Evaluation of Aggregate Particles as a Physical Barrier to Prevent Subterranean Termite Incursion into Structures

T. Chris Keefer[1], Dan G. Zollinger[2], and Roger E. Gold[3]

Abstract. An alternative to chemical barriers to protect structures from infestation by subterranean termites is the use of aggregate particles as a physical barrier to termite incursion into structures. Such physical barriers are less to threaten non-target organisms likely than chemical termiticides applied to soil. Glass-tube bioassays of individual aggregate particle sizes retained on American Standard of Testing Materials (ASTM) sieve sizes 8, 10, and 12 were optimal for inhibiting subterranean termite incursion into structures. A factorial combination of numbers 8, 10, and 12 was generated to use all three sizes in physical barriers against subterranean termites. Engineering analysis of the aggregate particles (numbers 8, 10, and 12) indicated that angularity, fineness modulus, and weighted particle size were variables related to the success of physical particle barriers against subterranean termites. This study showed that all aggregate ratios of particle sizes 8, 10, and 12 were effective in inhibiting tunneling by subterranean termites. In the context of the critical aggregate particle sizes, angularity, weighted particle size, and fineness modulus, there was zero penetration by subterranean termites in 12 of the 19 ratios of numbers 8, 10, and 12.

Introduction

Termites are wood-destroying insects that damage timber structures, live trees, and crops (Raina et al. 2001). Approximately 2,300 termite species have been identified, of which 183 damage wooden structures (Edwards and Mills 1986, Su and Scheffrahn 1998). Damage by termites results in major maintenance expense (preventative and/or remediation) to structure owners worldwide. Reproductive potential (Howard et al. 1982, Grace et al. 1989) and abundant food allow termites to thrive in urban areas (Su and Scheffrahn 1990). The National Pest Management Association estimated the annual cost to control termites in the United States to be at least $5 billion (NPMA 2005). When building repair is included, the cost can be as much as $11 billion in the United States (Su 2002). Five termite species -- eastern subterranean termite, *Reticulitermes flavipes* (Kollar); *R. virginicus* (Banks); western subterranean termite, *R. hesperus* Banks; *R. tibialis* Banks; and Formosan subterranean termite, *Coptotermes formosanus* Shiraki, are responsible for 90% of the cost associated with termite control in the United States

[1]Assistant Research Scientist, Department of Entomology, Texas A&M University, College Station, TX 77843. Corresponding author email: tckeefer@tamu.edu
[2]Professor, Department of Civil Engineering, Texas A&M University, College Station, TX 77843.
[3]Professor and Endowed Chair, Department of Entomology, Texas A&M University, College Station, TX 77843.

(Forschler and Lewis 1997, Austin et al. 2005). Treatments to control subterranean termites include, but are not limited to, liquid sub-soil treatments, above-and in-ground baiting systems, stainless steel mesh, diatomaceous earth, insecticide-impregnated polymer barriers, sand, salt, post-construction application of chemical directly to wood, and particle barriers (Mampe 1991, Grace and Yamamoto 1993, Robertson and Su 1995). The goal of termite treatment is to protect structures by reducing pest abundance or preventing foraging (Su and Scheffrahn 1998). Strategies using liquid sub-soil treatments to protect structures have been effective for 50 years (Gold et al. 1994, 1996), so effectiveness of physical barriers to control subterranean termites has not been adequately studied. But in recent years regulatory agencies have stopped the sale and use of many long-lasting insecticides such as chlorinated hydrocarbons in the United States, so there is renewed interest in natural and sustainable barriers to protect structures from subterranean termites. Termite prevention and control require a vast amount of knowledge in many subjects to successfully implement an integrated pest management plan (Gold et al. 1993). In addition to knowledge of termite behavior, ecology, and biology, experience in understanding insecticide labels, different control tactics, tools and equipment, landscape and hydrology surrounding the structure, and construction science are necessary (Forschler and Jenkins 2000).

Use of particles as a physical barrier to protect structures from subterranean termites has been investigated. Many substrates including diatomaceous earth (Yates et al. 2000), crushed basalt (Tamashiro et al. 1990), granite (Smith and Rust 1990, French 1991), quartz and coral sand (Su et al. 1991), silica sand (Ebeling and Forbes 1988), glass shards (Pallaske and Igarashi 1991), crushed limestone, and natural sand (Myles 1997a,b) physically prevent subterranean termites from attacking structures. If applied in appropriate sizes all the substrates if applied in appropriate sizes prevent subterranean termites from gaining access to structures. Unfortunately, different sizes of particles are needed to control different species of subterranean termites. That is, if a region is known to be infested with multiple termite species, a single size of physical barrier may not be the optimal choice for control (Yates et al. 2000). The specific particle sizes needed to control a termite species are thought to be related to dimensions of the mandible and head capsule (Su et al. 1991).

In a laboratory, Ebeling and Pence (1957) determined that sand and cinder particles 1.2-1.7 mm were optimal in preventing western subterranean termite from tunneling through a substrate to reach food. Tamashiro et al. (1987a) used crushed basalt to exclude Formosan subterranean termites from food and found no penetration by termites when particles ranged from 1.7-2.4 mm. Laboratory studies by Smith and Rust (1990) on western subterranean termites with granite particles 0.85-2.36 mm found no penetrations into treatments. Su and Scheffrahn (1992) determined in a laboratory that the optimal sand particles to prevent Formosan subterranean termites from tunneling were 2.00-2.80 mm. They also found only slight tunneling by eastern subterranean termites in particle barriers 1.70-2.00, 2.00-2.36, or 2.36-2.80 mm. French et al. (2003) concluded the optimal particle size of granite to prevent Formosan subterranean termites from tunneling was 1.7-2.4 mm in a laboratory study. Similar field studies have been done using a basaltic barrier 1.6-2.5 mm (Tamashiro et al. 1987b).

Despite studies finding that particle barriers exclude termites, use of particle barriers by the pest management industry has been mostly overlooked because of availability of inexpensive liquid termiticides that offer long term protection.

Therefore, the primary goal of this research in a laboratory was to determine ratios and properties of an aggregate particle barrier and effectiveness in limiting tunneling of subterranean termites.

Materials and Methods

Sand Samples and Engineering Properties. Two samples of sand were obtained from a silica mine in the coastal Texas region west of Houston. The particles were hydraulically mined from a natural source of silica. The only distinguishable difference between the two samples was color because of the age of the material. The particle-size profile of the two samples was determined by sieving through American Society of Testing and Materials (ASTM) standard sieves by using ASTM C136 procedures (ASTM 2006) (Table 1).

