylinders containing the fine substrate. Termites had penetrated the medium substrate in mound 5. However, the column had been disturbed on the previous inspection (after four weeks), allowing the agar plug to be completely eaten, causing the substrate to shift down the column. The termites had been able to pass through gaps left by the collapsed substrate.

The activity of workers from five *C. lacteus* mounds in the Boola Boola State Forest through cylinders of granite aggregates after 4 and 8 weeks are presented in Table 4.

Table 4. Activity of workers from five *C. lacteus* mounds in the Boola Boola State Forest through cylinders of granite screenings after 4 and 8 weeks. Proportion of cylinders with termite activity (5 mounds).

Granite Substrate used	Period of inspection			
	4 weeks		8 weeks	
	In	On	In	On
Coarse (+2.4 mm)	0/5	0/5	1/5	0/5
Medium (2.4-1.7 mm)	0/5	0/5	0/5	1/5*
Fine (-1.7 mm)	0/5	0/5	1/5	0/5
Control	5/5		5/5	

Key: In = the position of the bait in the centre of the substrate in the trench; On = the bait on the surface of the substrate in the trench. *Column found with no activity after 4 weeks, but due to disturbance of substrate during the inspection termite penetration was recorded at 8 week inspection.

Field experiment 2 - Substrate with fines in mound

The results of inserting numerous plastic containers with the substrate with > 10% fines into a single large and active mound of C. lacteus are shown in Table 5. The results show that termites were able to move across all the substrate sizes and feed on the cork baits.

The termites were able to move across the surface of the granite substrate, regardless of particle size. They constructed shelter-tubes of mud and faecal material over the surface and readily fed on the cork baits. All but two of the baits in the above substrates were located and attacked within two weeks of installing the experimental units. The remaining two baits attacked within four months. After four months, termites had penetrated all of the substrate sizes. In the coarse and fine substrate only a single unit of each was penetrated, whereas in the medium substrate, one unit was penetrated. At any time, and for any substrate, termites were more active above than below the substrate.

Table 5. Ability of *C. lacteus* to walk across and/or penetrate various sizes of substrate with fines in plastic containers inserted into a single mound colony in Boola Boola State Forest.

Proportion of boxes with termite activity (3 boxes per substrate size and position)					
Granite Substrate	Entry Level	Inspection time			
		2wks	2mths	4mths	8mths
Coarse (+2.4 mm)	Above substrate	2/3	2/3	3/3	3/3
	Below substrate	0/3	0/3	1/3	1/3
Medium (2.4-1.7 mm)	Above substrate	3/3	3/3	3/3	3/3
	Below substrate	0/3	0/3	1/3	1/3
Fine (-1.7 mm)	Above substrate	2/3	3/3	3/3	3/3
	Below substrate	0/3	0/3	1/3	1/3

Key: mths = months, wks = weeks

Field experiment 3 - Trenches outside mounds using baits on the surface of the substrate.

Termites were able to construct shelter-tubes over the surface of the various sized substrates and attack the cork baits on the surface (see Table 6). Although by the last month of inspection the termites had traversed the surface of all the various substrate sizes, it was only in the medium sized (2.4 - 1.7 mm diam.) substrate that no termite penetrated up through the substrate to attack the cork baits. Termites penetrated the fine and coarse substrates within two months to attack the cork baits from below rather than on the surface.

Field experiment 4 - Trenches outside mounds using baits in and on surface of the substrate.

The results of the experiment after six and twelve months are shown in Table 7. The termites attacked none of the baits at the centre of the 2.4 to 1.7 mm diameter substrates in any of the trenches. Only in one mound (number 3), did the termites attack the cork bait on the surface of the substrate. In this case again the termites built a shelter-tube across the substrate and reached the cork bait.

