

**DEVELOPMENT OF A
TERMITE BARRIER/DRAINAGE LAYER FOR
RESIDENTIAL HOUSING**

BY

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*A thesis submitted in conformity with the requirements for the degree of Masters of
Applied Science
Graduate Department of Civil Engineering
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ABSTRACT

Basements are a common source of difficulties in residential housing. Leaks through the foundation wall create an inhospitable basement environment; excess moisture can lead to mold, mildew and decay. Compounding the problems presented by water leakage, termites can infest houses through cracks in the basement wall and cause considerable damage. The cost of termite control is estimated at \$1 M per year in Toronto, Ontario and \$1.2B per year in the United States (Su 1994). A solution has been proposed that uses a termite barrier sand as a combination drainage layer/termite barrier. The sand is mixed with a degradable binder and installed using shotcreting technology.

This thesis presents theory supporting the solution as well as results of laboratory investigations involving this barrier system. Suggestions are made for further field testing and implementation.

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1 INTRODUCTION

1.1 The Problems

Basements are perhaps the most common source of difficulties encountered in houses. Some of the more common problems are due to mold and mildew, dampness, rotting in wood next to the basement wall, and radon gas. The most prevalent problems have been associated with the ingress of water into the basement. To address this issue, the 1993 Ontario Building Code (Section 2.10.5) has mandated the use of a drainage layer next to the foundation wall to reduce the incidence of leaks into the basement due to bulk water from the ground encompassing the basement. While this change to the Code is an advance in building practice, it can also be viewed as a benefit to occupant health and safety. The ingress of water into assemblies in the basement, can lead to mold, which can affect human health.

This new requirement also has negative impacts in the form of increased cost and labour associated with the provision of the drainage layer. These costs will inevitably be passed along to the consumer in the form of increased housing cost. Examples of some drainage layers presently used are air-gap membranes, mineral fibre insulation, and vertical layers of granular material. For air-gap membranes and mineral fibre insulation, often a crew of two workers is required to painstakingly attach the drainage system to the foundation wall. Intensive labour is also required with the use of granular material since the process of backfilling becomes a tedious series of steps consisting of placing some granular then backfilling with some soil, followed by more granular and so on, until backfilling is complete. To minimize the negative impacts described above, there is a need to provide a drainage system that is both economical and requires minimal labour for installation.

Another notable problem that has continued to increase in prominence is the infestation of houses by wood-destroying termites. The problem is thought to cost Toronto residents about \$1 million per year (T.Star, July 20, 1993); in the United States an estimated \$1.2 billion per year is spent on the control of subterranean termites (Su 1994).

1.2 The Development of a Solution

This thesis outlines an approach that effectively addresses the problems of water leakage and termite infestation. This solution is one that is easily implemented, easily inspected, does not introduce new

hazards to the local eco-system, and is a natural component of an Integrated Pest Management program. The proposed system uses very simple and natural materials that are applied using a proven technology.

The solution uses a uniform granitic sand mixed with an easily degradable paste as a binder. This mixture is applied to the foundation walls using existing shotcreting technology. A continuous layer of sand is formed over the wall where it can then be easily inspected. After backfilling, naturally occurring organisms within the soil rapidly multiply and degrade the binder into water soluble and soil enriching products, leaving a vertical layer of densely placed, freely draining, termite impermeable, non-toxic, persistent sand.

This thesis will begin by examining the problems of termites and moisture to gain an understanding of the dynamics that underly them. A discussion of termite behaviour and the approaches for controlling them will be presented. This will be followed by a an examination of the moisture problem and the driving forces behind moisture movement.

The theoretical background supporting the technology of the proposed solution is outlined next. The characteristics of the aggregate used in the barrier are examined. To act as a successful filter, the aggregate must meet certain requirements. The aggregate's performance in relation to these requirements is then discussed. The drainage requirements that the system must meet to satisfy the building code are then examined. Finally, the characteristics of the binder are outlined including its chemical composition, the physics of adhesion, and the process of biodegradation.

The theoretical considerations of the proposed system are then complimented with a series of laboratory investigations, which verify the system's properties. These investigations deal with the permeability of the system, its rate of drying, rate of biodegradation, strength and rate of strength loss. In addition, a half-size model was built and investigations of the effect of impact pressure on the degree of adhesion of the barrier material were done.

To complete the considerations of this system, a proposal for full-sized field testing is included that outlines a method to be used for demonstrating the barrier system. Also, details demonstrating how the system would be installed in new construction are included for the final stage of development involving house trials.

2 BACKGROUND

2.1 The Termite Problem in Ontario

Termites are not native to Ontario and are commonly considered to be a problem only in more tropical climates. Contrary to this misconception, it has been estimated that 40% of Ontario's population (and 20% of Canada's) live in areas populated by termites (Myles 1992). Termites in Ontario have been found as far north as Kincardine, Ontario (44°11'N) (Grace et al. 1989). The migration of termites north is thought to be attributable to the trend toward milder winters. The presence of termites in a certain locale does not necessarily imply an infestation of neighbouring structures; numerous other sources of cellulose are available for termites to feed on such as tree roots, scrap wood and fence posts. However, the presence of termites means that structures are vulnerable to attack if these are not adequately designed to deter termite ingress.

2.1.1 Termite Behaviour and Characteristics

In order to create an effective barrier for termites, it is necessary to have an understanding of termite behaviour. Coulson and Witter (Coulson and Witter 1984) provide a good treatment of some basic characteristics of termites, which is summarized here.

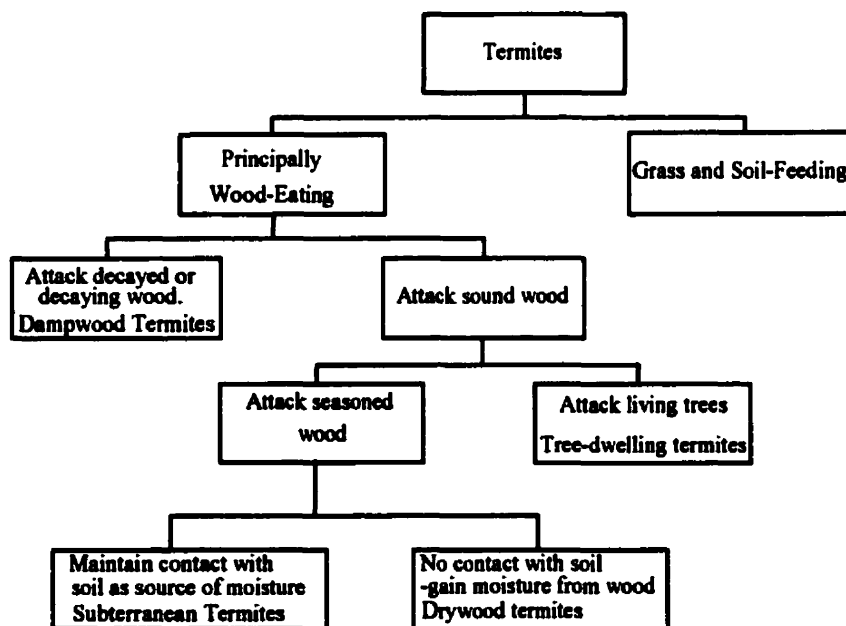


Figure 1 - System to differentiate species of termites. (Creffield 1991)

There are more than 2500 species of termites and luckily only about 300 of these are thought to cause damage to structures (Logan et al. 1990). Varieties include grass and soil-feeding, dampwood, drywood, tree-dwelling, and subterranean termites. Creffield (Creffield 1991) differentiates among these varieties using a flow chart found in Figure 1. A more thorough coverage of the various species is given by Logan (Logan et al. 1990).

Trait	Termites (Isoptera)	Ants (Hymenoptera)
Colour	light, creamy depending on contents of stomach	dark, reddish brown to black
Body	soft	hard
Petiole	never present	always present
Thorax	Inconspicuous, smaller than head and abdomen	distinct, may be the size of the head or larger than abdomen
Legs	short, do not reach end of abdomen	long, may reach past head and abdomen
Antennae	straight, beadlike 11-15 segments, moliform	elbowed - geniculate
Wings	front and hind similar	front larger and have more veins than hind
Wing position at rest	flat over abdomen	held above body
Rate of movement	sluggish	quick
Mandible	ends in a point	ends with a saw edge
Compound eye	absent	obvious
Neck	not obvious	distinct and thin
Runways, trails	Rarely in the open	commonly found in the open
Anal end	blunt - never has a sting	may end in a point and have a sting
Behaviour when disturbed	escape to find shelter from light, don't sting, bites hardly perceptible	scurry, do not attempt to hide - may bite or sting
Odour	almost odourless when crushed	may have a pungent odour when crushed
Poison	soldiers may eject a milky fluid from head	never eject milky fluid from head but may have poison in sting
Damage to wood	Attack wood until only a paper thin veneer remains	May use wood to nest

Table 1 - Distinguishing physical traits between termites and ants. (Coulson and Witter 1984) and (Creffield 1991)

While termites are insects bearing a resemblance to ants, there are a number of marked differences in their appearance. Table 1 lists some of the attributes that distinguish ants from termites.

A subterranean termite known as *Reticulitermes flavipes* (Kollar) is the variety found in the Toronto area. Other subterranean species occurring in North America are outlined in Table 2.

Species	Regions	Comments
<i>Reticulitermes flavipes</i> (Kollar)	Central to eastern US, ON	Described below
<i>R. hesperus</i> (Banks)	US far west, BC	Similar to <i>R. flavipes</i>
<i>R. tibialis</i> (Banks)	Western and central US	Similar to <i>R. flavipes</i>
<i>Coptotermes formosanus</i> (Shiraki)	TX, LO, SC, Hawaii, tropical and subtropical Asia	Queen may lay up to 1000 eggs per day!

Table 2 - Subterranean Termite species common to North America. Summarized from (Coulson and Witter, 1984. p 590)

Four types of members comprise a termite colony: primary and supplementary reproductives, soldiers and workers. If a colony loses its king or queen, the supplementary reproductives may step in to fulfil the role. In larger colonies, supplemental reproductives may also be involved in reproduction. Defense of the colony rests with the sterile soldiers who protect the colony from threats such as ants, which are a termite's most notorious insect enemy (Cornelius and Grace, 1994). The remainder of colony functions fall to the workers who are responsible for foraging, tunnel building, and chewing the wood that is fed to the rest of the colony proctodeally and by regurgitation. Workers are either sterile or are nymphs, which may mature into reproductives or soldiers. The workers are not able to digest the wood they chew; digestion is accomplished with the aid of a number of protozoa and bacteria in the gut of the termites. When the termites molt, these organisms are lost. Proctodeal feeding allows these termites to regain the flora lost in the molting process.

Colonies can spread using two different mechanisms. One mechanism can occur after a warm spring or summer rain. Winged reproductives, known as alates, fly off from the colony, mate and establish a new colony. The second mechanism, known as budding, predominates in northern climates. Supplementary reproductives leave the colony via tunnels to establish new colonies. In either case, the initial growth of a colony is slow for *R. flavipes* since only 6-12 eggs are laid by the queen and these require a year to mature into soldiers and nymphs. Supplemental reproductives, require three to four years to mature and will later

help in a more rapid growth of the colony that may have a population ranging from 0.2 to 5 million members (Su et al. 1993a).

Behaviour

Subterranean termites have developed a number of behaviours that are well suited to their environment. Remaining underground fulfils their need to be in a constant high humidity environment. If exposed to light or in low humidity, termites can easily become desiccated.

Termite workers spend much of their time foraging, searching for new supplies of food and moisture. Successful foraging underground necessitates continuous tunnelling and construction of shelter-tubes to span above ground surfaces. Foraging of a termite colony may extend for up to 79 m (Grace et al. 1989) and encompass an area up to almost 2400 m² (Su et al. 1993a). Upon encountering an obstruction such as a basement wall, termites tend to forage along the surface of the obstruction, which helps them find access into buildings through cracks in foundation walls (Myles 1994b). Termite workers are blind but have an olfactory sense that allows them to navigate the complex network of tunnels. Termites are able to lay down a pheromone trail that is recognizable by other colony members and provides a way of marking their own tunnel networks (Hickin 1971). Some odours such as wood decaying from brown rot fungi attracts termites. Conversely, ant semiochemicals, a type of defense mechanism used by ants, and white rot fungi are thought to repel termites (Cornelius and Grace 1994; Coulson and Witter 1984).

Termites have excretions from their exoskeletons, which when combined with moisture (due to their soil environment), cause dust and dirt particles to cling to their bodies. This protein rich excretion is thought to be attractive to fellow termites and encourages grooming of each other and in this process, foreign particles are also removed. The wood diet of termites is deficient in protein so grooming helps conserve vital nitrogen. Also, dead, surplus, or redundant colony members may be cannibalized as another way of conserving nitrogen. (Creffield 1991)

2.1.2 Methods of Abatement

Integrated Pest Management is the latest descriptive phrase describing effective termite control. IPM is more a philosophy of practice than a technology. By employing a number of methods of prevention and control, IPM minimizes the risk of damage wrought by the target pest. The implementation of IPM creates a number of lines of defence against the pest infestation. If primary defence strategies fail,

subsequent measures assist in preventing insect invasion. These modes of defence create redundancy, which is desirable for reducing the risk of ultimate failure.

Prevention and control are the two general types of measures that are employed against termites. Prevention includes designing buildings to exclude the entry of termites into the building and removal of deadwood from backfill (NBC 1995). Control measures may include attempts to form a chemical barrier around and under the structure, which would bar further entrance into the building. Termites caught within the house, behind the barrier, soon die since they cannot rejoin the colony and cannot gain access to a water supply. Control measures could also include treatment with termiticides or baiting techniques, which slowly spread a toxin throughout the colony.

2.1.2.1 Preventative Measures

East York, a borough of Toronto, Ontario, has experienced numerous instances of significant termite infestation. To address this, several measures of a preventative nature are outlined in the Termite By-Law of East York (By-law 52-85 1985). These measures reduce wood to soil contact, aid in the inspection of structures for shelter-tubes, and reduce wood contact with the basement floor in the event that cracks form beneath the wood/concrete contact points.

In addition to these methods, flashings at the tops of basement walls and around service entries to the building may be used. Other possibilities include impenetrable stainless steel mesh or aggregate barriers.

The focus of this thesis is the use of the aggregate barrier method of preventative termite management. Aggregate barriers exclude termites since the aggregate particles are too large and heavy for the termites to mine, the particles too hard for the termites to chew through, and the interstices between the aggregate particles too small to allow the passage of termites. The aggregate barrier has the following benefits:

1. Acts as a permanent, physically impenetrable barrier to termite foraging.
2. Provides a drainage layer. The lack of water makes foraging less desirable and avoids wood decay, which attracts the termites.
3. Chemical-free treatments are less prone to the development of resistance by termites. Since the termites are not killed, the process of natural selection is not engaged. Natural selection is

responsible for creating resistance to treatment, which can occur over time with chemical methods.

4. Applied only once. Chemical treatments must be applied every five to seven years to be effective.

The major disadvantage that has prevented the widespread use of aggregate barriers in new construction has been the cost of implementation (Myles 1994b). Installation has required either the painstaking backfilling to create a vertical layer of barrier sand or the replacement of all the backfill material with barrier sand. The first installation technique is labour intensive and therefore costly. The second installation technique is also costly because of the need to provide large amounts of the specialized sand and to haul away the native backfill, which when combined, could add as much as \$6000 per basement for a 10 m by 10 m house.

2.1.2.2 Methods of Control

Chemical methods

Control of termites is achieved primarily by chemical means using broad spectrum insecticides. As the name implies, broad spectrum insecticides are effective in controlling a number of insect species. Two main groups of termiticides used in current practice are organophosphates, which are effective in killing the termites, and pyrethroids, which work primarily by repelling the termites (Su et al. 1991). Cyclodienes, a subgroup of chlorinated hydrocarbon pesticides, had been widely used for termite control because of their persistence. The high potential for environmental contamination has led to the restricted use of this group of pesticides. Cyclodienes may accumulate in the fatty tissues of nontarget animals (Horn 1988, p.139). In addition, some members of this group of pesticides, namely, dieldrin, aldrin, DDT, and DDE are particularly risky since the contamination process is one of biomagnification. In this process, the pesticides become more concentrated as they are passed from plant, to insect, to small mammal, to birds without being metabolized (Pedigo 1989, p.365).

Another group of pesticides, organophosphates, were originally developed for human warfare and some varieties are very toxic, though less persistent than chlorinated hydrocarbons (Horn, 1988, p.139). They are known to decompose, within hours or days, into nontoxic products on exposure to light. Chlorpyrifos, unlike some more toxic cousins, is described as relatively safe (Pedigo, 1989, p.373). A summary of some of these chemicals is shown in Table 3.