Potentially relevant characteristics of particles as a physical barrier to prevent subterranean termite incursion into structures are aggregate size, shape, angularity, loose density, fineness modulus, and modification of the fineness modulus referred to as "weighted particle size." To our knowledge, no papers have been published on characteristics of particles for preventing subterranean termite incursion into structures. Results of tests on samples A and B and Quikrete Play Sand (Atlanta, GA) check material (hereafter referred to as the check) were analyzed for loose density, fineness modulus, and weighted particle size (Table 2). All aggregate characteristics were calculated following the appropriate ASTM standards of ASTM C29M (ASTM 2009 and ASTM C125 (ASTM 2011). ASTM C29M is used to determine the density of the solid portion of a large number of aggregate particles and provides a mean representing the sample. With this method, the density of aggregate particles determined is distinguished from the bulk density of aggregates which includes the volume of voids between the particles of the aggregate. ASTM C125 is the methodology for grading and determining the quality of fine and coarse aggregates. The method includes steps for determining fineness modulus of aggregates.

Table 1. American Society of Testing and Materials (ASTM) Standard Sieve Numbers and their Size in Millimeters

ASTM standard sieve numbers	Size in mm
4	4.75
6	3.35
8	2.36
10	2.07
12	1.77
14	1.48
16	1.18
30	0.50
50	0.29
100	0.15

Table 2. Common Engineering Properties of Aggregate Particles

Material	Loose density	Fineness modulus	Weighted particle size

Sample A	100.2	3.82	1.57
Sample B	104.7	3.85	1.89
Quikrete Play Sand (check)	104.3	1.56	0.24

The loose density was calculated by pouring a quantity of known (weight) aggregate material to the top measurement line of a graduated cylinder, then adding water to the top measurement line and weighing the contents of the cylinder. Loose density was calculated by subtracting the weight of the dry aggregate from the weight of aggregate with water (weight of water in the permeable voids).

The fineness modulus index was computed by adding the total percentages by weight of an aggregate retained on each of a series of ASTM sieves and dividing the sum by 100:

$$FM = \Sigma \text{ (cumulative percent retained)}/100$$

The fineness modulus reflects the relative amount of surface area manifested by a combination of aggregate particles and consequently, the resistance of the aggregate ratio to penetration by subterranean termites. A low fineness modulus indicates finer but larger surface-area material and a high fineness modulus indicates coarse and lower surface-area material. The fineness modulus value for fine aggregate commonly ranges from 0.6 to 3.2.

The weighted particle size calculation was not a standard method of analysis; it was computed based on a modification of the fineness modulus calculation. Weighted particle size was calculated by using the sum of the product of the percentage retained on an individual screen of a specific aggregate size on each sieve in the sample by the nominal sieve size. It represented the 'effective' size of the aggregate particles in the sample. Based on similarities between the particle properties of loose density, fineness modulus, and weighted particle size, test results on samples A and B (Table 2) were combined for analysis with respect to the replicated test results.

Effects of aggregate shape and angularity on penetration by subterranean termites were assessed relative to particle measurements by using an Aggregate Image Measurement System. A typical Aggregate Image Measurement System (AIMS) consists of image acquisition hardware, a computer to run the system and analyze data, top lighting, back lighting, an autofocus microscope and camera, and a scanning table. The components were essential to capture black, white, and grayscale pixel images at different magnifications on the x, y, and z scales of the particle so the instrument analyzed all the aggregate particle characteristics (Al-Rousan et al. 2005). The two-dimensional images by the instrument were used to measure the longest and shortest dimensions of a particle. Separate AIMS images of a particle were used to determine particle shape. The AIMS software sorted and analyzed the images to calculate sphericity and the form index. These data were used to determine the particles Form 2D, which ranged from 0 to 20, with a value of zero indicating a particle with a perfect circular form, and 20 as irregular (Pine Instrument Company 2009). Form 2D is defined as low (0~6), medium (6~12), and high (12~20) (Al-Rousan et al. 2005).

Form 2D quantified the relative shape from two-dimensional images of aggregate particles. The index of Form 2D was calculated using the formula:

$$Form2D = \sum_{\theta=0}^{\theta=360-\Delta\theta} \left[\frac{R_{\theta+\Delta\theta} - R_{\theta}}{R_{\theta}} \right]$$

where R_θ was equivalent to the radius of the particle at an angle of θ, and $\Delta\theta$ was equal to the incremental difference in the angle (Masad et al. 2006). A greater Form 2D value suggests a longer, more oblong, irregular shape.

The AIMS was also used to determine particle angularity. Angularity is a quantified value using the gradient method or angularity index. The AIMS angularity index ranges from 1-10,000 where a low value indicates only slight particle angularity (Masad et al. 2006). The index is a measurement of the difference in the gradient vector along the edge of a particle (Al-Rousan 2005). The index is calculated with respect to the inclination of gradient vectors along the particle edge with respect to the x-axis.

Gradient angularity describes variations at the particle boundary that influence the overall shape. It quantified changes along a particle boundary, with greater gradient values indicating a more angular shape. Gradient angularity has a relative scale of 0 to 10,000 with a perfect circle having a value of zero. The gradient angularity was analyzed by quantifying the change in the gradient on a particle boundary and was related to sharpness of the corners of two-dimensional images of aggregate particles, as seen in Fig. 1 (Chandan et al. 2004). The gradient angularity method calculates the inclination of gradient vectors on particle boundary points from the x-axis (horizontal axis in Fig. 1). The formula used to calculate the average change in the inclination of the gradient vectors was used as an indication of angularity (Wedding and Gaynor 1961):

$$GA = \frac{1}{\frac{n}{3} - 1} \sum_{i=1}^{n-3} \left| \theta_i - \theta_{i+3} \right|$$

where, θ = angle of orientation of the edge points, n is equal to the total number of points, and i is equal to the point on the edge of the particle. Using the ranges of the value, the angularity of a particle was defined as low for 0~3,300; medium for 3,300~6,600; and high for 6,600~10,000. Fig. 2 (Pine Instruments Company 2009) illustrates the analysis concept for angularity and Form 2D. Approximately 150 particles from a sample were uniformly placed on the scanning table. Particle orientation on the table was determined by allowing the particles to come to rest at random. All of the properties of the sampled aggregate particles were meaningful to this study because they indicated available interstitial space, sharp edges, and aggregate packing.

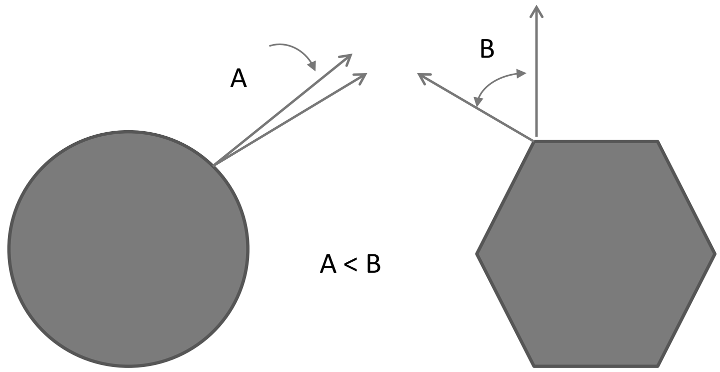

Fig. 1. Differences between smooth and angular particles (Chandan et al. 2001).