Field experiment 5 - Trenches outside mounds with boric acid

Throughout the 12 month exposure period of this experiment, there was no termite activity at any of the baits in the centre of the trenches that were filled with the medium sized substrate (2.4 - 1.7 mm diam.) (Table 8). However, the baits on the surface of the substrate were attacked by the termites, which gained access to the baits by walking across the surface of the substrate. The termite shelter-tubes were extended over the boric acid treated interface between the substrate and the edge of the trench. The boric acid may have leached down the side of this interface due to precipitation and weathering. While mound number 2 had to be abandoned because of damage due to logging operations in the area, the overall effect was that termites did not penetrate the substrate (2.4 - 1.7 mm diam.) after it was treated with boric acid.

Townsville, Queensland

Field experiment 6 - Substrate with fines in mounds

On inspecting the mounds four weeks after installation of this experiment, termites had tunnelled through all the various sizes of screenings. Termites can tunnel through coarse substrate > 2.4 mm diameter and certain proportion of fines within the range < 1.7 mm diameter. The actual proportion of fines in the solid substrate was not determined. As a consequence of this finding, the experiment was repeated using solid substrate with no fines.

Table 6. Proportion of cork baits attacked by *C. lacteus* on the surface of the various sized substrate in trenches around the mounds after two, four and six months in the Boola Boola State Forest.

Proportion of baits with termite activity. Mean of four replicates.			
Granite Substrate	Period of inspection		
	2 mths	4 mths	6 mths
Coarse (+2.4 mm)	3/4	4/4	4/4
Medium (2.4-1.7 mm)	1/4	2/4	3/4
Fine (-1.7 mm)	3/4	4/4	4/4
Control (cork only)	4/4	4/4	4/4

Key: mths = months

Table 7. Ability of *C. lacteus* from active mounds to tunnel and attack cork and wood baits placed in and on the granite substrate (2.4 - 1.7 mm diam.) in the trenches after six and 12 months in the Boola Boola State Forest. Proportion of baits with termite activity (5 mounds with baits in and on substrate).

Granite Substrate	Bait block placed			
	6 mths		12 mths	
	In	On	In	On
Coarse (+2.4 mm)	1/5	4/5	1/5	4/5
Medium (2.4-1.7 mm)	0/5	3/5	0/5	3/5
Fine (-1.7 mm)	5/5	3/5	5/5	3/5
Control	5/5		5/5	

Key: In = Refers to the position of the bait in the centre of the substrate in the trench; On = Refers to the bait on the surface of the substrate in the trench. Inspection after 12 months, indicated that the results were similar to those noted after six months Table 7, except that all the baits on the surface of all the substrate sizes had been located and attacked by the termites.

Table 8. Ability over 12 months of *C. lacteus* from active mounds the Boola Boola State Forest to tunnel and attack cork and wood baits placed in and on the granite substrate (2.4 - 1.7 mm diam.) in the trenches that were treated with boric acid solution.

Proportion of baits with termite activity. Mean of five mounds.					
Inspection months	Solvent Control		Treated Control		Untreated control
	In	On	In	On	
2	0/5	0/5	0/5	4/5	
4	0/5	0/5	0/5	2/5	5/5
6*	0/4	0/4	0/4	2/4	4/4
12*	0/4	0/4	0/4	2/4	4/4

Key: * A mound was abandoned due to logging operations disturbing trenches.

Field experiment 7 - Solid substrate with no fines in mounds

After four weeks there was no tunnelling in the 2.4 - 1.7 mm diameter screenings, with only the untreated controls having been breached. Another inspection at 8 weeks provided a similar result.

DISCUSSION

The various laboratory bioassays indicated that workers and soldiers of *C. acinaciformis* could not penetrate clean granite screenings within the range of 2.4 to 1.7 mm diameter as supplied by Mawson's. However, if the granite screenings in that same range were sieved damp or blended with over 10 percent fines, then workers and soldiers of this termite species could penetrate the substrate. Although the bioassays indicated that the termites penetrated (100%) both the fine and coarse substrate, but they only penetrated 5 mm depth in the medium substrate (2.4 – 1.7 mm) (see Laboratory Experiment 1). The termite workers penetrated through the medium substrate died at the distal end of this "tunnel". Also, this penetration occurred within 24 hrs of commencement. It seems that the termites either stuck or cut/rupture their lightly sclerotized abdomens, and thus perish. Furthermore, there is a giant leap between 5 mm penetration by solitary termites in such tunnels, and active recruitment of workers through such a substrate to forage and feed on suitable cellulosic materials.