Trade Name, Chemical name, Manufacturer	Type of Termiticide
Dursban TC and Equity †, 1% chlorpyrifos, DowElanco	Organophosphate - toxicant
XRM-5160, 0.75% chlorpyrifos, DowElanco	Organophosphate - toxicant
Dragnet FT†, 0.5% permethrin, FMC corp.	Pyrethroid - repellent
Prevail FT†, 0.3% cypermethrin, FMC corp.	Pyrethroid - repellent
Biflex FT, 0.031% bifenthrin, FMC corp.	Pyrethroid - repellent
Pryfon 6†, 0.75% isofenphos, Miles	Organophosphate - toxicant
Demon TC†, 0.25% & 0.5% cypermethrin, ICI Americas	Pyrethroid - repellent
PP321, 0.125% lambda-cyhalothrin, ICI Americas	Pyrethroid - repellent
Sumithion 20 MC‡, fenitrothion, Sumitomo Chem., Japan	Organophosphate - toxicant

† registered termiticide in the U.S.A., ‡Registered termiticide in Japan

Table 3 - Summary of some available termiticides. (Su et al. 1993b)

In most cases, these chemicals are injected around and beneath the affected structure. An undesirable side effect is the possibility that the termiticide may enter the water supply either through house drainage system connections to sewer lines or by contamination of the ground water supply. Cost of treatment is also significant, approximately \$1200 every five years.

A novel approach to attempt to control termites has been investigated by T. Myles at the University of Toronto. The method involves trapping about 1% of termites in a colony and painting them with a resin laced with sulfluramid, a slow-acting toxicant, and releasing these treated termites to rejoin their colony. Upon their return, the poison is spread throughout the colony by way of the termites' grooming of each other (Myles 1994c).

The use of slow acting toxicants has also been investigated by others (Su 1994). These toxicants are introduced into bait blocks planted throughout the infested area. Other types of chemicals used in bait techniques include insect growth regulators (Su 1994) that interfere with the normal development of the colony members. Such interference may ultimately lead to the death of the colony (Horn 1988, p. 164).

Both of these approaches, baiting and trap and treat, have the advantage of using less termiticide than regular barrier treatments. However, the potential exists, as with any chemical control measure, for the

termites to develop resistance to the treatments. Resistance is developed as a result of the biological process of natural selection (Horn 1988, p.150).

Non-chemical Methods

Non-chemical methods could include the use of nematodes, parasitic worms that infect the termite and fungi, which are infectious to termites (Grace 1991). These methods are currently confined to the laboratory (Logan et al. 1990; Creffield 1991). Logan (Logan et al. 1990) presents a comprehensive review of non-chemical methods of termite control.

Summary

The use of chemical barriers to control termite infestation has been widely used. While there will, no doubt, continue to be a place for chemical control measures, their use does pose the potential for adverse effects. Prime among these effects is the impact on 'non-target' organisms (i.e. other insects) and the possibility of developing insecticide resistance among termites. The role of chemicals should be viewed as a remedial approach within an IPM system.

It has been said that "an ounce of prevention is worth a pound of cure". Another truism states that "it is better to work with nature than against". Chemical control measures, which are efforts against nature, are likely to be met with failure or disaster in the long run. Prevention is among the strongest arguments for the use of aggregate barriers.

2.1.3 The Moisture Problem

Moisture is one of the most common sources of difficulties in buildings; practically every deterioration process and damage that can occur to a building can be associated with water (except for problems arising out of poor structural design). Excess moisture can lead to corrosion of metals, rotting of wood members, efflorescence, freeze-thaw deterioration, spalling due to subflorescence, mould and mildew problems as well as other difficulties. When it is considered that there has historically been a high incidence of basement leaks, estimates up to 60% of all houses, the true magnitude of the problem can be realized. A survey in the United States also estimated that "88% of builders have call-backs on leaky basements" (Platts 1992). In addition, there is significant cost associated with this damage and was estimated by Frank Ganone of Fram Construction in Toronto to cost approximately \$300 per basement. This estimate

was for hard costs, materials and labour associated with the repair, so the figure may be larger if soft costs, including administration time and opportunity cost, are considered. It is not surprising then, that the Ontario New Home Warranty Program requested changes to the Ontario Building Code (Marshall 1992). The 1993 Ontario Building Code, in an attempt to deal with this issue, introduced the requirement for a vertical drainage layer to protect the foundation wall (OBC, 2.10.5, 1993).

Three questions result from these considerations of moisture problems in basements: first, where does the water come from? second, why do basements leak? third, will the new requirements in the building code ensure that leaky basements are solely of historical interest?

Water and Basements

A recent paper deals with the issues of water and the design of dry basements in a comprehensive manner (Timusk et al. 1995) and will be summarized below.

Five different manifestations of water can be found within building materials or moving through them: bulk water, capillary water, adsorbed water, water vapour, and chemically combined water. These different types of water are distinguished by the potential, or driving force, that predominates in the behaviour of the water. Of these forms of water, chemically combined water does not lead to basement moisture problems since it is tightly held within the structure of a material by strong intermolecular forces. The other four types of water may participate in creating a basement with moisture problems.

In addition to understanding the various types of water that may lead to a wet basement, it is essential also to understand the mechanisms or driving forces that cause the water to move into the basement so that these potentials for water movement can be managed by design.

Driving Forces Causing Moisture Movement

For any change to occur throughout the universe, there must be a potential or gradient driving the system toward change. Newton's first law states this antithetically by suggesting that there will be no change in velocity (including zero velocity) of an object if there is no applied force, whereas the third law quantifies the relationship between the applied force (potential) and the resulting change.

From a thermodynamic point of view, this same assertion, that change occurs as the result of a potential, follows less obviously from the first and second laws of thermodynamics. The first law is a statement of conservation of energy. The second law states that entropy may never decrease. Entropy may be considered to be the degree of randomness within a system and bespeaks the underlying connection between thermodynamics and statistical mechanics. When these two laws are explored, the idea of a spontaneous change arises. A spontaneous change can be described as a change that produces an increase in entropy in the system without the addition of external work or heat. In thermodynamic terms, a spontaneous change may be predicted by considering the Clausius inequality for an irreversible process (a process that requires the provision of external work to return the system to its original state). The conclusion that follows from these considerations is the natural tendency of a system to move from a state of high energy to one of lower energy. This difference in energy, or ability to move from one state to another, is known as a potential or driving force. Some of the common driving forces are gravitational, chemical, and electrical potentials (Alberty 1983, pp.59-89).

Pursuing this idea of potential, if two systems having different potentials are brought together, there will be a flow toward a state of intermediate potential known as equilibrium. Gravitational potential leads to the manifestation of weight, commonly thought of as 'force' by civil engineers. This potential gives rise to the phenomenon of hydrostatic pressure and gradients in this potential lead to the flow of bulk water. Chemical potential may take the form of gradients in vapour pressure or temperature (leading to the flow of water vapour or heat, respectively, by diffusion) or gradients in Gibb's energy, also known as surface tension, (leading to adsorption or capillary rise). It is these various potentials that lead to the differing behaviours observed for the types of water outlined.

If a designer wishes to prevent excess water from entering into the basement, measures are needed to neutralize the potentials responsible for moving the water into the basement or to manage it once it is there. This can be likened to the concept of IPM discussed earlier. A philosophy of water management, by providing appropriate "water works" rather than waterproofing (an attempt to conquer the effects of water) is needed (Timusk 1992). Success is obtained when a basement is designed to make dryness its preferred state.

A summary of the four types of water, the driving forces (potential or gradient) behind them and the techniques for alleviating the potential are found in Table 4.

Type of Water	Driving Force	Direction of Moisture Movement	Management Techniques
Bulk	•Hydrostatic pressure	•Into basement (unless basement is already flooded)	•Drainage to alleviate hydrostatic pressure next to basement wall
Capillary	•Surface tension -R.H. -Temp. -pore size	•Toward low r.h. side -into basement	•Capillary break -dampproofing -create hydrophobic pore surface -granular material with large pores
Vapour	•Vapour pressure gradient	Into basement in winter Out from basement in summer	•Vapour retarder •Control indoor r.h. (i.e. dehumidifier)
Adsorbed	•Surface tension -R.H.	N/A	•Control r.h. •Create hydrophobic pore surface

Table 4 - Summary of types of water, their driving forces and techniques to neutralize gradients.

It can be seen from Table 4 that capillary water and adsorbed water both have surface tension as a driving force. In fact, these two types of water are closely related. Adsorbed water can be thought of as water vapour that comes to rest on the surface of a material. This 'coming to rest' produces a stabilizing effect on hydrophilic surfaces, which is to say that there is a reduction in the Gibb's energy of the surface. Thus, layers of water molecules line the surface and the number of layers is dependent on the relative humidity (which can be thought of as the moisture potential of the air). All adsorbed water, by definition, is influenced by the surface onto which it is adsorbed and it is this factor that distinguishes it from capillary water.

Capillary water is water held in a pore by surface tension as shown in Figure 2. Unlike adsorbed water, only the capillary's surface experiences any interaction with the pore surface and the adsorbed water layer. The remaining molecules in the capillary water experience the tension exerted by the meniscus. This hydrostatic tension accounts for capillary rise and more generally, the suction of water into the pores of a material.

The next part of our initial question is: "Why do basements leak?". More accurately put: " Why is there excess moisture in the basement?". Answering such a question without knowing the details of each particular situation, is a dangerous endeavour. It is possible, however, to demonstrate the possible

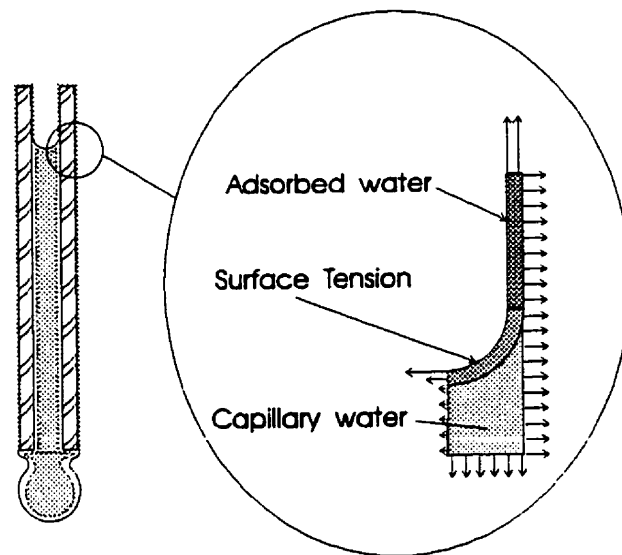


Figure 2 - Capillary tube demonstrating the difference between capillary water and adsorbed water.

shortcomings of older requirements. An example of the requirements for drainage is summarized by the pertinent section from the 1990 Code and Guide for Housing (2.10):

- (4) Unless it can be shown to be unnecessary, drainage shall be provided at the bottom of every foundation wall that contains the building interior.**

Figure 3 demonstrates a typical basement design that would satisfy the 1990 OBC requiring only drainage at the footing. The difficulty comes in the reliance on the combination of a relatively thin dampproofing layer and a weeping tile located at the bottom of the wall. The dampproofing can provide a capillary break at the wall surface, by virtue of the hydrophobic nature of the dampproofing. If any cracks were to occur in the concrete wall though, the dampproofing would not be able to span the cracks and the cracks could give clear access for water to move into the basement. For bulk water, if the clear opening of the crack poses less resistance to flow than does the soil between the water and the weeping tile, the water will take the low energy route, or path of least resistance, and leak through the crack in the basement wall.

Capillary water in the soil next to the wall may not find its way into the basement through a crack in the dampproofing since the shoulders of the crack are still coated with hydrophobic material. Thus, capillary continuity is still disrupted by the dampproofing unless bulk water or small soil particles enter the crack. However, it should be noted that this capillary effect would be insignificant in comparison to the water

entering the basement by leakage of bulk water.

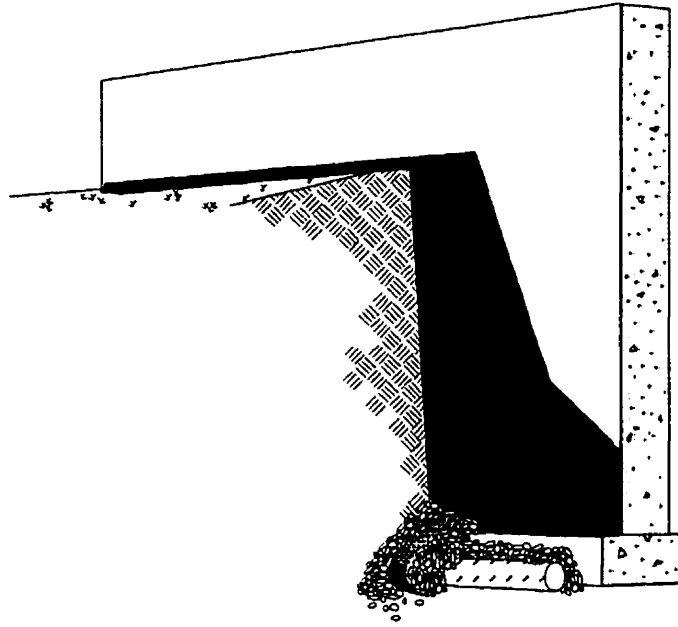


Figure 3 - Schematic of a typical basement wall complying with the drainage requirements prior to the 1993 OBC

The recent OBC requirements manage the mechanism of bulk water leakage. The vertical drainage layer provides an opportunity for hydrostatic pressure to be dissipated. The ease of flow through the drainage medium offers water a preferential route to lose its elevation potential. In this way, the available driving force of gravity is exploited by the draining medium. If hydrostatic pressure is dissipated, cracks occurring in the dampproofing become harmless.

Does this new OBC requirement now mean an end to wet and damp basements? No. There is still the possibility of dampness occurring in the basement due to other sources of moisture. Among these sources

of moisture is water vapour from inside the house, from the soil beneath the basement floor, and from construction moisture.

In the summer months, a higher vapour pressure may exist inside the basement than exists in the soil surrounding the basement, giving rise to a flow of vapour through the basement wall. If this water condenses and is trapped within the basement wall construction and cannot drain away, moisture problems can result. Conversely, in winter months, the indoor vapour pressure may be lower than that of the surrounding soil, leading to vapour diffusion through the basement floor slab. Low permeance materials, such as rubber backed carpeting, applied on the low vapour pressure side of the slab may retard vapour flow and insulate the slab, leading to condensation behind the low permeance surface. If this condensation is trapped, moisture problems may result.

Similarly, if construction moisture, in the form of vapour from the drying lumber and concrete (moisture that exists in larger capillary pores and is unable to participate in the continued hydration of the cement paste), reaches the dew point, condenses, and is trapped within the wall construction, moisture problems may occur. Therefore, the only assurance against wet basements is good building practice. Engineers have the opportunity to impact directly on the quality of new housing stock by providing thorough and specific details that include moisture management strategies within the design.

The necessity for superior detailing is emphasized by Drysdale (Drysdale 1991) in his study of construction failures occurring in multi-family dwellings. He notes that thorough and comprehensive plans with good details, tend to result in better constructed buildings with significantly fewer claims being filed with the Ontario New Home Warranty Program.

Proper basement design can manage the movement of moisture thus controlling the amount making its way through the building envelope in either direction. The most effective way to manage moisture is to provide a preferential route for its movement. By carefully choosing this route, excess moisture is directed away from the building envelope.

2.2 A New Solution

A solution to these combined problems is to provide a combination drainage layer/ termite barrier along the outside of the basement wall.

One of the issues that must be addressed is the method of installation of this drainage layer/termite barrier. As mentioned earlier, the possible methods of installation include manual separation during back-filling, supporting the layer with a form that would remain in the soil, or total replacement of the native backfill with termite sand. However, none of these methods are efficient and would require too much labour. The issue of installation may be resolved by spraying the layer into place using a method similar to "shotcreting".

The efficiency of this shotcreted system has the following benefits with regard to the construction process:

1. easily inspected - to verify continuity, workerly installation;
2. easily placed - minimum of labour or special skill required;
3. minimizes the number of passes around the basement;
4. minimal impact on critical path/ construction schedule; and,
5. minimizes the amount of specialized aggregate to be purchased and transported.

All of these benefits have a cumulative effect of reducing housing cost while simultaneously providing a drainage layer and a termite barrier.

2.3 Development of the Aggregate Barrier

2.3.1 Desired Characteristics for the Aggregate Barrier

It is desirable for the aggregate barrier to fulfill two functions. It should act as an effective filter excluding the passage of both termites and particles of base soil, but these two requirements are mutually exclusive. It should also provide the required drainage as mandated by the Ontario Building Code. These functions are distinct and will be considered separately.

2.3.2 Filter Requirements

The aggregate barrier may be thought of as acting as a 'filter' against termites, and as a filter to prevent migration of the base soil into the barrier. As a termite barrier, termites need to be prevented from migrating into or through the barrier. As a drainage layer, particles of the native base soil must be prevented from migrating through the barrier and into the weeping tile where they may settle and accumulate thereby reducing the capacity of the foundation drain. Also, if soil particles migrate into the

drainage layer and lodge within its pores, the permeability of the drainage layer would be reduced. However, it is worth noting that the passage of soil particles into the barrier sand would not deter from its performance as a termite barrier.