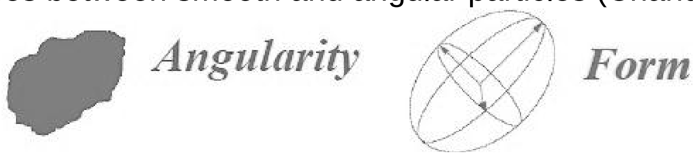

Fig. 2. AIMS software analysis properties (Pine Instruments Company 2009).

Aggregate Test Samples for Laboratory Bioassays of Subterranean Termites. Series of arenas were prepared to expose subterranean termites to combinations of aggregate particles to determine effectiveness of barriers to control tunneling. Arenas were 15 x 1.5-cm glass tubes (Su et al. 1993) assembled as in Fig. 3. Combinations of aggregate gradations consisted of various amounts of particles from number 6, 8, 10, 12, and 14 sieves.

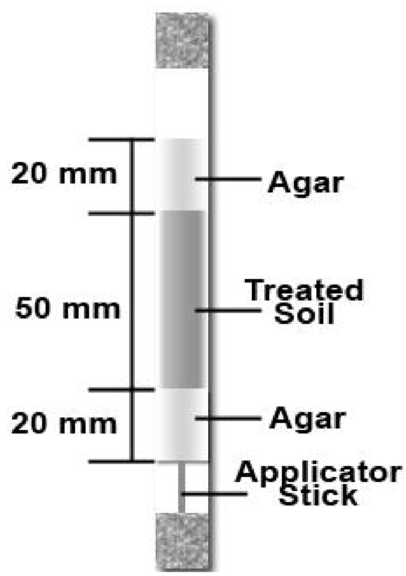

Fig. 3. Schematic showing components of glass-tube arenas used in termite tunneling bioassays (Gold et al. 1996).

Eastern subterranean termites were collected from the field at College Station, TX, and Formosan subterranean termites were collected at Beaumont, TX. Twenty worker termites and two soldiers of eastern and Formosan subterranean termites were added separately to glass-tube arenas after assembly. Distance tunneled into the aggregate particles was observed daily for 5 days. All treatments in each series of tests were replicated a minimum of six times except for Series 5 that was replicated three times because of lack of availability of aggregate particles. Statistical analyses on termite tunneling was done using SPSS v 18 where $p = 0.05$, and means were separated using Tukey's HSD test.

The aggregate samples in the Series 1 bioassays were in stock, or natural, gradation. The aggregates were added to each glass tube with little or no segregation. There were 20 replications of the aggregate sample and 10 of the check sample. The check was used in each series of testing and retained on an ASTM standard sieve 50. Series 1 testing consisted of a total of 60 glass tubes, 30 for each termite species. In Series 2-5, Samples A and B were combined.

The aggregate samples in the Series 2 bioassays were separated into individual sieve sizes 6, 8, 10, 12, and 14, and checks. The series of bioassays used 36 glass tubes for each termite species.

The aggregate samples in the Series 3 bioassays were graded and separated by sieve sizes 6 and 8. There were 24 glass tubes for each termite species. The particles were combined into 99:1, 1:99, and 50:50 ratios (percentages of numbers 6 and 8, respectively) and checks.

Series 4 aggregates were sieved and separated into numbers 8 and 10. A total of 24 glass tubes was constructed for each termite species. The particles were combined into 90:10, 10:90, and 50:50 ratios (percentages of numbers 8 and 10) and checks.

Series 5 aggregate combinations were made of numbers 8, 10, and 12. Three replications for each aggregate combination and the check were assembled, for a total of 60 arenas for each termite species. The three particle sizes were combined into 19 ratios based on factorial combinations. In using a factorial design, we optimized the process by evaluating important variables that helped build a mathematical model for prediction, and optimized our design (Lye 2002). The factorial approach also allowed for varying all factors in the experiment simultaneously which deals with interactions of each variable and allows maximization of the efficiency of each variable in the experiment in real time instead of trial-and-error method.

To prepare samples in the termite penetration test, Samples A, B, and the check were sieved through nested ASTM sieves by using ASTM C144 protocol (ASTM 2005). The percentages of Samples A, B, and the check passing through the nested sieves are listed in Fig. 4. In the 2^3 factorial design, six combinations were normalized for the fraction amounts to total 100%. This caused some proportions to be modified and some duplicated (25% of number 8, 50% of number 10, and 25% of number 12-sized materials). Thus, reduction in the number of factorial combinations resulted in 19 combinations (that would otherwise have been 24). An amount of 300 g was prepared for the termite penetration test in each of the 19 combinations in ratios shown in Table 3.

Results and Discussion

Sand Samples and Engineering Properties. Form 2D indices of all aggregates were distributed mostly in the low and medium ranges (Table 4). Most particles of aggregate were cylindrical rather than irregular regardless of size.

The mean angularity was less than 2,800 for all sizes of aggregate (Table 5). Because most particles were in the low range (based on cumulative percentage), the particles were classified as predominately circular. The mean loose density was 198.98 cm^3 which represents permeable voids (filled by water) with non-compacted aggregates (Table 6).

Laboratory Bioassays of Subterranean Termites. In Series 1, the mean tunneling distance (penetration) by eastern subterranean termite was longer than by Formosan subterranean termite (Table 7). There were significant differences in the distance tunneled between the two treatments and the nontreated check by both species of termite. The mean tunneling distance was 10.60 mm by eastern subterranean termite and 4.11 mm by Formosan subterranean termite. In the sand (check) the mean tunneling distance was 50.00 mm for both termite species which was the maximum possible distance tunneled.