The field trials at Boola Boola State Forest and Townsville, also demonstrated the importance of excluding fines from the granite screenings. If more than 8% fines occur within the 2.4 to 1.7 mm diameter solid substrate, there is sufficient space for the termites to penetrate the barrier after they have pulled or carried away the small fines material. However, when fines were excluded from the solid substrate termites were unable to penetrate this substrate at either of the field sites.

The field bioassays also showed that termites can bridge such physical barriers by walking across the surface of the barrier via a shelter tube when confined to plastic containers inserted into mound colonies. However, in a retro-fitted field test this type of foraging behavior did not occur (French & Ahmed 1997). This trial simulated more accurately the envisaged protection system, where larger squares of granite screenings 100 mm deep were not penetrated.

Ewart *et al.* (1991) evaluated granite screenings in Hawaii against *C. formosanus* and concluded that this termite could not penetrate particles within the range of 2.4 to 1.7 mm diameter. Su *et al.* (1991) tested the ability of *C. formosanus* and *R. flavipes* to penetrate physical barriers of ground coral particles of 50 mm in thickness. Their results suggested that a particle size range of 2.80-1.18 mm could be effectively used to prevent penetration by either *C. formosanus* or *R. flavipes*. Other workers have reported the use of sand barriers for subterranean termite control (Ebeling & Forbes 1988, Myles 1997, Vernard *et al.* 1996).

While *Coptotermes* species comprise the most economically important termites in Australia (Gay & Calaby 1970) there are a number of other species, such as *Schedorhinotermes, Nasutitermes, Heterotermes, Glyptotermes and Microcerotermes* that attack and damage timber-in-service. We have only evaluated the Rhinotermitids *C. acinaciformis, C. frenchi* Hill, *C. lacteus*, the Termitid, *Nasutitermes exitiosus* (Hill), and the sole member of the Mastotermitidae, *M. darwiniensis* Froggatt (Unpublished data) Apart from *M. darwiniensis*, none of the above mentioned termites penetrated granite screenings within the 2.4 to 1.7 mm diameter range (unpubl. data).

M. darwiniensis is a large termite 11-13 mm in length and 50 – 52 mg in mass, and capable of picking up in its mandibles granite screening within the diameter range of 2.4 to 1.7 mm. Thus, this termite can penetrate such a granite substrate. However, preliminary laboratory bioassays have shown *M. darwiniensis* cannot penetrate or tunnel through granite screenings between 2.4 and 3.7 mm diameter range (J.R.J. French, unpublished observations). This findings suggests a linear relationship between size of termite and size of granite screening required, and space between each screening.

The mechanism of impenetrability of the granite screenings is that the particles should be too large and heavy for the termite to grip in its mandibles, and move. Also, granite is too hard to be chewed into smaller pieces, and most importantly when this material is tamped into place, the spaces between the particles become too small for termites to squeeze through. Table 9 indicates body and head lengths and head widths of the most economically important subterranean termite species of the soldier caste, and Table 10 indicates the worker caste, that attack and damage timber-in-service in Australia and North America. The width of the head is the single most important measurement in a termite's ability to penetrate the various grade sizes of granite screenings. While we have not experimented with *C. michaelseni* (Wasmann),

Table 9. Morphological measurements of termite soldiers, the maximum and minimum body lengths, head lengths and head widths of the most economically important subterranean termite species in Australia (source: Hill, 1942) and in North America* (source: Su *et al.* 1991). Ranked in ascending order of maximum head widths.