Ripley (Ripley 1986) outlines the prerequisites for an effective filter:

1. particle size of filter;
2. low susceptibility to segregation; and,
3. 'crack stopper' capability.

These principles may be extended to include the requirements for an effective termite barrier and each of them will be considered in turn.

Particle Size

Filter performance is largely governed by the size and geometry of the network of pores occurring between particles comprising the filter. It is the pores of the filter that determine the filter's ability to prevent the penetration of termites or soil particles washed toward the filter by water, and pore size is related to the size of the particles in the filter.

There is an upper and lower limit restricting the size of particles in an effective termite barrier. The particle size needed to prevent penetration by termites through the filter's interstices will be referred to as the passage limit. Considering the lower end of particle sizes, if the particles comprising the filter are too small or too light, they may be excavated by termites in the course of foraging. This lower limit of the filter gradation will be referred to as the minability limit. For a termite barrier to be effective, the particle size and mass must be too large to be excavated and the pores too small to allow passage of the termites.

To provide effective filtering of the base soil, the pores of the filter must be small enough to prevent migration of the base soil particles through the filter.

The Passage Limit

This upper limit on the allowable grain size is required to exclude the passage of termites and soil particles, and has been investigated by both entomologists studying aggregate barriers for termites and by geotechnical researchers studying filter design. The key consideration is defining a grain size distribution that has a network of pores too small to be penetrated by the protected soil or by termites.

Research particularly relevant to this consideration has been done by Kenney (Kenney et al. 1985). His investigations considered the maximum spherically shaped particle that could pass through the filter medium. This pore size is called the controlling constriction size. The investigations are particularly helpful as they minimized the arching of soil particles across the pore openings of the filter.

From Kenney's investigations, relationships between soil geometry and controlling constriction size were found to yield ratios of $D^*/D_0 = 0.18$ (D^* is the controlling constriction size and D_0 is the minimum particle diameter of the filter medium) for $C_u = 1.2$ ($C_u = \frac{D_{60}}{D_{10}}$), $D^*/D_0 = 0.25$ for $C_u = 3$, and $D^*/D_0 = 0.26$ for $C_u = 6-12$ were determined. These relationships are valid for linear grain size distributions with porosity $n = 0.30-0.32$ for $C_u = 3$ and $n = 0.34-0.36$ for $C_u = 1.2$. In general, Kenney determined

$$D_c^*/D_5 \leq 0.25 \quad [1], \text{ or}$$

$$D_c^*/D_{15} \leq 0.20 \quad [2].$$

The sand used in this thesis has a linear grain size distribution with $C_u = 1.7$ implying that the use of $D^*/D_0 = 0.25$ is conservative. It is possible to use this relationship to determine the largest possible D_0 particle size that could be used within the barrier to exclude termites.

The other information needed to make such an estimate is termite size. For this purpose, it is desirable to use the dimension of the head capsule (Myles 1994a). Estimates based on head capsule dimensions (Su et al. 1991) may be found in Table 5. *R. flavipes* are generally more uniform in overall size than *Coptotermes formosanus* (Su et al. 1991).

There have been several studies to determine the particle sizes and grain size distributions that are effective in excluding *R. flavipes* and other subterranean species. These are summarized by Myles (Myles

1994a). For comparative purposes, the results of laboratory tests (Myles 1994a; Su et al. 1991) and field tests (Su et al. 1992) are summarized in Table 6 along with the predictions from Table 5.

Termite Species	Mean Size of head Capsule [mm]	Minimum Size measured [mm]	Max. D ₀ that will exclude termites [mm]	Max. D ₁₅ that will exclude termites [mm]
<i>R. flavipes</i> †	1.03 ± 0.10	0.91	3.64	4.55
<i>C. formosanus</i> †	1.29 ± 0.12	1.06	4.24	5.30
<i>C. formosanus</i> ‡	1.15	1.03*	4.12	5.15

† as measured by Su et al. 1991, ‡ as measured by Oshima, 1919, * estimate based on size range from Su et al. 1991

Table 5 - Estimation of minimum particle size that will effectively exclude termites

Termite Species	Smallest effective fraction	Largest effective fraction	Predicted largest fraction
<i>R. flavipes</i> [Su, 1991]	1.00-1.18	2.00-2.36	< 4.55
[Su, 1992]	1.70-2.00	2.36-2.80	
[Myles, 1994]	1.40-1.70	2.36-2.80	
<i>C. formosanus</i> [Su, 1991]	1.40-1.70	2.36-2.80	< 5.15
[Su, 1992]	2.00-2.36	2.36-2.80	

Table 6 - Summary of Aggregate Sizes for Effective Termite Barriers

This maximum aggregate size, estimated using the concept of controlling constriction size, is larger than that determined experimentally to be impermeable (Myles 1994a; Su et al. 1991; Su et al. 1992). The reason for this discrepancy can be attributed to the test method used. The soils were tested in containers of small diameter, which creates larger pores at the edges of the test container than exist through the rest of the soil as noted by Myles (Myles 1994a). This reasoning is borne out by Myle's observation that the termites passed along the walls of the container in the larger aggregate samples. While it may be argued that the upper limit set by Myles is appropriate to prevent the passage of termites along the interface created by service pipes passing through the barrier, a flashing with proper detailing, could provide adequate protection and allow a coarser gradation of sand to be used. Remaining within the upper limits determined experimentally does allow another layer of protection. Insuring the impermeability of the interface between the sand and a flat surface implies that termites would be unable to forage along the sand/wall interface, in the event that the termite barrier is breached for some reason. This reduces the probability of penetration by termites into the home, a consideration termed the interactive effect (Myles 1994b). This gain in protection should be balanced by the realization that a coarser gradation would allow the same barrier sand to be effective against other larger species of termites.

Minability Limit

The lower limit of the sand gradation must also be considered in order to prevent penetration of the barrier by termites. Particles must be large and heavy enough to prevent individual particles from being excavated by termites, which could result in penetration of the barrier. This lower limit has been determined experimentally and is included in Table 6. A complication arises when the lower limit is considered conceptually in relation to a gradation broader than the limits determined by testing. It may be possible to use a gradation of particles that contains particles finer than the minability limit; the fine particles could fill the voids between larger impermeable particles. The question becomes one of probability; what is the likelihood that the particles small enough to be excavated by the termites will lie contiguously through successive layers thereby allowing penetration? Myles (Myles 1994a) has suggested that an aggregate barrier would still be successful if a limit on the the proportion of fine particles, ranging in size between 0.22 mm and 1.40 mm, were set at a maximum of 25% by mass.

Fortunately, several combinations of grain sizes have been investigated (Myles 1994b). The range of impenetrable sand gradations is shown by the shaded region in Figure 4. Also plotted is the grain size distribution of the sand used in this thesis.

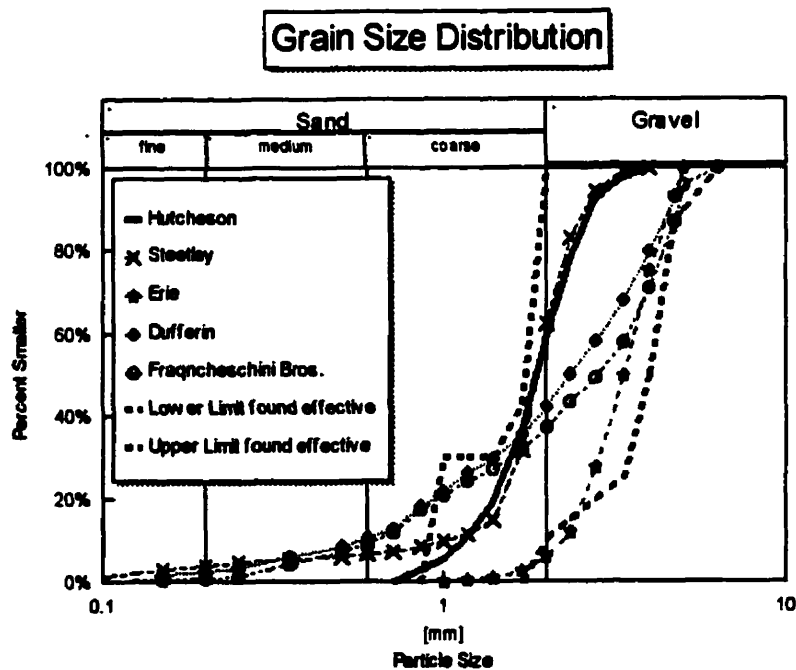


Figure 4 - Range of grain size distributions found to be successful as termite barrier. (Myles 1994a) Sands field tested by Myles (Myles 1994b) included .

Other species outlined by Myles requiring coarser gradations larger than 2.00 mm to be effective, include *Coptotermes spp.*, found from Texas through to the Florida, *Paraneotermes simplicicornis*, found in the southwestern states. *Mastotermes darwiniensis* Froggatt termites found in northern Australia are also quite large and would likely require a coarser aggregate barrier as theorized by Myles.

Filter Characteristics

The particle size of the sand, having been dictated by the need to act as a termite barrier, also makes it appropriate for use as a vertical drainage layer for the exterior of the basement wall. Due to its uniform gradation, this filter would be expected to remain unclogged over time, but would demonstrate a more binary type of behaviour, either allowing soil particles to pass through its pores or causing a thin skin of small particles to be formed along the outer face of the filter. Progressive clogging of filter media is a phenomenon observed with broadly graded filters that have a gradation size that borders the ranges for successful and unsuccessful critical filters (Vaughan and Soares 1982). The next task then, is to predict the size of soil particle that may pass through this uniform filter.

At this point, it is necessary to consider the level of surety required to prevent the passage of the native soil into the filter. Most filter criteria research for fine grained soils uses extreme test measures such as slurry testing and slot testing. Slurry tests suspend the base soil in the water over the filter while the water washes through the filter. The filter is successful if a skin forms over its surface, preventing the migration of soil particles through the filter, and flow stabilizes. In the slot test, the base soil is placed over the filter and a slot or hole formed in the base soil. Water flows through the slot simulating a concentrated leak and eroding the base soil. Again, the filter is successful if a skin forms over the filter surface (Sherard et al. 1984).

This degree of conservatism is warranted for filters that must seal off concentrated leaks occurring in earth-fill dams but would be considered excessive for the drainage layer of a residential building. The performance expected from a vertical drainage layer in residential housing is more in line with what is termed a 'noncritical' filter (Sherard et al. 1984). Sherard tested a highly erodable clayey silt using a less stringent method where the base soil was compacted directly next to the filter in a conventional filter test. This less demanding test demonstrated that filters were capable of preventing the migration of a wider range of base soil gradations. A filter grain size to base grain size ratio up to $D_{15}/d_{85} = 150$ was found to be successful. For the case of the termite sand, $D_{15} = 1.26$ mm, would be expected to successfully protect a base soil having $d_{85} = 8.4$ μm , the size of medium silt. This implies that termite sand would be expected to

protect all but extremely fine noncohesive or highly dispersive clay soils. It is worth noting that Sherard had tested 36 different fine grained soils and the finest of these had a d_{45} size of 10 μm . Also, initial tests demonstrated that none of the filters failed if the pressure was kept below a head of 10 m. A maximum head of 2 m would be expected in a residential setting, suggesting that the filtering capability of the sand should be quite adequate.

Segregation

This second requirement builds on the first by ensuring that the controlling constriction size desired in design, is obtained in practice; segregation may lead to local areas having controlling constriction sizes differing significantly from design values. Due to the uniformity of the termite sand used, segregation is not a concern.

Crack-Stopper

The third requirement ensures that the filter is self-healing; a crack in the filter medium could undermine the protection provided by the filter. The termite sand used is itself noncohesive. A complication arises due to the use of a binder for the installation of the sand. For the filter to provide reliably persistent protection, the cohesion provided by the binder material, must have ceased before the sand layer is likely to experience any movement that could give rise to the formation of a crack. This can be ensured by maximizing the rate of degradation of the binder, an issue that is dealt with later in this thesis. However, it should be noted that even if a crack were to form in the barrier, the void size at the barrier / wall interface is too small to allow the passage of termites. Since it is highly unlikely that the crack in the basement wall would coincide with the crack in the barrier, the barrier should still be effective even in the event of a crack developing.

The termite sand used for this thesis meets all three of the filter criteria described by Ripley. In addition, this granitic sand is chemically resistant and thus unlikely to change in its properties for at least the life of the building, making the use of this termite barrier and drainage layer technology a desirable and long-term preventative option.

2.3.3 The Drainage Requirement

The 1993 OBC (2.10.4) lists three options for providing a drainage layer:

- (a) not less than 19 mm (3/4 in) mineral fibre insulation with a density of not less than 57 kg/m³ (3.56 lb/ft³),
- (b) not less than 100 mm (4 in) of free draining granular material, or
- (c) a system which can be shown to provide equivalent performance to that provided by the materials described in Clauses (a) or (b).

The aggregate barrier proposed easily falls under Clause (b) if 100 mm is the thickness applied to the basement wall. If adhesion of such a thick layer proves to be an ongoing difficulty in practice, satisfying the requirements of Clause (c) may prove to be the viable alternative.

The idea of equivalency as it is introduced in Clause (c), has been addressed by the Canadian Construction Material Centre (CCMC). Two main classes of equivalency exist, Class A and Class B. The Class A category is known as the 'true drainage' category. Materials must have a flow rate of 0.72 m³/hr/m at a hydraulic gradient of 1 m/m to meet the Class A requirements; this performance likens the product to a free draining granular material. Alternatively, materials like mineral fibre insulation, which provide a capillary break, may fall into the category of Class B materials if a flow of 500 ml is shed within 15 minutes when tested under the side water inflow test (Waters, personal communication).

Employing the criteria for a Class A drainage system implies that the system must possess a hydraulic conductivity of at least 4 mm/s if the drainage layer is to be 50 mm thick. Similarly, to comply with the drainage requirements under the Class B category, the system would need to have a hydraulic conductivity of 0.01 mm/sec.

2.4 Development of the Binder System

Having determined the successful gradation for the aggregate, the next consideration is the binder that will adhere the aggregate to the wall temporarily, until the excavation is backfilled. Using the shotcrete process to install the barrier sand, it is possible to use a relatively thin layer of this specialized sand. This

saving of material reduces the material and transportation costs for providing the sand as well as reducing the haulage charges for removal of excavation material.

2.4.1 Desired Characteristics for the Binder

To complement the effectiveness of the aggregate barrier, an appropriate binder is required to assist in the barrier placement and enable the cost savings discussed above.

The desired characteristics include:

1. Sufficient cohesion to restrain the lateral pressure exerted by a vertical layer of filter 50-100 mm thick.
2. Sufficient adhesion to attach a vertical layer of sand/binder mixture to a damproofed wall without sloughing during the backfilling operation.
3. Minimal binder persistence to ensure the filter's inability to support a crack and ability to reach maximum permeability.
4. Minimal impact on the surrounding eco-system as the binder degrades.
5. Economy to ensure competitiveness with other drainage options.
6. Maximum ease of implementation.
7. Availability in potentially large quantities.

The first requirement can be met by using a binder that is in itself a cohesive mass. This cohesion must develop quickly given the shotcreting process proposed. A starch paste can meet these conflicting demands due to the thixotropic nature of the paste. Thus, the mixture can be pumped and shot, but shortly after impact, the mix is no longer fluid. This initial cohesion is later enhanced as the paste retrogrades. In the process of retrogradation, some of the starch precipitates, creating a stiffer gel. Retrogradation will be discussed in greater detail below.

2.4.2 Binders Investigated

Initially, any possible substance that possessed tack was considered. Low cost options such as casein and bitumen were disregarded because of their persistence. More careful consideration was given to two binders, starch and wax.

2.4.2.1 Wax

Crude wax, which consists mostly of paraffin wax and lower molecular weight waxes, did not perform well on its own. Crude wax failed to hold the sand in place during shooting. It allowed the sand grains to rebound from the surface, leaving only a generous coating of wax on the test wall. Some of the trials using mixtures of crude wax and a microcrystalline wax however, were successful.

Microcrystalline wax, on its own, was found to be ideally suited for providing the required cohesion and tack. Because the cost of microcrystalline wax is higher and the rate of deterioration slower (due to its higher average molecular weight than crude scale wax), a mixture of crude scale wax and the microcrystalline wax was used. A successful mixture consisted of 25% crude scale wax and 75 % of microcrystalline wax. Appendix A lists the wax mixtures tried.

The material cost for using wax was estimated to be \$26/m² (binder and sand, 50 mm thick) if rail-car quantities of wax were purchased from the supplier.

Paraffin coated paper cups are said to decay at the same rate as leaves (McEwen, personal communication). Since leaves are mainly composed of cellulose, it is reasonable to predict that this rate of degradation would be significantly slower than the rate of starch degradation based on the above analogy.

While similar to starch in being a polymeric chain built from glucose units, cellulose is "far more resistant to microbiological and enzymatic breakdown" (Alexander 1977, p.149). In addition, hydrocarbons can be metabolized, but their rate of metabolization decreases if given a "readily metabolized substrate" (Alexander 1977, p.211).