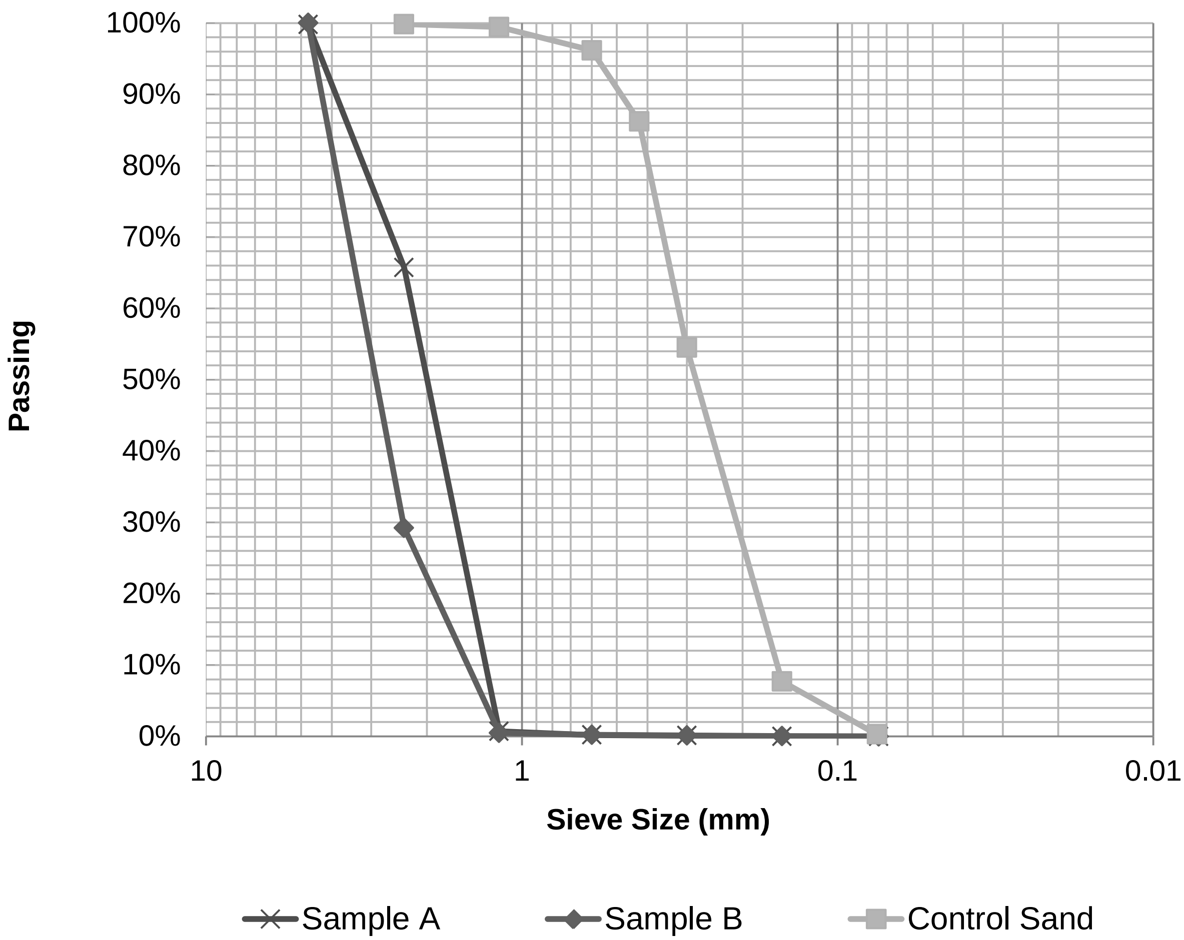

Fig. 4. Percentage of samples A, B, and the check passing through nested ASTM sieves that define gradation by ASTM C144.

Table 3. Ratios of Aggregate Particles Retained on Number 8, 10, and 12 ASTM Standard Sieves Used in Glass-Tube Bioassays to Evaluate Tunneling of *Reticulitermes flavipes* and *Coptotermes formosanus* Subterranean Termites

Treatment	Nos. 8, 10, 12	Treatment	Nos. 8, 10, 12	Treatment	Nos. 8, 10, 12

1	45:10:45	8	35:30:35	15	22:44:33
2	8:17:75	9	19:37:44	16	18:57:27
3	15:50:25	10	13:58:29	17	33:44:22
4	4:64:32	11	44:38:18	18	27:54:18
5	75:17:8	12	29:58:13	19	20:60:20
6	32:64:4	13	15:70:15		
7	5:90:5	14	30:40:30		

All ratios are listed as numbers 8, 10, 12

Table 4. Mean Form 2D of Selected Numbers 6, 8, 10, 12, and 14 of Aggregate Particles

Sample (retained on)	No. of particles tested	Mean Form 2D	S.D.[a]	Low (≤5.99)			Medium (6.00~11.99)			High (12.00~20.00)		
				No. of particles	%	Cum.[b] %	No. of particles	%	Cum. %	No. of particles	%	Cum. %
6	152	5.95	1.69	77	50.7	50.7	75	49.3	100	0	0.0	100
8	150	5.95	1.61	77	51.3	51.3	73	48.7	100	0	0.0	100
10	151	6.35	1.86	72	47.7	47.7	77	51.0	98.7	2	1.3	100
12	150	6.64	1.74	57	38.0	38.0	93	62.0	100	0	0.0	100
14	150	6.69	2.15	64	42.7	42.7	81	54.0	96.7	5	3.3	100

[a]S.D. = standard deviation
[b]Cum. % = cumulative percentage

Table 5. Gradient Angularity Test of Number 6, 8, 10, 12, and 14 Aggregate Particles

Sample (retained on)	No. of particles tested	Mean gradient anguarity	S.D.[a]	Low (≤2,999)			Medium (3,000~6,599)			High (6,600~10,000)		
				No. of particles	%	Cum.[b] %	No. of particles	%	Cum. %	No. of particles	%	Cum. %
6	151	2440.4	894.5	128	84.8	84.8	23	15.2	100	0	0.0	100
8	150	2509.1	977.7	124	82.7	82.7	26	17.3	100	0	0.0	100
10	151	2747.8	1093.4	106	70.2	70.2	44	29.1	99.3	1	0.7	100
12	150	2771.1	977.0	112	74.7	74.7	38	25.3	100	0	0.0	100
14	150	2688.7	981.3	116	77.3	77.3	34	22.7	100	0	0.0	100

[a]S.D. = standard deviation
[b]Cum. % = cumulative percentage

Table 6. Loose Density Calculated by the Measurements on Volume and Weight of the Ratios of Number 8, 10, and 12 Aggregate Particles Created by Factorial Combinations

Ratios of nos. 8, 10, 12	Volume (cm^3)	Weight (g)	Weight (g/cm^3)
45:10:45	196.00	300.02	1.53
8:17:75	199.00	300.07	1.50
15:50:25	198.00	300.48	1.51
4:64:32	199.00	300.00	1.50
75:17:8	201.00	299.93	1.49
32:64:4	196.00	300.01	1.53
5:90:5	199.00	300.00	1.50
35:30:35	199.00	299.96	1.50
19:37:44	198.00	299.99	1.51
13:58:29	197.00	299.97	1.52
44:38:18	198.33	299.94	1.51
29:58:13	198.33	299.95	1.51
15:70:15	199.33	299.90	1.50
30:40:30	199.33	300.02	1.50
22:44:33	199.33	299.87	1.50
18:57:27	200.33	299.88	1.49
33:44:22	200.67	299.91	1.49
27:54:18	200.00	299.32	1.49
20:60:20	203.00	299.96	1.47

Table 7. Mean (20 Replications per Treatment) Distance Tunneled (mm) at 5 Days Post-treatment by *Reticulitermes flavipes* and *Coptotermes formosanus* Subterranean Termites in Aggregate Particles (Series 1)

Treatment	Species	Distance tunneled (±SD)
Particles	*R. flavipes*	10.60 ± 14.22 a
Nontreated check (sand)		50.00 ± 0.00 b
Particles	*C. formosanus*	4.11 ± 11.72 a
Nontreated check (sand)		50.00 ± 0.00 b

Means followed by different letters for the species are significantly different (p = 0.05). Maximum possible distance tunneled was 50.00 mm.

In Series 2, the mean tunneling distance for eastern and Formosan subterranean termites was longest in number-6 aggregate particles (Table 8). There were significant differences in the distance tunneled by each species of termite in the different particle sizes. Both species of termite tunneled farthest in number-6 aggregate particles, and the checks were significantly different from all other treatments.