Termite Species	Body length (mm)		Head length (mm)		Head width (mm)	
	max.	min.	max.	min.	max.	min.
H. vagus	5.00	4.25	1.90	1.55	0.80	0.70
C. michaelseni	4.30	4.00	1.94	1.76	0.99	0.58
C. frenchi	5.20	4.00	2.05	1.77	1.21	0.58
*R. flavipes**	4.31	3.14	1.44	1.06	1.25	0.91
C. lacteus	4.75	4.00	2.31	1.90	1.28	0.62
C. acinaciformis	6.50	5.00	2.93	2.42	1.39	0.80
N. exitiosus	4.75	3.60	2.05	1.50	1.39	0.82
C. raffrayi	6.00	5.00	2.89	2.53	1.39	0.84
S. reticulatus	6.00	4.00	2.51	1.59	1.50	0.88
*C. formosanus**	6.33	3.92	1.78	1.02	1.53	1.06
S. intermedius	7.00	3.50	2.96	1.46	1.85	0.88
M. darwiniensis	13.00	11.50	4.88	4.85	3.25	3.00

Key: Min. = Minimum; Max. = Maximum

Table 10. Morphological measurements of termite workers the maximum and minimum body lengths, head lengths and head widths of the most economically important subterranean termite species in Australia (Sources: Hill, 1942 and laboratory measurements 1993 " an average of ten termites of each species") and in North America (Su *et al.* 1991).

Termite Species	Body length (mm)		Head length (mm)		Head width (mm)	
	max.	min.	max.	min.	max.	min.
C. raffrayi	3.80	3.20	1.30	1.00	1.50	1.00
R. flavipes	4.01	3.33	1.36	1.13	1.17	0.95
H. vagus	4.20	2.95	0.9	0.7	0.8	0.6
C. michaelseni	4.20	3.35	1.40	0.85	1.15	0.75
N. exitiosus	4.55	4.25	1.86	1.66	1.40	1.36
C. frenchi	5.00	3.60	1.40	0.80	1.20	0.90
C. lacteus	5.00	4.10	1.50	1.10	1.35	1.05
C. acinaciformis	5.10	3.80	1.75	1.25	1.15	0.80
C. formosanus	5.75	3.89	1.67	1.32	1.44	1.17
S. intermedius	6.20	4.50	1.70	1.30	1.50	1.20
S. reticulatus	7.00	4.50	1.73	1.40	1.80	1.40
M. darwiniensis	11.5	10.0	3.20	2.20	2.75	2.30

Key: Min. = Minimum; Max. = Maximum

C. raffrayi (Wasmann), *Schedorhinotermes intermedius intermedius* (Brauer) and *S. reticulatus* (Froggatt), their measurements suggest that they also would not penetrate a bed of 2.4 - 1.7 mm diam. screenings.

We have shown in the laboratory that *C. acinaciformis* was unable to penetrate 75 mm of tampered Granitgard™ (2.4 - 1.7 mm diam.) in over two months of testing. Whereas, these termites penetrated 75 mm of granite fines (-1.7 mm) within 24 hours and coarse granite particles (+2.4 mm) within 48 hours of exposure. We had a live display of *C. acinaciformis* in our laboratory that illustrated this aspect (Fig. 6).

CONCLUSION

The laboratory bioassays and field tests described here showed that the two species of *Coptotermes* studied were unable to penetrate granite

Fig. 6. A laboratory demonstration showing that *C. acinaciformis* workers can penetrate 75 mm bed of, on the left, fine (<1.7 mm diam) and on the right, coarse (>2.4 mm diam.) granite screenings but not the central medium grade (2.4 - 1.7 mm diam), and so feed on the wood blocks. Termites penetrated 75 mm of fine grade within 24 hrs and the coarse within 48 hrs. Period of test: 2 months.

screenings within the range of 2.4 to 1.7 mm diameters. Granite screenings of this grade (1.7 – 2.4 mm) acquired national accreditation as a termite physical barrier, for use in regions south of the Tropic of Capricorn, where *M. darwiniensis* does not occur. This product is now marketed in Australia as Granitgard™ and has been used successfully in excess of 100,000 structures.

ACKNOWLEDGMENTS

We like to acknowledge that this study was partially funded by E.B Mawson and Sons Pty Ltd and prepared, in CSIRO laboratories and field sites. We would also like to express our appreciation to Dr L. Cookson and Mr Kevin McCarthy of CSIRO and Dr. D. Ewart, and Mr. John Mawson, Granitgard Pty Ltd, for their critical review and comments of this manuscript.

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