The slower rate of degradation can be explained by the very low solubility of wax in water and the possible toxicity of lower molecular weight compounds formed during degradation (Morgan and

Watkinson 1994). These low molecular weight compounds may act as a solvent on cell membranes of degrading organisms.

Waxes are aliphatic hydrocarbons. Paraffin waxes consist of shorter chains than microcrystalline waxes. Alexander (Alexander 1977, p.208) indicates that increased chain length reduces the rate of degradation. Thus, the mixture of waxes used for the binder would likely degrade even more slowly than the crude scale wax considered above.

2.4.2.2 Starch Paste

Early indications pointed to a greater economy and degradability for a starch binder compared to the binders noted above. For these reasons, the starch binder became the focus of investigation. For this study, corn or maize starch was used because it is readily available in large quantities in Ontario at a reasonable price.

Molecular Description of Starch and Gelatinization

Starch is composed of two types of molecules, amylose and amylopectin. While they are composed of the same base units of polymerized glucose (Zorbel 1984), or more accurately glucopyranose (McMurry 1984), the manner of assemblage differs. This difference in assembly yields widely differing properties between the molecules.

Amylose, poly-(1-4)- α -D-glucan, is predominantly linear and is helical shaped. This shape is assumed to help stabilize the molecule because the α -1-4 arrangement is not particularly stable (Lazarus 1983). The chemical name describes much of the molecule's structure. The α indicates that this molecule is the *trans* anomer (anomers are molecules that have the same components but differ in that the *trans* anomer has two functional groups that are on opposite sides of the ring, while these groups are on the same side in the *cis* molecule). The D, which stands for dextrorotatory, indicates that the molecule also exists in an enantiomeric pair. Enantiomers are isomers that are mirror images of each other, giving them a handedness called chirality. The D enantiomer is naturally occurring and, while some physical properties may be similar to other enantiomers, differing enantiomers tend to react differently biochemically.

Amylopectin, in comparison, is also composed of these same chains but is highly branched, attached via α -1-6 linkages. The difference due to assemblage is again seen in the comparison of these molecules to cellulose, which is also composed of glucopyranose base units.

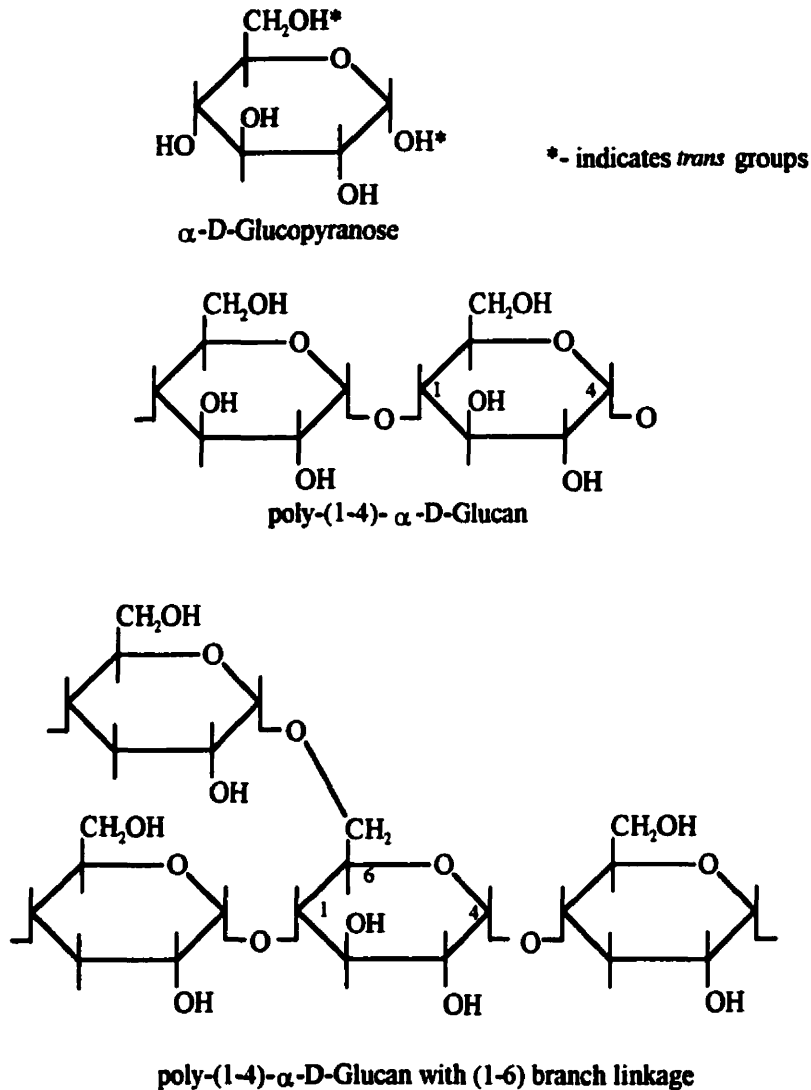


Figure 5 - Diagram showing the difference between unbranched and branched glucan units. Cellulose molecules have their base units assembled at the β 1-4 position; base units in amylopectin are attached at the α 1-4 position. This cellulose linkage is more stable, allowing long straight molecules (Lazarus 1983) to be formed. Obviously, the long straighter chains of cellulose are able to align more intimately with each other, accounting for the greater strength of wood as compared to starch gels. This increased stability also accounts for the greater resistance of cellulose to biodegradation, which will be discussed later.

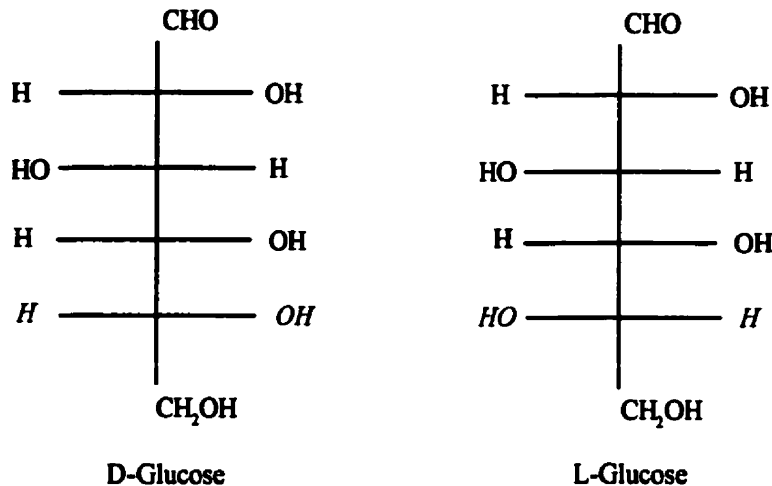


Figure 6 - Illustration of enantiomers of Glucose using Fischer projections.

While starch is insoluble in cold water, it is none-the-less, hydrophilic. As mixtures of starch and water are heated, the starch granules absorb water until the mixture reaches the gelatinization temperature, which is dependent on the source of the starch. At the gelatinization temperature, the granules take on large amounts of water, swelling 10 - 100 times in volume. If all the starch in the mixture is not able to become saturated in water, the solution develops a very thick consistency.

There are a number of starches that will produce a gel. However, as documented by Kruger and Lacourse (Kruger and Lacourse 1990), only corn and wheat produce very high gel formations upon cooling.

Amylose chain length is also dependent on the source of the starch. Chain length has a significant impact on the behaviour of the paste. Shorter chains tend to come out of solution, grouping together by hydrogen bonding (Lazarus 1983), more quickly than longer chains. This process of dissolution is known as "set-back" or retrogradation and results in a significant increase in the viscosity of the paste (Zorbel 1984). Retrogradation is similar to thixotropy but, unlike thixotropy, is usually not reversible (Lazarus 1983).

Corn starch was chosen as the desired type of starch since it develops a stiff gel as noted above. This desired characteristic may be explained in terms of the amylose to amylopectin ratio, and amylose chain length. The other consideration for the choice of corn starch, was its wide availability for a modest price. The material cost for using corn starch was estimated to be \$6/m² (binder and sand, 50 mm thick) if

rail-car quantities of starch were purchased from the supplier. This compares favourably to the estimate of \$26/m² if wax were used. Pastes made from other sources of starch (eg. wheat) may also prove to be feasible. Availability, price and the physical characteristics of the paste, need to be considered if different starches are to be used.

The paste mixture considered most successful consisted of 20% corn starch by mass in tap water. A table of all formulations investigated is found in Appendix B. In later work, tap water was replaced with a nutrient broth to aid in the biodegradation of the paste. The mixture was prepared by first weighing the components, then combining them while stirring, to decrease the tendency to settle (if the swollen starch granules were allowed to settle, they formed a compact mass at the bottom of the vessel and became difficult to redisperse). The mixture was stirred constantly as it was heated to a temperature of approximately 70°C. Upon reaching the target temperature, gelatinization began and the viscosity of the mixture rapidly increased. The cooking process was stopped once the paste was uniformly translucent.

This paste was cooled and covered to slow the process of degradation; it was kept covered until the time it was mixed with the sand, which was within a day of the paste being made. On cooling, the paste formed a rigid gel. Mixing in a standard mixer for about three minutes was sufficient to uniformly incorporate the paste into the sand. The proportions of the sand/paste mixture used was 20% paste by mass.

2.4.3 Adhesion

Adhesion is, in itself, a broad field of study, and includes the areas of surface chemistry, physics, and rheology. This discussion will focus on those aspects that are relevant to our purposes here.

A successful adhesive must meet two requirements. First, the adhesive must act as an adsorbent, wetting the adherand, or substrate, in order to create an interface. This wetting process is termed intrinsic adhesion (Gent and Hamed 1990). The nature of this interaction ranges from chemisorption (including covalent and ionic bonds), which creates strong bonds, to adsorption (including H-bonding and van der Waals interactions) (Alberty 1983, p.287), which creates weaker bonds. In addition, the adhesive must possess viscosity, or shear strength, to prevent slip from occurring within itself. Viscosity is one aspect that differentiates adhesives from lubricants.

For adsorption to occur, the adherand must be wetted by the adhesive. Thermodynamic motivation is necessary for wetting to occur; this motivation is a decrease in the Gibbs free energy, which is a term that incorporates the internal energy, work and entropy of the system. Gibbs free energy is defined as:

$$G \equiv U + PV - TS = H - TS \quad [3] \text{ (Alberty 1983, p.88).}$$

Because the process of a liquid adsorbing on a substrate causes molecules to be more orderly than they were within the liquid, there is a decrease in entropy. This decrease causes an unfavourable increase in the Gibbs energy. Thus, for adsorption to occur, there must be a release of heat or decrease in enthalpy, for adsorption to be favourable.

In less theoretical terms, the Gibbs energy per unit area is the surface tension, γ ($\text{N}\cdot\text{m}^{-1}$), of the surface of the liquid or solid (Alberty 1983, p.275). This leads to the generalization that low energy liquids will spread on high energy surfaces (unless the film adsorbed creates a lower energy surface than that of the liquid as occurs with autophobic liquids)(Zisman 1977). Dupré further summarized the process of a liquid wetting a solid by defining the work of adhesion, W_a , as

$$W_a = \gamma_{SV} + \gamma_{LV} - \gamma_{SL} \quad [4].$$

Zisman (Zisman 1977) goes on to develop this and show that spreading requires the surface energy of the liquid to be lower than the surface energy of the solid.

Adhesion need not occur via a film spreading over a surface; there are several ways that the adhesive and adherand can be brought into intimate contact. One such mechanism is employed for pressure sensitive adhesives. These adhesives form the adhesive interface with the aid of applied pressure. This is a viable mechanism for adhesives that are too thick to flow or are unable to spread on the surface of the adherand.

Dampproofing is applied to the exterior of basement walls to act as a vapour retarder and capillary break. This dampproofing layer is also used here to act as the adhesive for the starch binder. Because the dampproofing layer is thin and unable to flow, the starch paste must be brought into intimate contact with the dampproofing layer. The resulting system can be described as a pressure sensitive adhesive. The pressure is applied by virtue of the conversion of momentum into force upon impact. In this way, the dampproofing layer is able to 'wet' the starch. The result is a solid-adhesive-adhesive-solid system. The starch adheres to the sand and the dampproofing is adhered to both the starch and the concrete wall. In

addition, the impact may cause individual grains of sand to pierce the starch coating and adhere directly to the dampproofing layer. This last hypothesis was verified by shooting unpasted sand directly at the dampproofing layer. While much of the sand rebounded, a number of grains were nevertheless able to adhere soundly to the dampproofing.

A complication arises when attempting to make generalizations regarding dampproofing formulations, since the formulations possible are numerous and range from emulsified asphalts, to solvent diluted asphalts, to hot-melt asphalt mixes. Also, the composition of asphalts is variable, dependent upon the source and the extent of refining. Asphalts may have softening points that range from 25°C to 55°C (Speight 1980, p.452) or higher.

Asphalts are defined as the nondistillable portion of crude oil; they are the residual found at the bottom of vacuum distillation towers in the refining process (Altgelt and Boduszynski 1994; Speight 1980, p.452). The composition of asphalt is complex. It is generally described in terms of three main components: oils, resins and asphaltenes. Oils are predominantly aliphatic (composed of straight chains with few carbon - carbon double bonds) while resins are more aromatic in nature and asphaltenes are the most aromatic components. The importance of the aromatic component in dampproofing is its ability to be polarized. Aromatic substances, composed of a series of 'Lego-like' benzene rings, produce a diffuse cloud of charge from the staggered double bonds. This electron cloud acts in a fluid way in response to a polar substance. When a polar molecule is near, electrons may pool or retreat, creating a polarization within the aromatic compound. For this reason, asphaltenes have the ability to hydrogen bond as suggested by Speight (Speight 1980, p.252).

Given the variation in composition, it is surprising and fortunate that surface tension of petroleum substances varies over a narrow range of 24 -38 $\times 10^{-3}$ N m⁻¹ (Speight 1980, p.89). Given the aromatic nature of asphalt, the estimate of 35 $\times 10^{-3}$ N m⁻¹ based on a phenyl ring edge protruding from the surface (Zisman 1977), is a reasonable number. Thus, the surface tension of asphalt is too low to be wet by water ($\gamma = 71.69 \times 10^{-3}$ N m⁻¹), but is just low enough to wet starch ($\gamma = 39 \times 10^{-3}$ N m⁻¹) and its gel constituents (amylose, $\gamma = 37 \times 10^{-3}$ N m⁻¹ and amylopectin, $\gamma = 35 \times 10^{-3}$ N m⁻¹) (Shafrin 1975). It is interesting to note the excellent adhesion of the waxes tested, which were not highly dependent on the pressure applied. The low surface tension of waxes easily explains this observation ($\gamma = 25 \times 10^{-3}$ N m⁻¹) (Speight 1980).

The particular arrangement of adhesives, where the dampproofing adheres a starch paste, was not found in the literature. Testing using this adhesive system demonstrated that low impact energies, due to low

nozzle-velocities, resulted in inadequate adhesion. This implies that significant force is required to bring the starch and bitumen surface into intimate contact. In addition, higher nozzle velocities also increase the density of the aggregate within the paste matrix, allowing the internal friction of the sand to be exploited.

The stiffness of the corn starch gel complements the adhesive action between the dampproofing and the starch gel. The result is an effective binder system that is able to hold the aggregate layer in place until back filling is complete.

2.4.4 Biodegradation

One of the requirements for the termite barrier system is the short persistence of the binder that is used for application of the barrier sand to the wall. After the excavation is backfilled, it is desirable for the binder to desist, allowing the sand to regain its self-healing property and to develop its ultimate degree of permeability.

In addition to meeting the requirement of short persistence, the binder also meets the duty of care that is necessary when creating any new product or system that will have access to the waste water system and the ground water ecosystem. The binder is a naturally occurring product; its degradation will pose no hazards to the environment. The increase in BOD (Biochemical Oxygen Demand) on influent to waste water treatment facilities would be slight since the release of degradation byproducts would occur over the course of weeks and the byproducts themselves are readily degradable.

Starch is a polysaccharide and falls into the broad category of carbohydrates. An assortment of polysaccharides naturally occur within soil and are a source of metabolites for microorganisms. These organisms use the organic carbon for energy and convert it into CO₂. The CO₂ is then used by plant-life to form plant tissue via photosynthesis. Thus, these sugars are an important part of what is known as the carbon cycle (Alexander 1977, p.113).

The hydrolysis of starch in soil is not rare. Hankin (Hankin et al. 1974) found that the frequency of amyolytic activity, associated with the degradation of starch, fell between the most frequent process of protein transformations and the least frequent process of cellulose transformation. Against this reassuring background, the mechanism of degradation and factors that aid or hinder this process will be discussed.