In Series 3, eastern subterranean termites tunneled into particles of all three aggregate ratios and there were no significant differences between the tunneling distances in the aggregate ratios and the check (sand). Both species of subterranean termite tunneled farthest in sieve 6:8 (99:1) ratio particles. The mean distance tunneled by eastern subterranean termites in sieve 6:8 (99:1) ratio particles was 48.33 ± 2.88 mm and for Formosan subterranean termite was 32.33 ± 17.78 mm (Table 9). All sieve 6 and 8 ratio treatments were penetrated by both

Table 8. Mean (Six Replications per Treatment) Distance Tunneled (mm) by *Reticulitermes flavipes* and *Coptotermes formosanus* Subterranean Termites in Different Aggregate Particles at 5 Days Post-treatment (Series 2)

Nos. of aggregate particles	Distance tunneled (±SD) *R. flavipes*	*C. formosanus*
6	28.00 ± 17.94 b	17.00 ± 9.11 b
8	3.00 ± 3.00 a	10.66 ± 10.98 a
10	1.00 ± 3.01 a	3.16 ± 1.83 a
12	0.66 ± 1.63 a	0.83 ± 2.04 a
14	1.50 ± 3.67 a	1.16 ± 1.63 a
Nontreated check (sand)	50.00 ± 0.00 c	50.00 ± 0.00 c

Means followed by different letters in a column are significantly different (p = 0.05). Maximum possible distance tunneled was 50.00 mm.

Table 9. Mean (Six Replications per Treatment) Distance Tunneled (mm) by *Reticulitermes flavipes* and *Coptotermes formosanus* Subterranean Termites in Different Ratios of Aggregate Particles at 5 Days Post-treatment (Series 3 and 4)

Series # (particle nos.)	Ratio	Distance tunneled (±SD) *R. flavipes*	*C. formosanus*
Series 3 (6, 8)	99:1	48.33 ± 2.88 a	32.33 ± 17.78 ab
	90:10	35.00 ± 17.32 a	24.33 ± 17.92 ab
	50:50	22.33 ± 19.65 a	13.00 ± 2.00 a
Nontreated check (sand)		50.00 ± 0.00 a	50.00 ± 0.00 b
Series 4 (8, 10)	90:10	2.50 ± 2.73 b	0.00 ± 0.00 a
	10:90	0.00 ± 0.00 a	1.16 ± 2.85 b
	50:50	3.33 ± 6.05 b	2.83 ± 4.91 b
Nontreated check (sand)		50.00 ± 0.00 c	50.00 ± 0.00 c

Means followed by different letters in a column are significantly different (p = 0.05). Maximum possible distance tunneled was 50.00 mm.

species of termite. There were significant differences between all aggregate ratio treatments and nontreated checks by Formosan subterranean termites.

In Series 4, the distance tunneled by both species of termite into the 50:50 ratio of sieve 8 and 10 particles was longest. Eastern subterranean termites did not tunnel into the 10:90 ratio of sieve number 8 and 10 aggregate particles, and Formosan subterranean termites did not tunnel into the 90:10 ratio of sieve 8 and 10 particles. The distance tunneled into the check by both species of termite was significantly different from all treatments.

In Series 5, particles were categorized into 19 factorial combinations based on calculation of weighted particle size (Table 2). Eastern subterranean termites tunneled into six and Formosan subterranean termites tunneled into nine of the 19 combinations (Table 10). There were no significant differences in tunneling distance into the treatments by either termite species, but all particle combinations were significantly different from the nontreated check by both species.

Parameters were analyzed to find key trends in the data. Variance associated with the replication test results from each series was analyzed for variables listed in Table 11, along with data generated from the regression analysis of the results.

For Series 1, the tunneled distance was significantly correlated to weighted particle size and fineness modulus. A plot of means of the same results associated with Samples A, B, and the check is shown in Fig. 5 to illustrate effective particle size that corresponded to zero tunneling. The trends in the Figure suggested the critical size was within ranges noted by Smith and Rust (1990), Su and Scheffrahn (1992), and French et al. (2002).

The data collected for Series 2 considered the weighted particle size as well as angularity determined from testing by the AIMS. Testing summarized in Table 11 indicated high significance for the data from Series 2, indicating that aggregate angularity was important for penetration by termites. Although not shown, a similar conclusion would be found from analysis of Form 2D measurements. It is also important to note that particle sizes in the tests were larger than the effective size associated with zero penetration in Fig. 5. Data trends of penetration and weighted particle size means shown in Fig. 6 reinforce the finding of others that particle size approximately 2 mm is effective for zero penetration by termites. Data in Fig. 7 indicated that as angularity increased, penetration by termites decreased and the threshold of angularity for zero penetration was approximately 2,770, which is slightly irregular. Although interaction between

Table 10. Mean (Three Replications per Treatment) Distance Tunneled (mm) Ranked from Most to Least Penetration by *Reticulitermes flavipes* and *Coptotermes formosanus* at 5 Days Post-treatment in 19 Ratios (Ratios of Numbers 8:10:12) of Aggregate Particles (Series 5)

Treatment # (ratio)	*R. flavipes* distance tunneled (± SD)	Treatment # (ratio)	*C. formosanus* distance tunneled (± SD)
Nontreated check	50.00 ± 0.00 a	Nontreated check	50.00 ± 0.00 a
10 (19:37:44)[a]	4.01 ± 5.92 b	8 (5:90:5)	6.67 ± 11.55 b
16 (15:70:15)	3.00 ± 5.20 b	10 (19:37:44)[a]	4.00 ± 6.93 b
4 (4:64:32)	1.67 ± 2.89 b	3 (25:50:25)	3.33 ± 5.77 b
2 (8:17:75)	1.00 ± 1.73 b	5 (75:17:18)	2.67 ± 4.62 b
5 (75:17:8)	1.00 ± 1.73 b	7 (32:64:4)	1.67 ± 2.89 b
1 (45:10:45)	0.73 ± 0.58 b	16 (15:70:15)	1.67 ± 1.00 b
7 (32:64:4)	0.00 ± 0.00 b	2 (8:17:75)	1.33 ± 2.31 b
8 (5:90:5)	0.00 ± 0.00 b	4 (4:64:32)	1.37 ± 2.33 b
3 (25:50:25)	0.00 ± 0.00 b	1 (45:10:45)	0.92 ± 0.51 b
9 (35:30:35)	0.00 ± 0.00 b	9 (35:30:35)	0.00 ± 0.00 b
12 (13:58:29)	0.00 ± 0.00 b	12 (13:58:29)	0.00 ± 0.00 b
13 (44:38:18)	0.00 ± 0.00 b	13 (44:38:18)	0.00 ± 0.00 b
15 (29:58:13)	0.00 ± 0.00 b	15 (29:58:13)	0.00 ± 0.00 b
17 (30:40:30)	0.00 ± 0.00 b	17 (30:40:30)	0.00 ± 0.00 b
18 (22:44:33)	0.00 ± 0.00 b	18 (22:44:33)	0.00 ± 0.00 b
20 (18:54:27)	0.00 ± 0.00 b	20 (18:54:27)	0.00 ± 0.00 b
21 (33:44:22)	0.00 ± 0.00 b	21 (33:44:22)	0.00 ± 0.00 b
23 (27:54:18)	0.00 ± 0.00 b	23 (27:54:18)	0.00 ± 0.00 b
24 (20:60:20)	0.00 ± 0.00 b	24 (20:60:20)	0.00 ± 0.00 b

Means followed by different letters in a column are significantly difference (p = 0.05). Maximum possible distance tunneled was 50.00 mm.