The average length of the chains comprising the starch and proportions of amylose to amylopectin would be thought to affect the rate of degradation. Longer chains would require more time to degrade by virtue of requiring a larger number of cleaving reactions to depolymerize the starch. Amylopectin is thought to degrade more slowly since it must rely on various enzymes to cleave the various linkages in its structure. As previously mentioned, micelle/granule size (the capsules that are constructed from the starch molecules), chain length, and amylose to amylopectin ratio are characteristics that vary with the source of starch. Stark and Tetrault found that some starches are more easily degraded by a given organism than others. Differences in degradability may exist among different brands of the same type of starch and even among different batches of the same brand. By testing soluble starch (made from partially hydrolyzed potato starch), and the starches of potato, corn, rice and arrowroot, they found that soluble starch and rice starch were more easily degraded, while corn and potato starches were less easily degraded (Stark and Tetrault 1951).

Degradation Process

The degradation process, known as hydrolysis, is enabled by organisms called enzymes. Enzymes, produced by bacteria, fungi and many other organisms in nature, are proteins that catalyze specific chemical reactions. Amyolytic enzymes act on the glucose to glucose bonds within the chains of amylose and amylopectin. The enzymes involved in the degradation process, known generally as amylosaccharidases, include α -amylase, β -amylase, glucoamylase, and α -glucosidase. α -Amylase is known as an endo enzyme, which indicates that it randomly attacks the α -1-4 bonds of amylose and amylopectin. These random attacks create a variety of products including dextrans (short versions on starch), glucose, maltose (consisting of 2 glucose units), and maltotriose (consisting of 3 glucose units). β -Amylase also attacks the α -1-4 bonds but, since it is an exo enzyme, does so more systematically, starting from one end of the chain and cleaving every second bond, making maltose the only by-product formed. Glucoamylase acts in a similar fashion to β -amylase but instead cleaves off singular units of glucose. Some glucoamylases are also able to cleave the 1-6 bonds that occur at the branch points of amylopectin. α -Glucosidase, an exo enzyme, acts on the α -1-4 bonds of the dextrans, maltose and maltotriose reducing them to glucose. Ultimately, glucose is the end product resulting from this enzymatic activity (Alexander 1977, pp.189-190).

Table 7 is a non-exhaustive list of organisms that produce amylosaccharidases.

Microorganism	Enzymes produced
Bacteria	
Bacillus [†]	α -, β -amylase; α -glucosidase, and others
Pseudomonas [†]	α -, β -amylase, isoamylase
Clostridium [†]	α -, β -amylase; α -glucosidase, CGTase, glucoamylase
Thermoanaerobacter	α -glucosidase
Thermotoga	α -, β -glucoamylase
Pyrococcus	α -amylase; α -glucosidase
Others	
Aeromonas ¹ , Bacteriodes [‡] , Chromobacterium [•] , Corynebacterium [†] , Cytophaga [•] , Eikenella [‡] , Flavobacterium [†] , Fusobacterium [‡] , Gardinerella [‡] , Gemella [‡] , Lactobacillus [‡] , Micrococcus [•] , Streptobacillus [‡] , Streptococcus [†] , Vibrio [‡]	
Actinomycetes	
Streptomyces	α -, β -amylase; α -glucosidase isoamylase
Thermoactinomyces	α -, β -amylase
Others	
Micromonospora [•] , Nocardia [•]	
Yeasts	
Saccharomyces	α -amylase; isoamylase
Endomycopsis, Candida	glucoamylase, α -glucosidase
Fungi	
Aspergillus	α -, β -amylase; glucoamylase
Rhizopus	α -, β -amylase; glucoamylase
Trichoderma	α -, β -amylase; glucoamylase
Fusarium	α -glucosidase
Others	
Fomes [•] , Polyporus [•]	

Note: 1 - species common in surface and tap water. May become involved via this route. (Horsnell 1996a)

[†] Varieties known to be able to be isolated from soil (Horsnell 1996a)

Table 7 - Partial listing of organisms that produce enzymes that degrade starch. (Ramesh et al. 1994). [•](Alexander 1977, p.189), [‡](Horsnell 1996a)

As seen from Table 7, many organisms produce one or more of the enzymes that participate in the degradation of starch, making starch paste significantly susceptible to biodegradation. Among the

organisms that hydrolyze starch are yeasts, fungi, and bacteria. The optimal environment is unique for each organism and metabolites may be converted in various ways. Organic carbon, in the form of glucose or other sugars, can be converted into CO₂, enzymes, organic acids or cell mass (Vogt and Staffeldt 1975). Glucose produced by the hydrolysis of the starch paste can go on to degrade further if it is not washed away. The glucose molecule is small enough and water soluble enough to be directly used as a source of carbon by microorganisms. It is in the degradation or utilization of glucose that a host of end products may be formed, including a number of organic acids, depending upon the environmental conditions.

Vogt and Staffeldt (Vogt and Staffeldt 1975) studied naturally occurring fungi and bacteria indigenous to two different soils. They found that a variety of *Bacillus spp.* was the most effective organism in degrading starch, out-ranking the starch-consuming fungi species and many other bacteria present in the soils. The majority, 86%, of carbon was converted to CO₂, while little carbon went to the production of cell mass, enzymes, and organic acids. It should be noted that, in Vogt's study, the environment was the same for each soil sample.

In addition to the effect of the degrading species on the end-products formed, Greenwood (Greenwood 1968) noted that the amount of oxygen and nutrients available to the bacteria is also a significant factor in determining the end-products formed, regardless of soil type. Under aerobic conditions, glucose was metabolized into CO₂ and cell mass. Under anaerobic conditions, the end-products consisted of larger amounts of volatile fatty acids and lesser amounts of cell mass. The fatty acids produced include acetic acid and butyric acid. The odour of these acids can, at best, be described as undesirable. Alexander (Alexander 1977, p.143) adds methane and hydrogen gas to the list of products formed by anaerobic degradation.

Variables affecting rate of degradation

Having established how degradation occurs, it is also necessary to consider the rate of degradation. A general idea of this rate may be inferred from the work of Cheshire (Cheshire et al. 1969) who found practically no trace remaining of the starch in a soil sample after 84 days of incubation at 20°C. The loss of starch was determined by the use of C¹⁴ to label starch added to the soil. After 84 days, the relative proportion of sugars in the soil returned to their original levels. Cheshire (Cheshire et al. 1969) added an amorphous (gelled) 0.5% solution of wheat starch to a soil sample and after incubating the sample for 28

days at 20°C, found that the soil was able to re-establish the relative proportion of several sugars to their original values. After 84 days, 60-80% of the starch was liberated as CO₂. The rate found is not a fixed and certain value; it is dependent upon many variables.

There are ways of increasing the rate of degradation of the paste mixture. One option is to enhance the environment for the growth of organisms. The other possibility is to select organisms that prefer to use the paste mixture as a substrate.

In improving the environment for the organisms, some practical concerns limit possibilities. Organism growth is predominantly a function of temperature, pH, availability of water, oxygen (for aerobic organisms), substrate, and nutrients (Alexander 1977, p. 21). It should be noted that cost and feasibility may limit the amount of control that can be exerted on the underground environment.

Temperature

Increased temperature increases the rate of growth. Temperatures of 30°C to 35°C, which would significantly increase the rate of degradation, would be impractical to maintain in soil to a depth of 2m. It may be helpful, though, to slow the cooling of the soil by increasing its thermal lag. This could be accomplished by horizontally insulating the soil around the house. Seepage of ground water toward the drainage layer, however, could subvert the effectiveness of this insulation. A study of the variation of soil temperature with depth, in an open field in Ottawa, demonstrated that a range from 8°C to 13°C exists at a depth of 2m. When the house is initially backfilled, the temperature of the soil near the foundations is likely to be closer to the average seasonal temperature. There is a considerable lag in the temperature at 2m depth as stated by Hutcheon and Handegord (Hutcheon and Handegord 1989, p.196), who show the maximum temperature at 2m to occur in November. The lowest temperature at 2m occurred in March. If the soil temperature at the time of backfilling is significantly warmer than the customary temperature at 2m, the length of time for the temperature to drop to its minimum value would be longer, and the minimum temperature reached, would be higher. It should be noted, though, that soil temperature is not a well behaved and easily predicted quantity. Factors such as soil type, ground cover, weather patterns, soil draining ability, level of the ground water table, and amount of heat flow from the abutting basement wall, have a large impact on the thermal climate that the soil will experience.

Soil pH

While the pH of soil is difficult to change *en masse*, the paste mixture can easily be made to have an optimal pH for bacterial growth. Any difference between the pH of the paste and the surrounding soil would be neutralized at the interface of soil/paste contact, but water held in the gel structure, would likely hold with it the hydronium or hydroxyl ions, maintaining the pH of the paste for a longer period. Over time, the pH would approach that of the soil; the initial paste pH may exist long enough to enhance initial bacterial growth. For this reason, correcting the pH of the paste is a reasonable measure provided the cost is not prohibitive.

Soil Moisture

The natural presence of moisture in the soil is beneficial since water is necessary to sustain bacteria and other organisms (Alexander 1977, p. 21). An excess of moisture though, will decrease the soil's ability to transfer gases, since voids hold air more effectively than water. Cyclic wetting and drying could then increase the rate of degradation by introducing oxygen into the soil matrix during the drying phase. Greenwood (Greenwood 1968) rationalized that this increase in the rate of degradation could be due to interparticle movements that occur as a result of drying and rewetting; these movements allow the bacteria access to regions inaccessible prior to drying. The process of drying and rewetting can be likened to the opening and closing of a door within the soil structure. This increased rate of degradation was verified by Sørensen (Sørensen 1974). Sørensen studied glucose degradation in soils using C¹⁴ labelled glucose and found soil samples liberated more CO₂ if air dried and rewetted every 30 days than similar samples kept continuously moist.

Oxygen Supply

As mentioned above, partial drying enhances gas transfer within the pores of the soil. This transfer is beneficial in increasing the rate of the decomposition process. The influence of the rate of oxygen supply was noted by Clark (Clark 1968). He demonstrated that an increase in flow rate increases the rate of decomposition of wheat straw. Further, for the same amount of oxygen provided to the soil during a given time period, oxygen provided at a higher concentration significantly enhanced the rate of decomposition. This indicates that the concentration of oxygen provided to the soil has a greater effect than the flow rate

provided. However, for similar oxygen concentrations, increased flow rate does increase the rate of decomposition.

In addition to organisms' other needs, several nutrients are essential for their proliferation. The specific needs depend upon the particular organism considered. Examples of requirements for two bacteria are shown in Table 8, adapted from Alexander (Alexander 1977, p.118).

	Pseudomonas sp.	Bacillus subtilis
Energy source	Glucose	Glucose
Carbon source	Glucose	Glucose
Minerals	NH ₄ Cl K ₂ HPO ₄ MgSO ₄ FeSO ₄ CaCl ₂	NH ₄ Cl K ₂ HPO ₄ KH ₂ PO ₄ MgSO ₄ Na ₂ SO ₄ FeSO ₄ MnSO ₄ CaCl ₂
Growth factors	-	Glutamic Acid Cysteine

Table 8 - Nutrient requirements for two common bacteria

The listing of nutrients above can be seen to vary depending on the organism; some of the factors they share in common though, are the availability of K⁺, PO₄²⁻, SO₄²⁻, NH₄⁺, Ca²⁺ and Fe²⁺ ions to the organism. Clark (Clark 1968) reported that glucose was degraded at a maximum rate if the C:S ratio (carbon to sulphur ratio) was 900 or less.

Sørensen (Sørensen 1974) also found that the addition of unlabelled glucose during the degradation process increased the release of labelled CO₂. This was termed the priming effect by Clark (Clark 1968).

In a more general sense, it is the soil environment that affects the rate of degradation. This environment necessarily encompasses all of the above issues. The soil environment is shaped by its history. The range of available organisms that will compete for the substrate have, no doubt, been influenced by factors such as previous land use. This general consideration of the influence of soil environment on the degradation process was considered by Hankin (Hankin et al. 1974). Hankin's study investigated the ability of several

soils from Connecticut to create degradative enzymes. The influence of past and present use on the percentage of active enzymes was examined and it was found that amylolytic enzymes were significantly affected by these differences in land use. The percentage of bacteria that produce amylolytic enzymes ranged from 5% in a tidal marsh soil to 60% in a cultivated soil. These figures are average values taken from the various soil samples tested. A ranking of seven soils in order of increasing enzymatic activity was determined as follows: tidal marsh, orchard, forest, forest litter, pasture, swamp, and cultivated soils. Under another classification system used by Hankin, slightly acid, well-drained soils of the limestone uplands had the highest numbers of desired bacteria while the worst soils were the poorly-drained, saline soils of the tidal marshes. While there is a great deal of scatter in their data, tidal marshes and orchards both showed fewer desired bacteria. Based on these observations as well as the beneficial effect of cyclic wetting and drying, the starch paste binder should degrade easily. Its presence amid a drainage layer, which by its nature is well-drained and subjected to cyclic wetting and drying, should facilitate the degradation of the starch.

This flushing activity that occurs in the drainage layer would have other beneficial effects. Water soluble sugars produced as intermediates in the degradation process would be flushed from the sand matrix as well as undesirable fatty acids. Also, the drainage layer is quite porous, which enhances the level of aeration. The availability of oxygen allows a more complete aerobic degradation of the starch, thereby reducing the amounts of undesirable fatty acids produced.

Selection of Organisms

Another way of increasing the rate of degradation is to select organisms that prefer to use the paste mixture as a substrate. Gary Horsnell (Horsnell 1996b), a microbiologist with the Ontario Ministry of the Environment, suggested that it is possible through successive isolation, to separate a colony from within a species of organisms that has superior performance to other colonies. This superior colony is then diluted and the best colony is again isolated. In this manner, it is possible to isolate a specialized, yet still naturally occurring organism that is most ideally suited to its environment. In addition, if the selection process is performed on a spore forming organism, it might be possible to cause the bacteria to sporulate and then collect the spores. Spores are more hearty than the parent bacteria and can be stored in a dry state where they remain inactive. These spores could then be dispersed in water and applied to the

installed barrier. Upon encountering a moist, nutrient and food rich environment, the spores would germinate and produce colonies to degrade the starch binder.

This process could have a number of key benefits. The most successful organism could be used to degrade the starch quickly. It might also be possible to select an organism that has a limited tendency to produce undesirable organic acids. As this termite protection technology may find use in other countries, this selection process could also be used to develop organisms reared from native soil flora and adapted to regionally specific conditions, which would pose few concerns related to the introduction of non-indigenous organisms (bringing unknown results).

Summary

Some attention has been given to the formation of butanoic acid (also known by the trivial name of butyric acid) during the degradation of starch and cellulose. Butanoic acid is a rather foul smelling organic acid and has been targeted as reducing indoor air quality. This acid can be among many organic acids produced during degradation, but the final by-products of degradation are dependent on the species of organisms present. To focus on one possible end-product, would border on an over-simplification of the degradation process. As it applies to this thesis, the end products produced by the degradation process are unlikely to enter the house. Butyric acid is not water soluble, which would prevent it from being transported through capillary water in the concrete, and into the house. Also, there is a high probability that many of the degradation by-products would be flushed into the weeping tile around the house. While butyric acid is not water soluble, it, as well as other organic acids, would be soluble in the damp-proofing material. As noted above, it is unlikely that the presence of the acids in the dampproofing would affect indoor air quality. Also, the organic acids, produced by the degradation of starch, naturally occur within soil and, to date, the occurrence of organic acids in the soil has not been connected to indoor air quality problems. Thus, the production of organic acids in the process of binder degradation is not considered to pose a hazard to the indoor air.

3 LABORATORY INVESTIGATIONS

This chapter will describe the investigations done using the sand and paste barrier system. The topics covered include:

1. Preparation of specimens and the method of placement of the material.
2. Permeability of the sand and the sand/paste system.
3. Rate of drying.
4. Rate of biodegradation.
5. Strength and strength loss of the system with time.
6. Half-size model of the barrier system.
7. Impact testing.

3.1 Termite Barrier Properties

The termite barrier properties of the sand used in these experiments was investigated by Myles (Myles 1994b) and shown to be effective.

3.2 Application/Placement of Samples

3.2.1 Method of Preparation

Tables listing all the wax and corn starch mixtures tried in the course of development can be found in Appendices A and B, respectively. The most successful binder consisted of 20% by mass purified food powder corn starch and 80% tap water. In later work, the tap water was substituted with a nutrient broth. These nutrients were provided to enhance the ability of microorganisms to degrade the starch paste. The composition of this broth is based on the proportions of a Basal synthetic medium. Basal synthetic medium is used for investigating a bacteria's ability to use a particular carbon source (Collins, Lyne, and Grange 1995). In this case, the carbon source is the starch paste binder. Similar ratios of P:K:Mg were

maintained per litre of water and the details of proportions are found in Table 9. Calcium carbonate, 4% by mass, was also added to the paste to provide a source of calcium for *Bacillus spp.*.

Component	Mass
20/20/20 fertilizer (See Appendix E)	1.26 g
TSP (Trisodium Phosphate)	1.13 g
MgCl	0.10 g
Water	1000 ml
pH (adjusted with HCl -Muriatic Acid)	~6

Table 9 - Composition of nutrient broth used.