[a]Treatment numbers are the same for exact ratios of aggregate materials associated with the two species of subterranean termite.

Table 11. Regression Analysis Summary of Results of Tunneling by Subterranean Termites in Aggregate Particles

Combination	Dependent variable[a]	R^2	F	α	Species
Series 1	WPS[b]	0.843	150.460	0.000	Cf[d]
		0.730	75.604	0.000	Rf[e]
	FM[c]	0.843	150.460	0.000	Cf
		0.730	75.604	0.000	Rf
Series 2	WPS	0.485	26.328	0.000	Cf
		0.572	37.375	0.000	Rf
	Angularity	0.483	26.205	0.000	Cf
		0.401	18.771	0.000	Rf
Series 3	WPS	0.287	2.821	0.137	Cf
		0.368	4.079	0.083	Rf
Series 4	WPS	0.978	955.985	0.000	Cf
		0.979	1031.165	0.000	Rf
Series 5	WPS	0.049	0.831	0.376	Cf
		0.075	1.217	0.287	Rf

[a]Independent variable was distance tunneled
WPS = weighted particle size
[b]FM = fineness modulus
[c]Cf = *Coptotermes formosanus*
[d]Rf = *Reticuliterms flavipes*

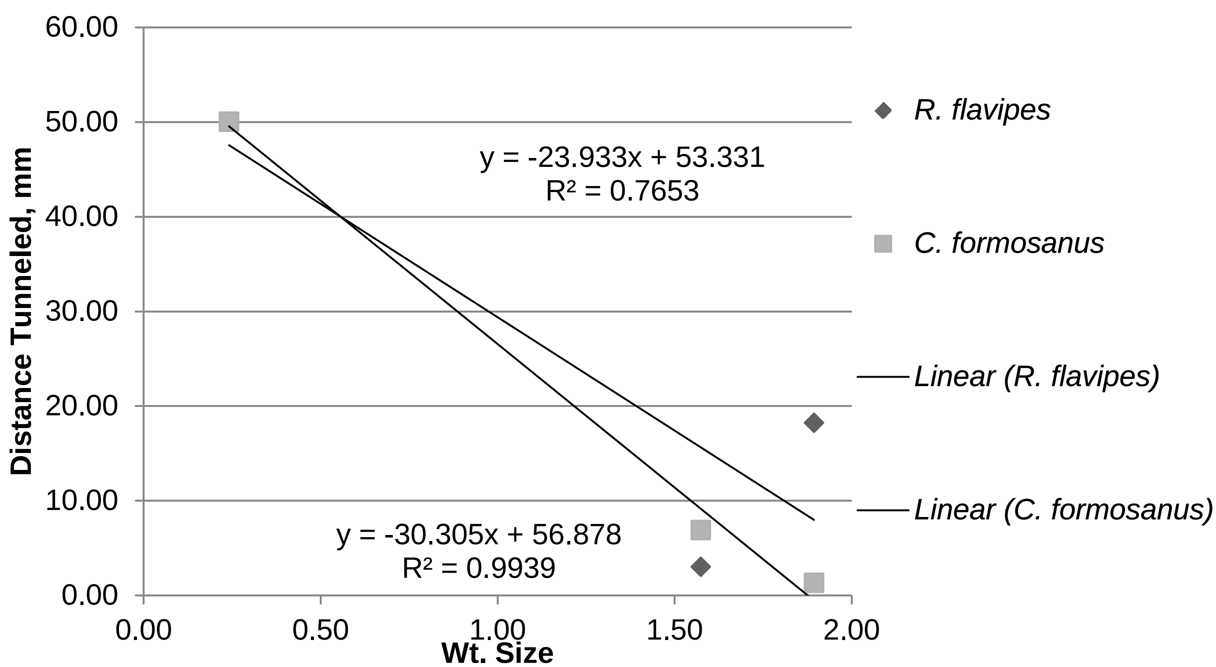

Fig. 5. Series 1 *Reticulitermes flavipes* and *Coptotermes formosanus* tunneling results versus mean weight size (wt. size).

particle size and angularity was significant, there is little evidence to suggest that particle shape or angularity depend on the size of the particle but rather the origin or method of manufacture of the aggregate.

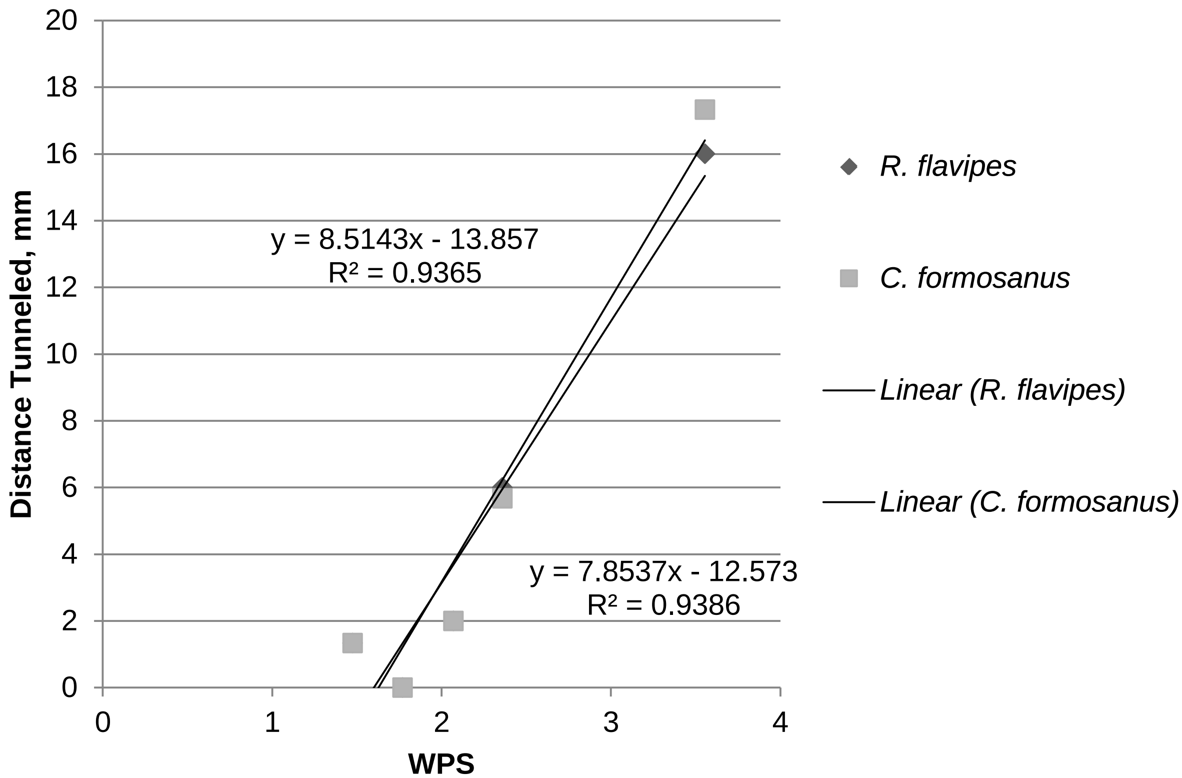

Fig. 6. Series 2 *Reticulitermes flavipes* and *Coptotermes formosanus* tunneling results versus mean weighted particle size (WPS).