Initially, the aim was to maintain the same concentration of nutrients in solution. However, the suggested proportion of starch to be added to this broth is 0.2%. As the binder is comprised of 20% starch, perhaps up to 100 times the concentration of nutrients could have been present in the solution for the starch binder.

To make the paste, the starch, calcium carbonate, and nutrient broth were weighed out and combined, and then heated while stirring until gelatinization was complete. The paste was either mixed immediately with the sand or left to cool and later mixed with the sand. While it appeared that fresh paste gave the mixture better tack, the usual practice was to make the paste a day before testing. This routine was adopted for reasons of convenience and to ensure conservative results.

3.2.2 Method of Placement

All trial samples were shot into place using a gun designed to roughly simulate a wet-mix shotcrete machine. The gun, pictured in Figure 7, was powered by compressed air supplied within the lab. The material was fed into the machine by hand. The air supply that provides compressed air to the Building Science laboratory, where testing was done, normally operates at 586 kPa (85 psi) and at a maximum of 827 kPa (120 psi). The maximum flow rate that can be supplied is 4.1 m³/min (68.4 l/sec or 145 cfm). It should be noted that this air supply is not dedicated to one laboratory. As a result, the maximum flow rate was not always available due to simultaneous use of the air supply elsewhere in the building, which sometimes reduced the available pressure at the gun during shooting.

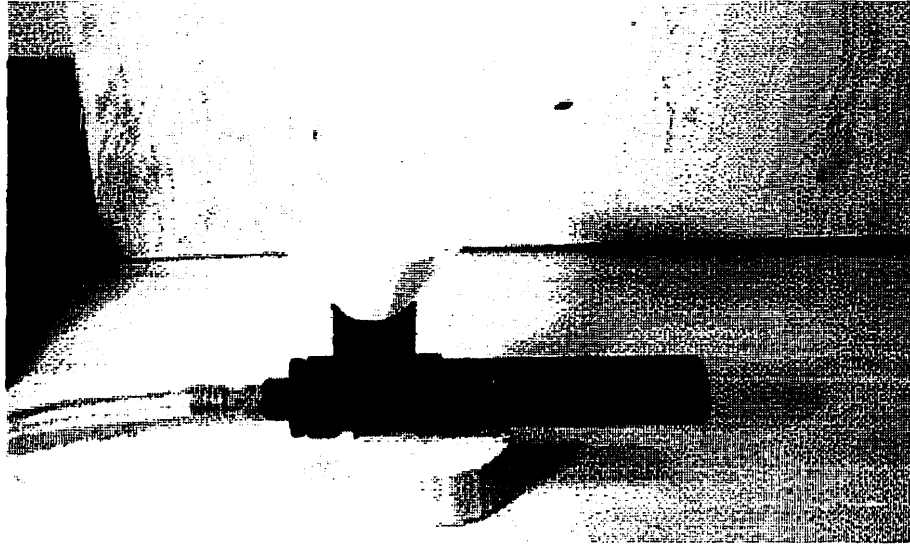


Figure 7 - Picture of the gun used in testing.

3.2.3 Density as placed

The density of material was measured 'as-placed'. The test was done in the evening when the available compressed air capacity was at a maximum. The sand paste was shot into a 4 litre container that had been coated with a solvent based asphalt solution used for dampproofing. The mass of the barrier material placed was determined and divided by the measured volume of the container. The density was found to be 1730 kg/m^3 (g/l).

In comparing the density of cylindrical specimens prepared for the strength tests, the density of the shot material was lower. The cylinders were compacted in three layers, each layer being rodded 25 times; the density of the cylinders ranged from 1840 kg/m^3 to 2050 kg/m^3 .

It is thought that a continuous stream of material shot at a higher nozzle pressure would compact the barrier material more densely. Thus, the deficiencies of the delivery method are considered to be the cause of the lower density of the shot material in comparison to the rodded specimens.

3.3 Engineering Properties

3.3.1 Permeability

3.3.1.1 Method

Permeability tests were conducted on both the termite sand itself, as well as the sand/paste mixture. A variation on the constant head test was used to measure the soil permeability. The testing equipment used in these tests is shown in Figure 8. This equipment was used instead of more standard equipment because it was desirable to test the permeability of the sand 'as placed'. The equipment used allowed the sand/paste mixture to be shot directly into position, providing a more accurate evaluation of the material's permeability as-placed. Secondly, the purpose of these investigations was to evaluate relative changes in permeability more than to measure the sand's absolute permeability.

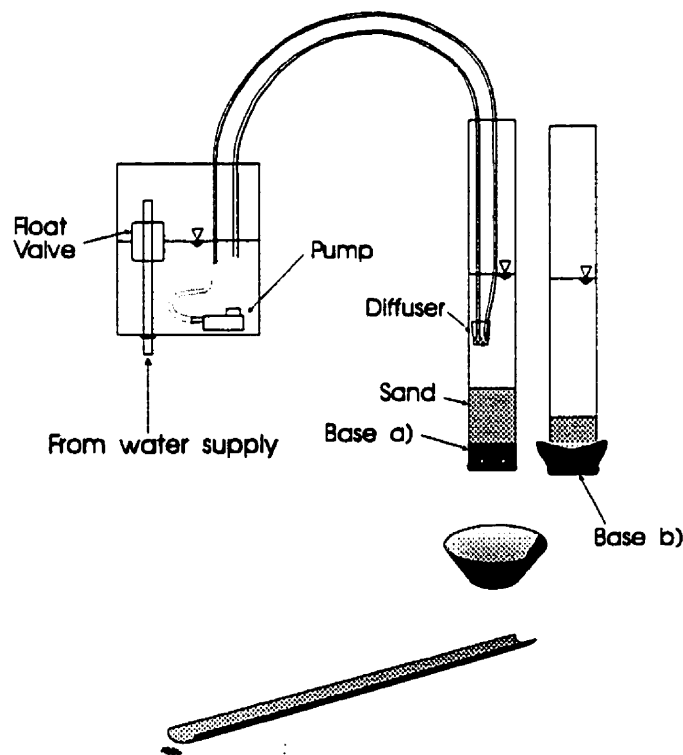


Figure 8 - Schematic of permeability test setup.

Two variations of the tests were done. In the first type, pictured in Figure 8 a), the base consisted of a large opening screen (18 mm x 44 mm across the vertices of the diamond shaped opening), covered with a 20 mm thick layer of selected 19 mm gravel and topped with a 20 mm thick layer of 10 mm clear washed

gravel. The second type of test, pictured in Figure 8 b), used a layer of fibreglass mesh (1 mm x 2 mm openings) as a base covering the large opening screen. In both cases, the sand or sand paste mixture was then placed over the prepared base.

The permeability tests were started by initiating the water supply lines to the testing column with the aid of a small pump. Care was taken to ensure that the initial flow of water was gentle to avoid disturbing the top layer of the test material. The column was then filled to the height that would be used in the tests and time allowed for the flow to stabilize. This stabilization time varied depending on the height of the water column and the flow rate. The flow was considered to be stabilized when the height fluctuations in the column of water followed the fluctuations occurring in the reservoir.

The thickness of the test layer of material was then measured and recorded. Before measuring the flow rate, the height of the column of water over the material was measured. The flow rate was then measured by diverting the draining water into a graduated cylinder while measuring the filling time with a stop watch. After measuring the flow rate, the height of the column of water was again measured and the average value was used for calculations. Several sets of measurements would be made to help alleviate variations in measurement due to reaction time.

Two tests were performed on the termite sand itself; one used the first set-up, and the other used the second set-up. For the barrier material, which consisted of the sand and the corn starch paste (made with tap water), the change in permeability over time was also investigated for two cases.

The first test on the barrier material studied the effect of silt sized particles on the permeability of the system. Initially, silt sized particles were mixed into the column of water over the sand/paste material while water was flowing through the test set-up. These particles were allowed to settle and then the permeability was measured. The process of incorporating the silt included two additions of 75g followed by additions of 200g and 150g of silt. Finally, silt was added to form a uniform layer, 19 mm thick, over the sand and again the permeability was measured. The water was stopped and the silt layer allowed to dry. A long term test was then performed to determine if progressive clogging of the sand would occur due to the presence of the silt. Water flow was provided continuously, with the exception of breaks in the siphon supplying the water, over the course of a week.

The second study of change in permeability with time considered the effect of biodegradation on permeability. The paste binder was shot into place over the base as shown in Figure 8 b). It was allowed

to degrade and the permeability of the mixture was measured periodically. Once the permeability seemed to plateau, the column was carefully removed from the screen and transferred to a base constructed in the same manner as shown in Figure 8 a). This was done in order to compare the difference in head-loss between the two systems.

3.3.1.2 Results

Results for the two tests on the sand alone can be found in Table 10. As a comparison, Hazen's relationship (Craig 1992) can be used to approximate the permeability of sands with the equation:

$$k = 10^{-2} \cdot D_{10}^2 \quad (m/sec) \quad [3],$$

where k is the permeability constant and D_{10} for the sand was 1.14 mm.

	Set-up as in Figure a)	Set-up as in Figure b)	Predicted by Eq. 3
Permeability of Termite Sand	3.0 mm/sec	5.3 mm/sec	13 mm/sec

Table 10 - Permeability of termite sand for each test set-up.

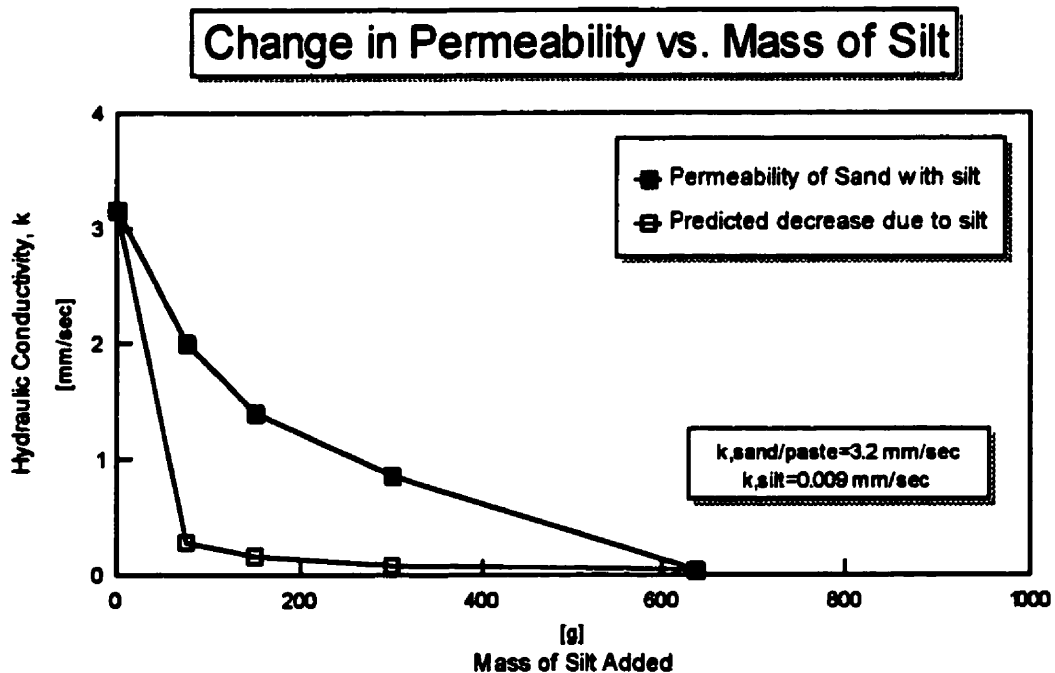


Figure 9 - Plot of the change in permeability with addition of silt.

The results of the test studying the effect of silt on the filter's permeability over time are summarized in Figure 10. In the first tests, shown in Figure 9, the silt initially added did not cover the surface of the sand uniformly. This is demonstrated in the results where the measured change in permeability was much less than the predicted change. The hydraulic conductivity of the silt was calculated based on the change in permeability of the system from the state of the sand/paste mixture alone to the state of the 19 mm layer of silt covering the sand/paste mixture. The prediction of change in permeability for the system found in Figure 9, which includes the sand/paste mixture and the layer of silt, was based on the value of hydraulic conductivity determined for the silt.

Figure 10 demonstrates the change in permeability with time due to the effect of silt. The test was performed to determine if the sand would clog over time. After a week of testing with nearly continuous flow, no noticeable decrease in permeability was noticed. There was significant variability in the results shown in Figure 10. This is due to unevenness occurring in the layer of silt. If there was a break in the siphon providing the water supply, due to release of dissolved gases in the water, the water supply would need to be re-initiated, inevitably disturbing the layer of silt. As seen from Figure 10, differences in the depth of this relatively thin layer of silt had a significant impact on the permeability of the system. If such fluctuation is used to view the results, it is apparent that the permeability of the system remained basically unchanged after a week of testing.

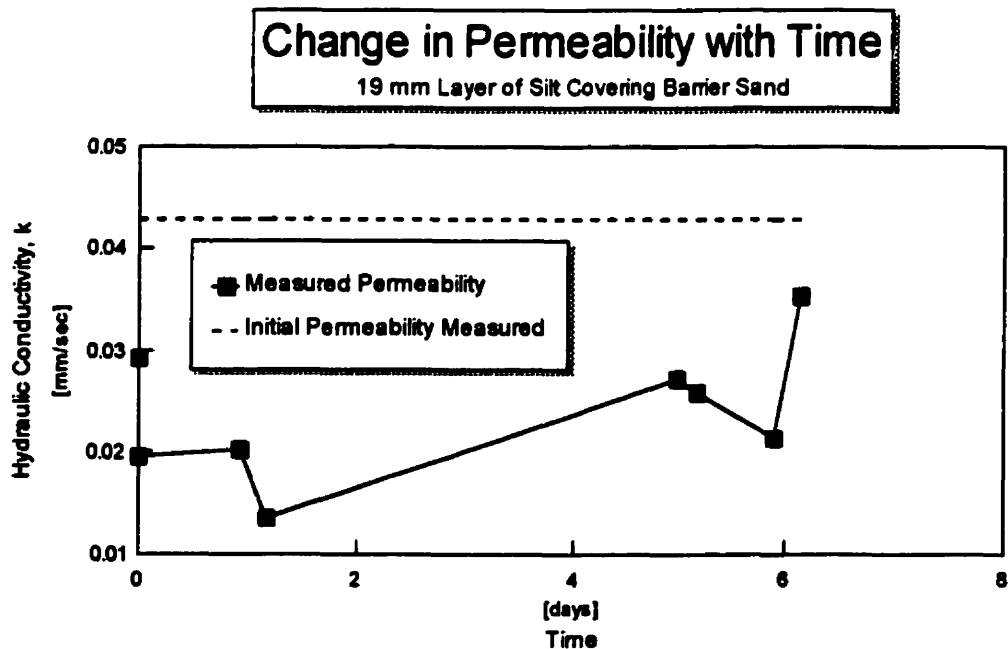


Figure 10 - Plot of the change in permeability over time - effect due to silt.

In the second set of tests, the change in permeability was measured over a longer period of time and the results are shown in Figure 11. The increase in the permeability of the system as the binder left the pores of the sand was to be expected. It is worrisome to note that the permeability remained low after a significant amount of time had passed.

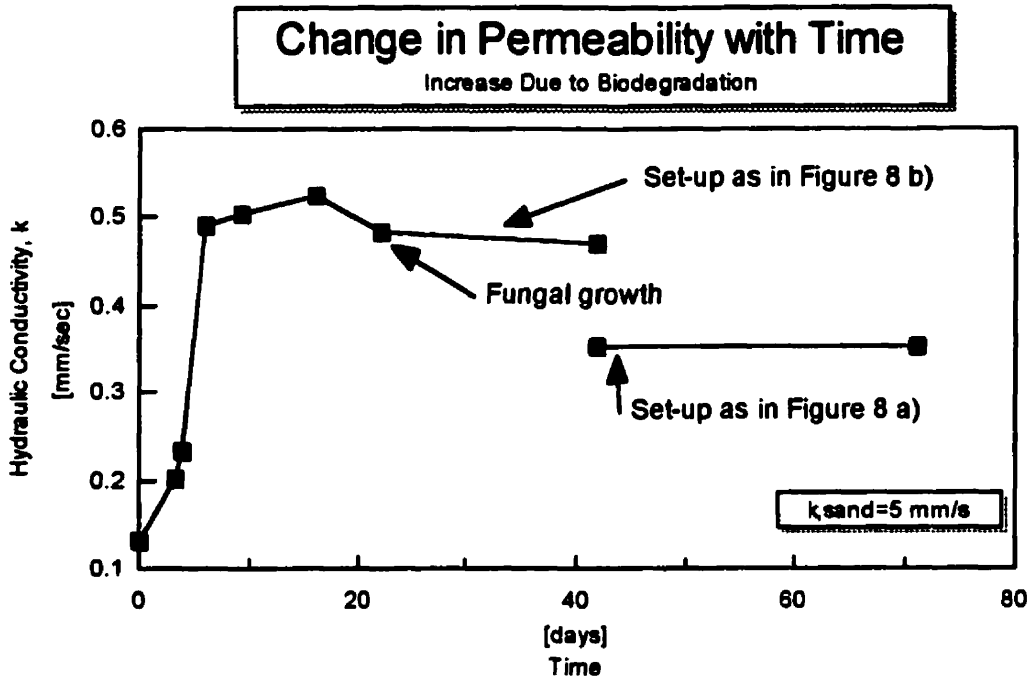


Figure 11 - Plot of the change in permeability over time - effect due to biodegradation.