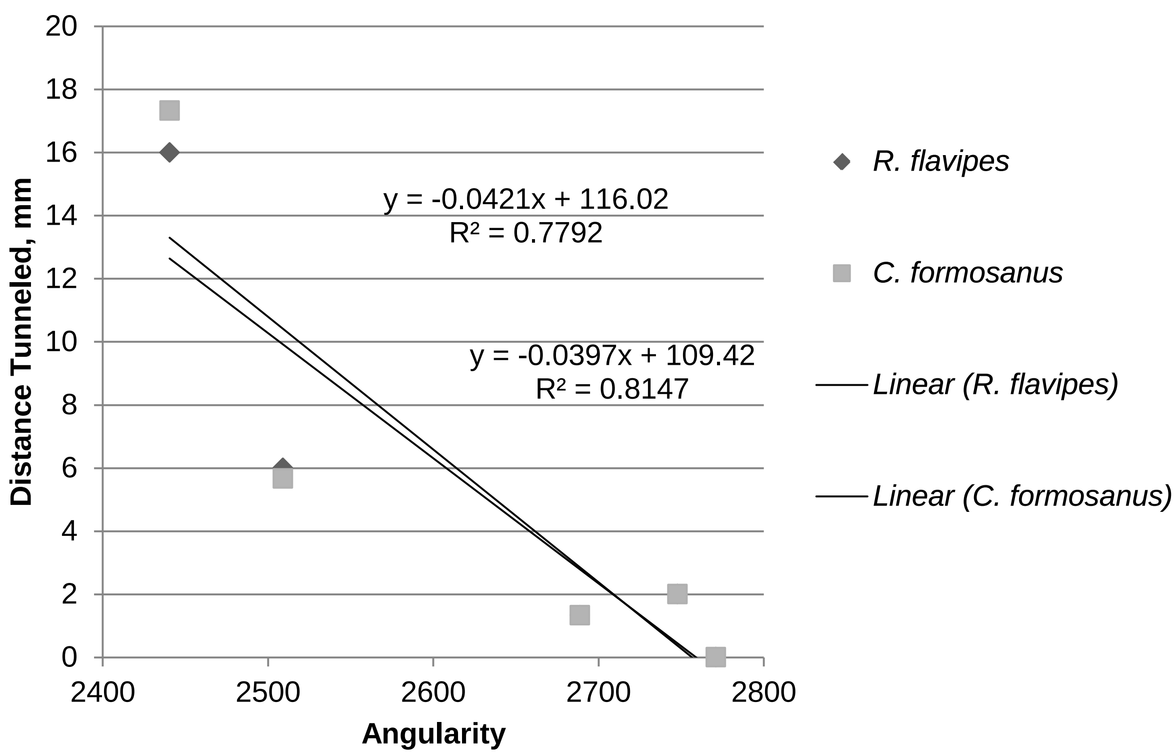

Fig. 7. Series 2 *Reticulitermes flavipes* and *Coptotermes formosanus* tunneling results versus mean gradient angularity.

Regression analysis results are shown in Table 11; however, the correlation to weighted particle size was not as strong for Series 3 and 5 as for Series 1 and 2. The results for Series 5 are not unexpected considering the effectiveness of sieve numbers 8 to 12 in limiting penetration in any combination.

The number-6 aggregate seemed to be least preferred in a barrier to prevent access to structures because subterranean termites were able to tunnel completely through glass tubes that had number 6 particles. The most economical way to create a physical barrier to tunneling by subterranean termites would be to use common gradations of aggregate materials. It is clear from this study that termite barriers must be limited to a specific size range (numbers 8-12). Ratios penetrated least had approximately three equal parts of number 8, 10, and 12 aggregate particles. Ten aggregate combinations of numbers 8, 10, and 12 were not penetrated by either species of subterranean termite.

The results from this study validate findings from previous research that the effectiveness of unbound, aggregate barriers to impede termite incursion depends on aggregate size. However in this study, analysis of fineness modulus, aggregate angularity, and weighted particle size, a modification of how particle size is considered in granular termite barrier research, were important in selection of aggregate particles in the critical range (numbers 8, 10, and 12). It may be possible to examine a wide range of aggregate shape and angularity relative to critical sizes to achieve zero penetration although the evidence was somewhat compromised by the uniformity of the samples in this study. Further examination of the effect of particle shape, angularity, weighted particle size, and fineness modulus on barrier effectiveness is warranted, especially as it relates to manufactured materials in stockpiles throughout the United States. Compared to widely used liquid termiticide barriers that degrade over time, physical barriers including aggregates of specific size, angularity, weighted particle size, and fineness modulus should be important elements in the future of protection of structures from subterranean termites.

Acknowledgment

The authors would like to thank Sang Ick Lee of the Texas A&M Transportation Institute for his time and expertise in helping with this research.

References Cited

Al-Rousan, T. M., E. A. Masad, M. Leslie, and C. Speigelman. 2005. New methodology for shape classification of aggregates. J. Transportation Res. Board 1913: 11-23.

American Society of Testing Materials (ASTM C 144). 2005. Standard specification for aggregate for masonry mortar. ASTM International, West Conshohocken, PA.

American Society of Testing Materials (ASTM C 136). 2006. Standard specification for nonloadbearing concrete masonry units. ASTM International, West Conshohocken, PA.

American Society of Testing Materials (ASTM C29M). 2009. Standard test method for bulk density and voids in aggregate. ASTM International, West Conshohocken, PA.

American Society of Testing Materials (ASTM C 125). 2011. Standard specification for nonloadbearing concrete masonry units. ASTM International, West Conshohocken, PA.

Austin, J. W., A. L. Szalanski, R. H. Scheffrahn, and M. T. Messenger. 2005. Genetic variation of *Reticulitermes flavipes* (Isoptera: Rhinotermitidae) in North America applying the mitochondrial rRNA 16S Gene. Ann. Entomol. Soc. Am. 98: 980-988.

Chandan, C., K. Sivakumar, T. Fletcher, and E. Masad. 2004. Geometry analysis of aggregate particles using imaging techniques. J. Comp. Civil Eng., ASCE 18: 75-82.

Ebeling, W. R., and C. F. Forbes. 1988. Sand barriers for subterranean termite control. IPM Practitioner 10: 1-6.

Ebeling, W. R., and R. J. Pence. 1957. Relation of particle size to the penetration of subterranean termites through barriers of sand or cinders. J. Econ. Entomol. 50: 690-692.

Edwards, R., and A. E. Mills. 1986. Termites in Buildings: their Biology and Control. Rentokil Limited, W. Sussex, UK.

Forschler, B. T., and T. M. Jenkins. 2000. Subterranean termites in the urban landscape: understanding their social structure is the key to successfully implementing population management using bait technology. Urban Ecosystems 4: 231-251.

Forschler, B. T., and V. Lewis. 1997. Why termites can dodge your treatment. Pest Control 65: 42-53.

French, J. R. J. 1991. Physical Barriers and Bait Toxicants: the Romeo and Juliet of Future Termite Control. International Research Group on Wood Preservation Document IRG/WP/1503.

French, J. R., B. Ahmed, and A. Trajstman. 2003. Laboratory and field evaluation of granite aggregate as a physical barrier against subterranean termites of the genus *Coptotermes* spp. (Isoptera: Rhinotermitidae). Socio 42: 1-21.

Gold, R. E., H. N. Howell, and E. A. Jordan III. 1993. Horizontal and vertical distribution of chlorpyrifos termiticide applied as liquid foam or foam emulsions, pp. 140-155. Pesticides in Urban Environments. American Chemical Society, Washington DC.

Gold, R. E., A. A. Collins, B. M. Pawson, and H. N. Howell Jr. 1994. Termiticide technology-the isofenphos dilemma. Technology: J. Franklin Inst. 331: 19-198.

Gold, R. E., H. N. Howell Jr., B. M. Pawson, M. S. Wright, and J. C. Lutz. 1996. Evaluation of termiticides residues and bioavailability from five soils types and locations in Texas, pp. 567-484. *In* K. B. Wildey [ed.], Proceedings of the 2nd International Conference on Insect Pests in the Urban Environment, Edinburgh, Scotland, 7-10 July.

Grace, J. K., and R. T. Yamamoto. 1993. Diatomaceous earth is not a barrier to Formosan subterranean termites (Isoptera: Rhinotermitidae). Socio 23: 25-30.

Grace, J. K., A. Abdallay, and K. R. Farr. 1989. Eastern subterranean termite (Isoptera: Rhinotermitidae) foraging territories and populations in Toronto. Can. Entomol. 121: 551-556.

Howard, R. W., S. C. Jones, J. K. Mauldin, and R. H. Beal. 1982. Abundance, distribution, and colony size estimates for *Reticulitermes* spp. in southern Mississippi. J. Econ. Entomol.11: 1290-1293.

Lye, M. L. 2002. Design of experiments in civil engineering: are we still in the 1920's? Annual Conference of the Canadian Society of Civil Engineering. Quebec, Canada, 5-8 June.

Mampe, C.D. 1991. Termite control: what we learned in 1990. Pest Control 59: 28, 30.

Masad, E., A. Luce, and E. Mahmoud. 2006. Implementation of AIMS in measuring aggregate resistance to polishing, abrasion and breakage. Texas Transportation Report 5-1707-03-1.

Myles, T. G. 1997a. Penetrability of some Ontario construction aggregates by the eastern subterranean termite (Isoptera: Rhinotermitidae). Socio 28: 327-335.

Myles, T. G. 1997b. Comparision of the penetrability of smooth and crushed sand by subterranean termites (Isoptera: Rhinotermitidae). Socio 30: 295-303.

National Pest Management Association (NPMA). 2005. Cost to control subterranean termites in the United States. http://pestworld.org/database/Article.asp.

Pallaske, M., and A. Igarashi. 1991. Glass splinters as physical barriers: optimized material properties in use with and without insecticidal pretreatment minimizes environmental contaminations. International Research Group on Wood Preservation Document IRG/WP/1476.

Pine Instrument Company. 2009. Aggregate Image Measurement System, Model AFZ2A/AFA2C Operation Manual, Pine Instrument Company, Test Equipment Division, Grove City, PA.

Raina. A., W. Woodson, and A. Lax. 2001. Current and future management strategies for subterranean termites. Entomol. 26: 29-36.

Robertson, A. S., and N.-Y. Su. 1995. Discovery of an effective slow-acting insect growth regulator for controlling subterranean termites. Down to Earth 50: 1-7.

Smith, J. L., and M. K. Rust. 1990. Tunneling response and mortality of the western subterranean termite *Reticulitermes hesperus* (Isoptera: Rhinotermitidae) to soil treated with insecticides. J. Econ. Entomol. 83: 1395-1401.

Su, N.-Y. 2002. Novel technologies for subterranean termite control. Socio 40: 95-101.

Su, N.-Y., and R. H. Scheffrahn. 1990. Comparision of eleven soil termiticides against the Formosan subterranean termite and eastern subterranean termite (Isoptera: Rhinotermitidae). *J. Econ. Entomol.* 83: 1918-1923.

Su, N.-Y., and R. H. Scheffrahn. 1992. Penetration of sized-particle barriers by field populations of subterranean termites (Isoptera: Rhinotermitidae. J. Econ. Entomol. 85: 2275-2278.

Su, N.-Y., and R. H. Scheffrahn. 1998. A review of subterranean termite control practices and prospects for integrated pest management programmes. Integr. Pest Man. Rev. 3: 1-13.

Su, N.-Y., R. H. Scheffrahn, and P. M. Ban. 1991. Uniform size particle barrier: a physical exclusion device against subterranean termites (Isoptera: Rhinotermitidae). J. Econ. Entomol. 84: 912-916.

Su, N.-Y., R. H. Scheffrahn, and P. M. Ban. 1993. Barrier efficacy of pyrethroids and organophosphate formulations against subterranean termites (Isoptera: Rhinotermitidae). J. Econ. Entomol. 86: 772-776.

Tamashiro, M. J., J. R. Yates, and R. H. Ebesu. 1987a. The Formosan subterranean termite: Hawaii's most damaging insect. Hawaii Architect 16: 12-14, 40.

Tamashiro, M. J., R. Yates, and R. H. Ebesu. 1987b. The Formosan subterranean termite in Hawaii: problems and control, pp. 15-22. *In* M. Tamashiro and N.-Y. Su [eds.], Biology and Control of the Formosan Subterranean Termite. College of Tropical Agriculture and Human Resources, University of Hawaii, Honolulu.

Tamashiro, M. J., J. R. Yates, R. H. Ebesu, and R. T. Yamamoto. 1990. Effectiveness and longevity of termiticides in Hawaii. HITAHR Res. Ext. Series 119, University of Hawaii, Honolulu.

Wedding, P. A., and R. D. Gaynor. 1961. The effect of using crushed gravel as the coarse and fine aggregate in dense-graded bituminous mixtures. Proc. Association of Asphalt Paving Technologists Vol. 30, Association of Asphalt Paving Technologists, Minneapolis, MN.

Yates, J. R., J. K. Grace, and J. N. Reinhardt. 2000. Installation guidelines for the Basaltic Termite Barrier: a particle barrier to Formosan termites (Isoptera; Rhinotermitidae). Socio 35: 1-16.