A possible explanation of this effect is the onset of biological clogging. While microorganisms are degrading the starch, they are also multiplying. The biomass that is created would cover the grains of the sand. This layer over the grains of sand would prevent the permeability of the system from attaining the permeability of the virgin sand. This clogging effect has been studied by others and the results due to clogging produce similar decreases in permeability (Allison 1947). The effect of biological clogging resulting from a fungal growth is shown in Figure 11. Twenty two days after the test had been started, fungal growth was observed on the surface of the sand in the column. The permeability measured that day was lower than observed in the previous measurement. While there was a noticeable decrease in the permeability, it was not significant. Considering the permeability of the system, despite partial clogging by microorganisms, it is hopeful to note that the permeability is still sufficient to meet the requirements of a Class B drainage layer as outlined by CCMC and discussed in Chapter 2.

The method used for testing could lead to another explanation for the plateauing in permeability that occurred. For these tests, tap water was used and allowed to drain away; this water was not recycled through the system. Tap water contains residual chlorine, which is maintained in many municipal water supplies because it inhibits microbial growth in water mains. Thus, it is thought that the residual free chlorine present in tap water could have inhibited the growth of the starch hydrolyzing organisms. Natural runoff and infiltrating water would not have residual chlorine and would be rich in microorganisms washed in from neighbouring soil. Consequently, the effect of rain water and ground water washing through the filter would produce better results, possibly increasing the rate of loss of the binder. Further tests that would study the change in permeability over time using distilled water could provide insight as to the mechanism responsible for preventing the sand from attaining only 10% to 17% of its maximum permeability. These tests could be run in an adapted form of the ASTM D1987 - 91 Standard Test Method for Biological Clogging of Geotextile of Soil/Geotextile Filters.

In addition, the density of the material tested was subject to significant variation. Varied densities of the same material from one test to another would produce differences in the permeabilities measured.

3.3.2 Rate of Drying

3.3.2.1 Method

It may be helpful in future investigations of this barrier system to know its rate of drying. The binder is significantly stronger when it is dry than it is in its wet state. Fears of sloughing during the backfilling process could be allayed if the material was dry. To determine the rate of drying of the barrier material, two tests were done.

In the first test, the barrier material was compacted into a 100 mm deep by 110 mm in diameter. This container was then left open to the ambient environmental condition in the laboratory, from June through to November. The temperature was 21°C (\pm 2°C) while the relative humidity ranged from 30% to 60% depending on the season.

The second test was performed under more controlled conditions. Barrier material was compacted into 150 mm diameter cylindrical molds. The three molds, 50 mm, 100 mm, and 150 mm deep were placed in an air-tight plexiglass box. The humidity was regulated within the box using a saturated salt bath of sodium chloride (Hickman 1970) with a fan circulating air over its surface. The conditions for drying

were 75% r.h. and 21°C (± 2°C) and were checked using wet and dry-bulb thermocouples situated in front of the fan's air stream. The temperature was the ambient temperature in the laboratory.

3.3.2.2 Results

The results for the first and second tests are summarized in Figures 12 and 13 respectively. In each case, the data was fit to a power function of the type $W=bt^a$ (W , moisture loss; t , time in days) and the coefficients for each test are found in Table 11. The correlation with the power law fit was good.

Upon inspection of Figure 12, which plots the results for the sample exposed to the laboratory environment, a slight increase in the rate of drying can be seen. This is likely due to the cooler outdoor weather that resulted in decreased indoor relative humidity.

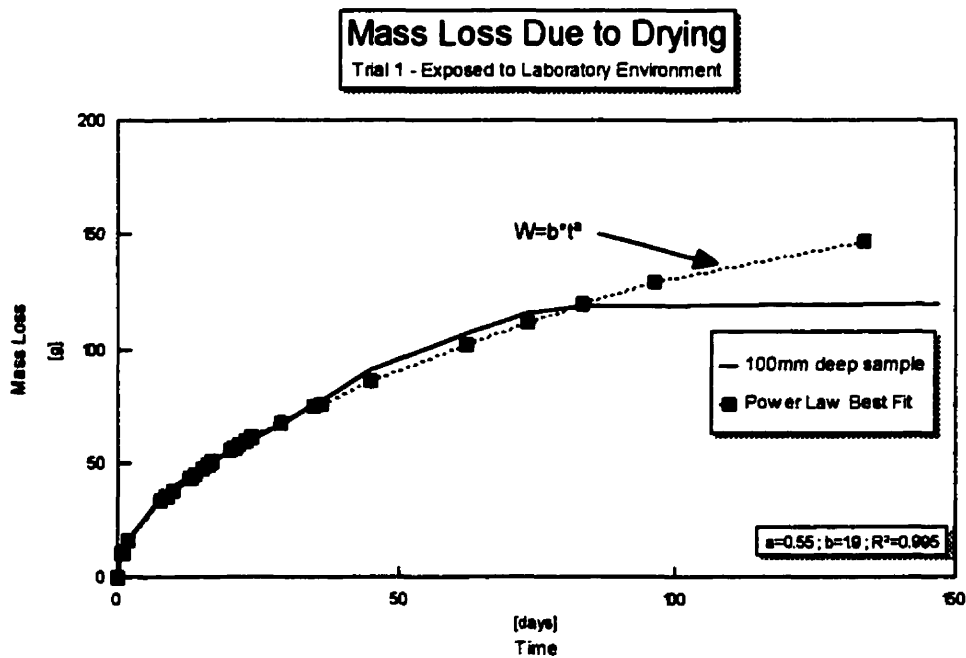


Figure 12 - Plot of moisture loss on drying versus time for first test.

	Trial	
	1	2
Temperature	21°C ±2°C	21°C ±2°C
Relative Humidity	30% - 60%	75%
a	0.55	0.67
b	1.90	8.40
R ²	0.995	0.997

Table 11 - Power law coefficients describing results from rate of drying tests

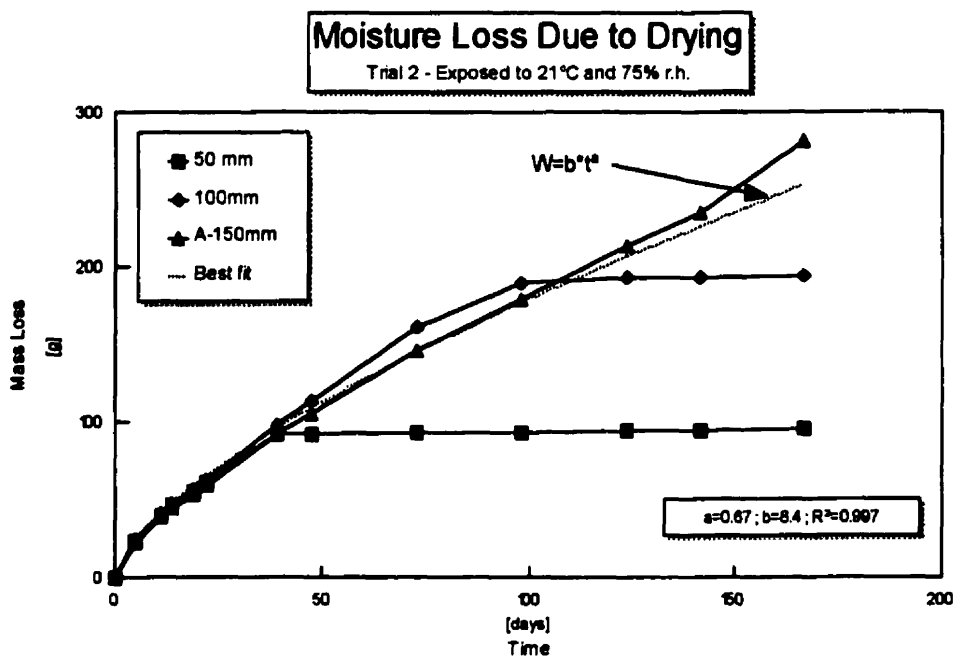


Figure 13 - Plot of moisture loss on drying versus time for second test.

While an attempt was made in this test to approximate one dimensional flow, cracks due to drying, which occurred at the top edge of the specimens, created another path for drying to occur. Thus, the results describe a situation where drying would occur more quickly than in a true one-dimensional case; when the material is on the wall of a basement, one-dimensional drying would predominate if no cracks formed in the barrier. If cracks due to drying shrinkage were to form on the basement wall, the rate of drying might be similar to the test results.

These test results indicate that the barrier system dries rather slowly. If the system was left without being backfilled, nearly six weeks would be required for complete drying of a 50 mm layer. In comparison, more than three months would be required for complete drying of a 100 mm layer of the barrier system. While solar radiation and wind would increase the rate of drying, further study of the influence of these factors would be needed to determine the full impact of these effects. The slow drying of the barrier material has a benefit; the moisture needed for biodegradation can be held by the barrier material for a considerable length of time. This would ensure the continuation of the degradation process even during short periods of drought.

3.3.3 Rate of Biodegradation

It is desirable that the binder lose its cohesive strength soon after the basement is backfilled to ensure that the self healing qualities of the sand are realized. It is reasonable to believe that the binder's strength would be reduced as it degrades. The purpose of these tests was to obtain an estimate of the rate of degradation of the starch binder while part of the sand mixture.

These tests were run before the paste was adapted with the addition of nutrients. Thus, the rates are likely conservative. Also, the seed used to inoculate these specimens was not as aggressive as it could have been. Of the bacteria present, only 0.54% were capable of hydrolysing starch (Horsnell 1996a). The report containing these results can be found in Appendix C.

3.3.3.1 Method

When starch decays, CO₂ is one of the end-products produced. It has been observed that the amount of CO₂ liberated during degradation may be as much as 86% of the original amount of starch by mass (Vogt and Staffeldt 1975). Thus, the extent of degradation was measured using loss in mass, due to the off-gassing of CO₂, as a surrogate indicator. The mass lost was corrected for change in moisture content. The remaining loss of mass would be due to liberation of CO₂ or other gases and volatiles. However, CO₂ and other gaseous by-products are only some of the final products of degradation as indicated in the discussion in Chapter 2. The non-volatile degradation products may include polysaccharides and increased biomass. Comprehensive measurement of degradation activity is beyond the scope of this thesis. While the rates of degradation obtained are not definitive, they do provide useful estimates of the rate of degradation.

The first set of tests consisted of the paste/sand mixture compacted into three 150 mm deep by 150 mm diameter cylinders having 1 mm mesh screen bottoms. These samples were kept above water in a closed container at 23°C.

The next series of tests used a set of eight specimens. Each set contained three samples measuring 60 mm x 60 mm x 40 mm deep. These eight specimens were initially made to investigate loss of strength due to degradation of the starch binder. The testing was to be done in a direct shear testing machine, but transferring the specimens to the machine caused excessive disturbance to the test samples. The remaining seven specimens were then kept and used to monitor the rate of degradation. Sample 1 was kept over water at 16°C while the others were kept over water at 30°C. All specimens were inoculated with the seed mentioned above, except for sample 7, which was not inoculated.

3.3.3.2 Results

The results, corrected for change in moisture content, are summarized in Figures 14 and 15. Figure 14 demonstrates the mass lost over time for the three cylinders tested. It is worth noting that the sample receiving the washes with tap water, sample C, demonstrated increased mass loss. Some of the spikes occurring in the curve can be easily explained; it takes some time for the wash water to drain from the

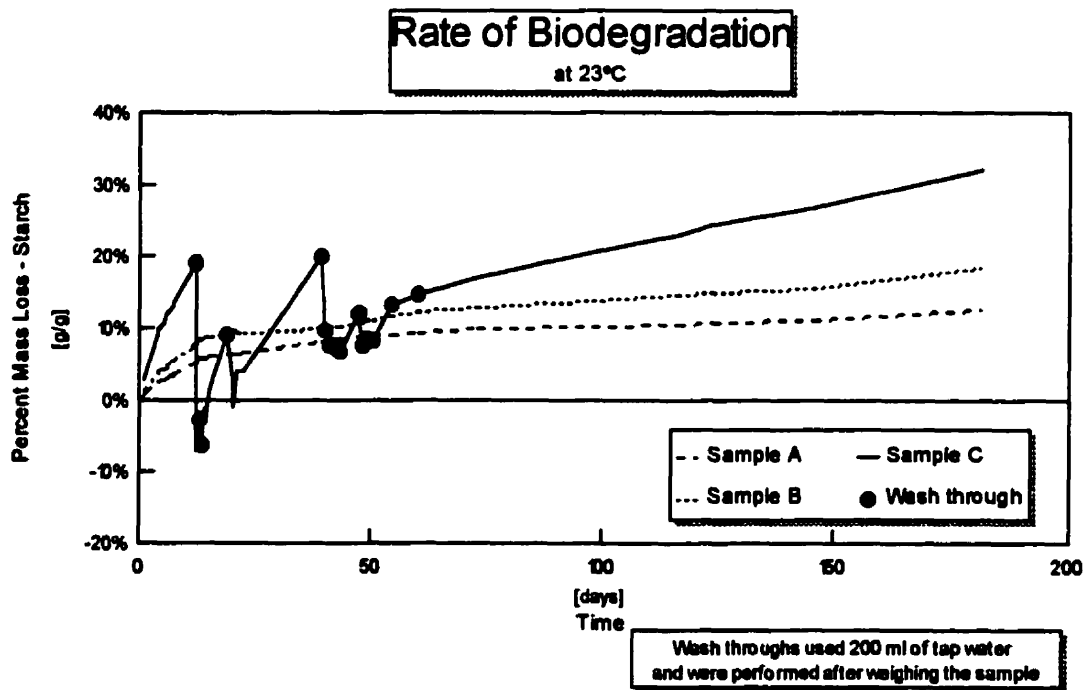


Figure 14 - Mass loss due to biodegradation over time - first trial.

sample therefore increasing its moisture content temporarily. However, one curious trend occurs at about the fiftieth day of the test. At fifty days, the amount of mass lost remained below its former value for a period longer than the time that would be required to return the sample to its equilibrium moisture content. One explanation for this observation might be due to an increase in biomass at this stage in the degradation process. Such an increase would also explain the later increased rate of degradation relative to the other samples.

Figure 15 plots the mass lost by the second set of tests. Six of the seven specimens were inoculated with a weak microbial seed. The seventh specimen was not inoculated; thus, only organisms present already in the sand, the corn starch, or the air were available for starch degradation. This absence of any inoculum is significant. The first specimen was kept at 16°C while the others were maintained at 30°C. The difference in temperature did not seem to significantly affect the rate of mass loss contrary to what was expected. It is significant to note however, that inoculation of the samples was seen to markedly increase the rate of degradation.

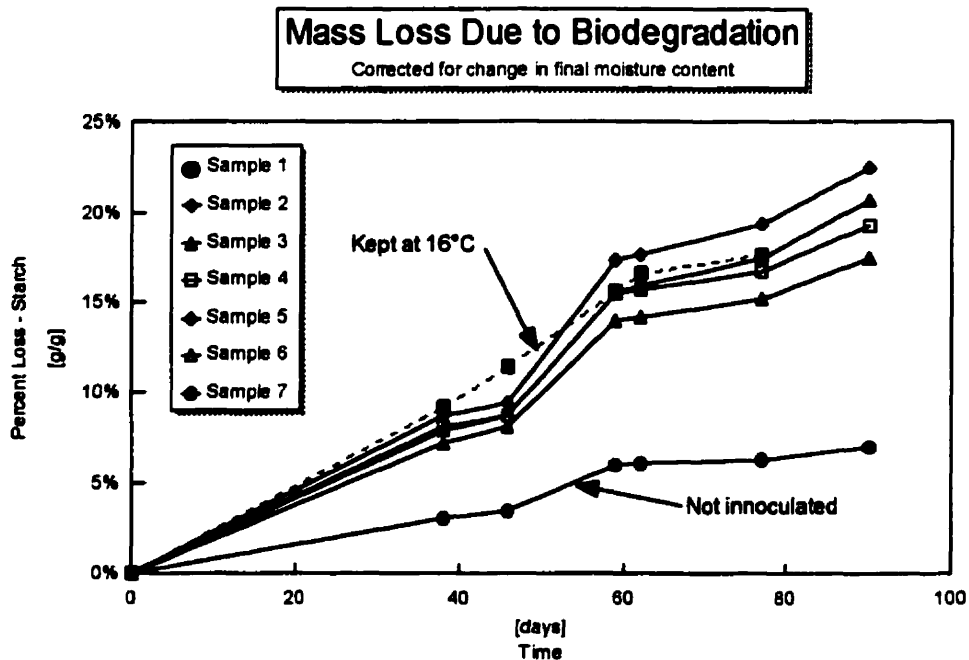


Figure 15 - Mass loss due to biodegradation over time - second trial.

3.3.4 Strength

One of the key parameters required to ensure the efficacy of the termite barrier is the quick loss of cohesive strength within the barrier material. A qualitative test was run to determine the length of time required until a crack could not be supported in the barrier material. In addition, two separate trials performed on samples incubated at 16°C and 30°C, measured strength loss with time.

3.3.4.1 Method

The qualitative strength test used the same square molds that were used in the biodegradation tests, measuring 60 mm x 60 mm by 40 mm deep. The test was conducted to determine the length of time required for the barrier material to lose the strength required to support itself vertically. Barrier material was compacted into the two end sections and one side removed leaving a vertical face of material. The sample was kept in a container over water, at ambient laboratory temperature, and washed with 1 mM of nutrient broth at day 22 and day 40. Bulging of the sides of the sample was observed after 4 days and a crack developed in the bulge after 7 days of testing. By day 13, a piece of the barrier material had spalled off from one end and after the washing at day 40, the end sloughed off from the rest of the specimen as pictured in Figure 16.

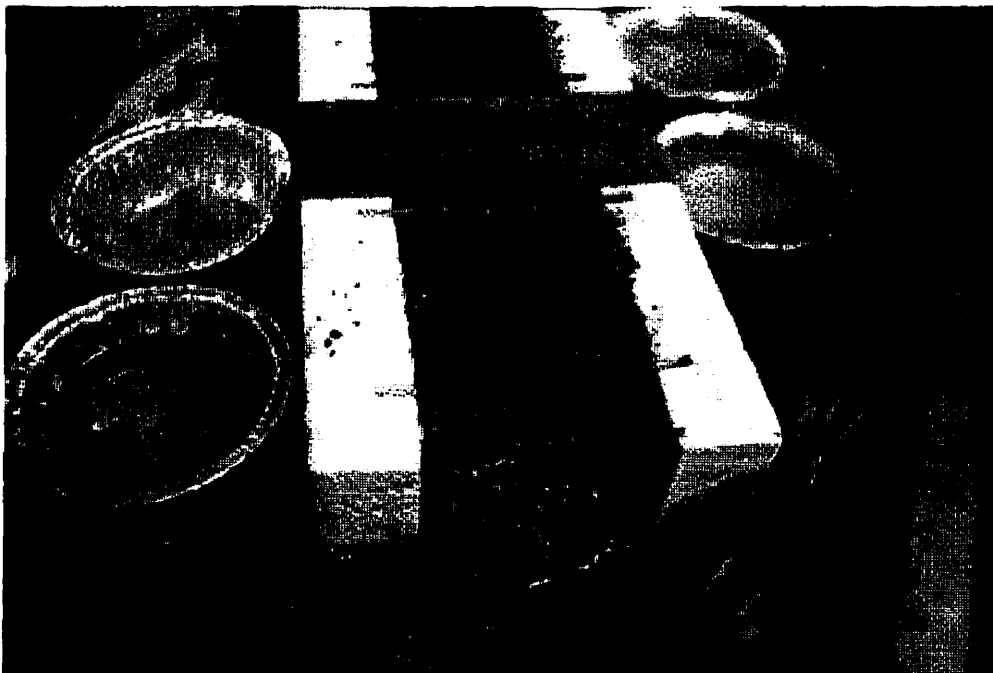


Figure 16 - Final state of qualitative strength test at 40 days.

In the quantitative tests, strength was determined by uniaxial compression tests using the machine pictured in Figure 17. Two sets of specimens were each tested over a period of 60 days. Each specimen was 50 mm in diameter and 100 mm high.

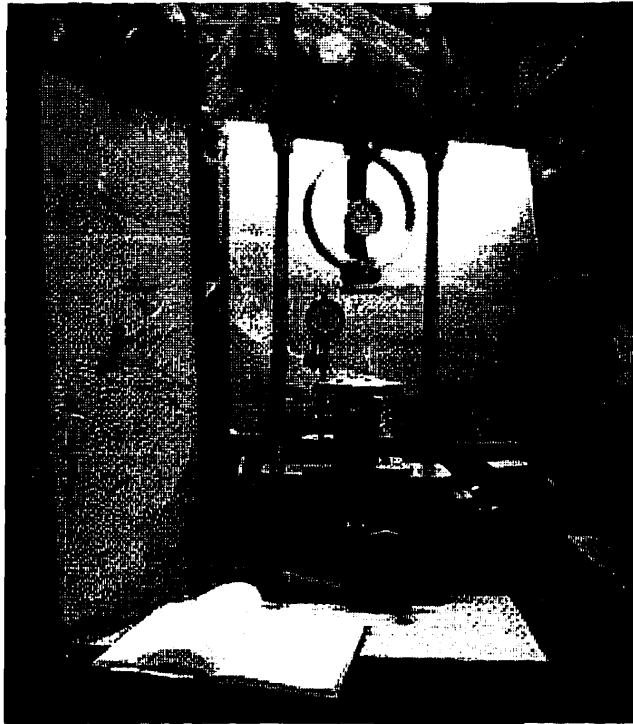


Figure 17 - Uniaxial compression testing machine used in strength determinations.

The first set of specimens were compacted in a split mold lined with fibreglass mesh having 1 mm by 2mm rectangular openings. Once the specimen was compacted, the mold was opened and the sample carefully removed. Split bands were slid around the specimen to hold the mesh in place. In this first set of tests, the paste used was made from tap water. In addition, these samples were inoculated with the mild inoculum mentioned above. This first set was placed in a sealed container suspended over water and kept at 30°C until testing.

The second set of samples was made using the paste that had been modified with the addition of the nutrient broth described above. This second set was wrapped in polyethylene instead of the mesh. The polyethylene decreased the availability of oxygen to the specimens and maintained a higher moisture content in the specimens. This second set was also kept over water but was stored at 16°C, to more closely simulate the temperature that might be expected beneath the ground's surface. The inoculum used for this set was more potent than the one used for the first set of tests, and is described below.

The improved inoculum was cultured from a fresh sample of rich soil . The soil was mixed (10% soil by mass) with nutrient enriched paste and nutrient broth. This mixture was kept at room temperature (~21°C) for a few days until noticeable activity developed; bubbles, from the evolution of carbon dioxide, indicated the activity of microorganisms. A portion of this solution was then used and mixed with fresh nutrient broth and paste, and again incubated. After repeating this process about four times, some of the sample was taken, diluted with nutrient broth and used as the inoculum for the second set of strength tests.

For both sets, the initial weight of each sample was recorded and specimens were weighed periodically as testing proceeded. In the second set of tests, the samples were held above the water by a layer of sand. This strategy lead to difficulties since some of the sand attached itself to the bottoms of the samples making mass determinations for the samples inaccurate. The samples were tested periodically over the course of 60 days. After testing, the moisture content of the tested specimen was determined by drying to constant weight at 110°C.

3.3.4.2 Results

Fresh

Prior to the two sets of tests being run, samples of the same dimensions were made and tested as practice using the testing machine. These trial runs when combined with the fresh samples for the two sets of trials, demonstrated a relationship between the compacted density of the specimens and the strength measured. The results are plotted in Figure 18 along with the relationship that was derived from these results. This relationship was later used to predict the initial strength for the samples tested.

Strength Loss Due to Biodegradation

The results for strength loss tests require interpretation to determine the cohesive strength component, which is the quantity of interest. The result sought through these tests was the change in cohesive strength provided by the binder, over time. The uniaxial compressive tests do not measure cohesive strength directly, but yield the principle stresses defining the failure envelope. Knowing the principle stresses and the internal angle of friction of the sand, it is possible to determine the cohesive strength component of the samples tested.

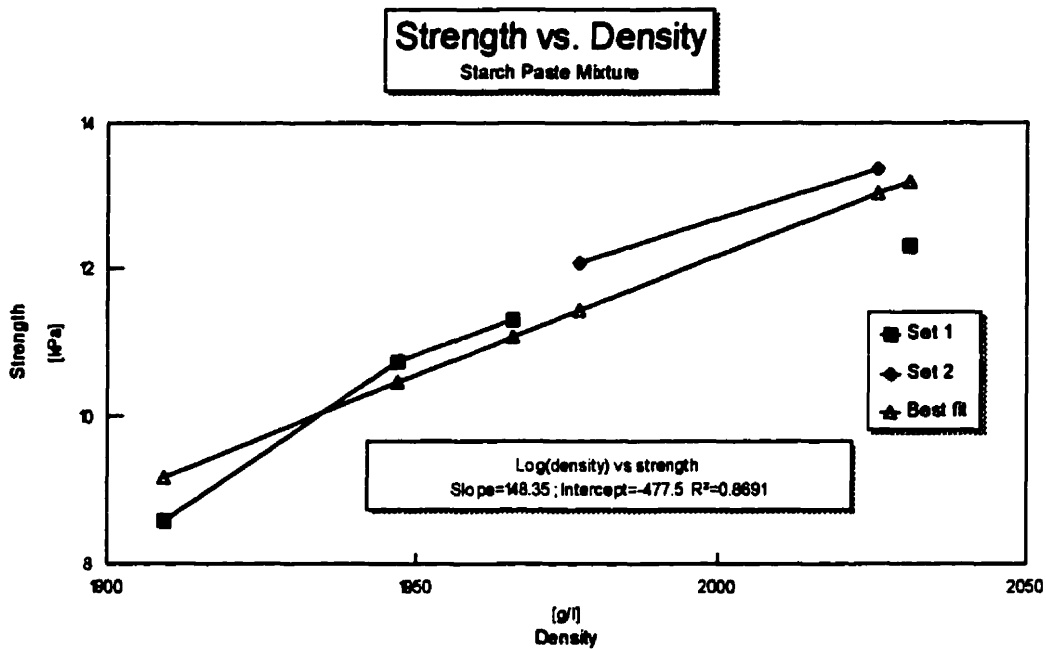


Figure 18 - Plot of fresh strength versus initial density.

The compressive strength of the samples consists of two elements, the frictional strength of the sand and the cohesive strength of the paste. The contribution from each component may be determined using Mohr's circle. Assuming the frictional strength of the sand remains constant, the cohesive strength may be determined by drawing a line tangent to the failure envelope. The angle that the tangent line makes

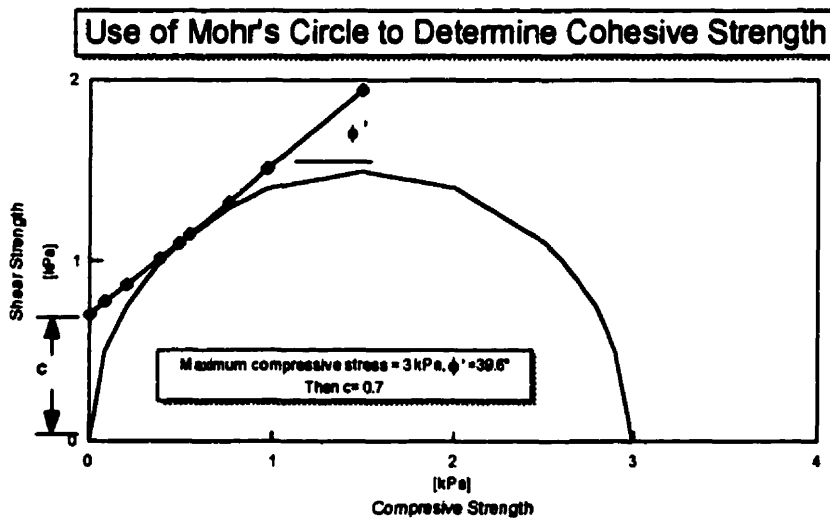


Figure 19 - Use of Mohr's circle to determine cohesive strength.

with the axis is the frictional angle of the sand. The intersection of the tangent line with the axis of zero compressive stress gives the value of cohesion provided by the paste as pictured in Figure 19.

The frictional angle of the sand was determined by direct shear tests on saturated sand; the results, summarized in Figure 20, showed the frictional angle to be 39.6° . Using the concept of Mohr's circle, the cohesive strength of the sand/paste mixture was determined assuming drained conditions. This assumption is based on the relatively porous nature of the sand mixture, suggesting that pore water pressures would be easily and quickly dissipated. The strength loss was determined by predicting the specimen's initial strength based on its initial density using the relationship described in Figure 18.

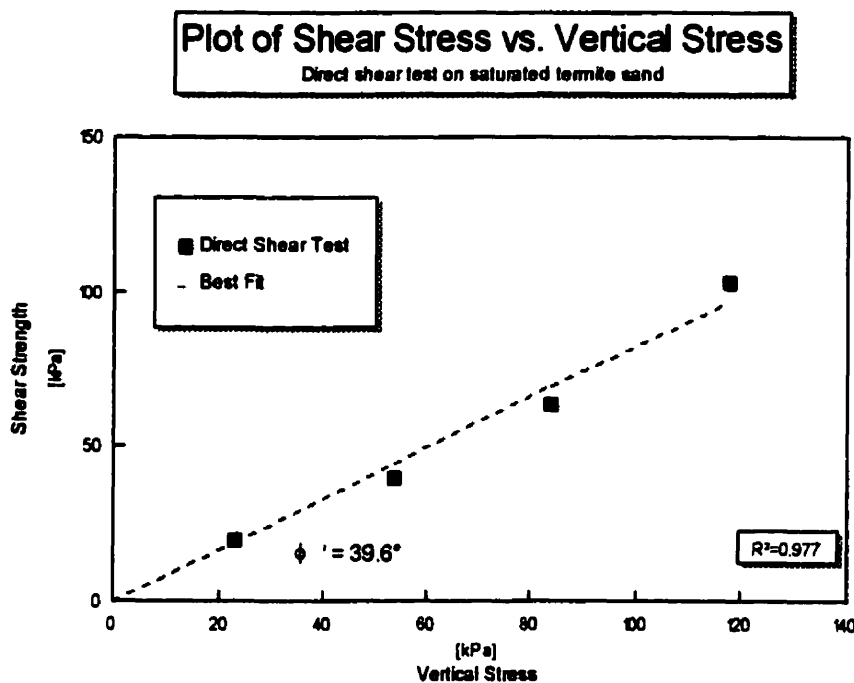


Figure 20 - Plot of vertical stress versus shear stress for direct shear tests.

Figure 21 shows the percent loss of starch with time for the 11 specimens of the first set tested at 30°C , while Figure 22 is the similar plot for the 10 specimens in the second set tested at 16°C .

To determine the percentage of starch lost, corrections were required due to the change in moisture content during the course of the test. The reason for the change in moisture content is likely due to the test set-up used in the first trial. Toward the end of testing in the first trial, moisture contents drifted downward from a relatively consistent 13.5% to 12.8% and finally to 7.6% in the last specimen. In the second set of tests, moisture contents remained consistently above 15%, which is attributable to the

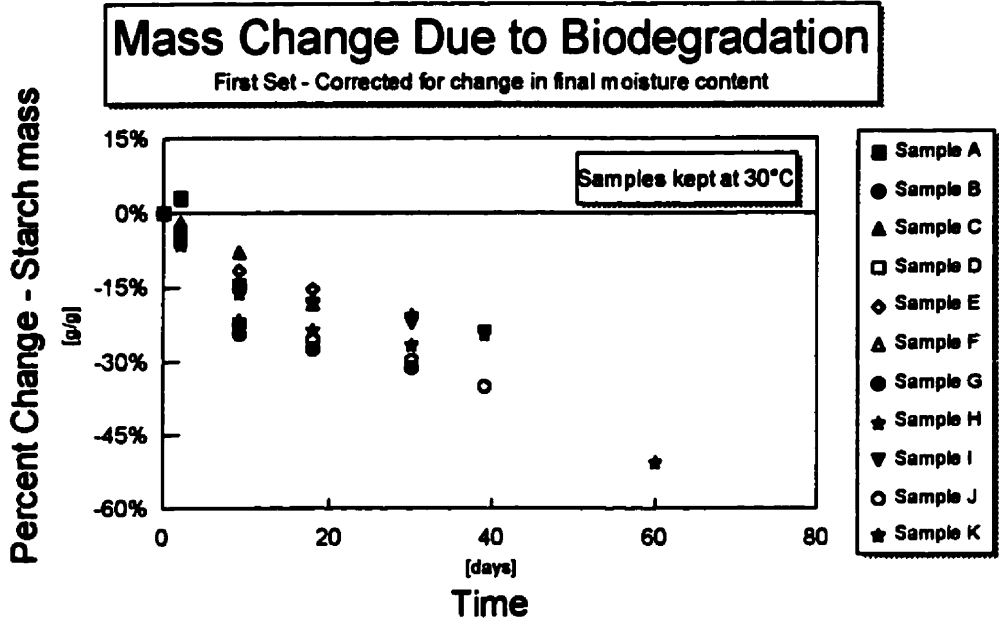


Figure 21 - Percent loss of starch over time for the first set.

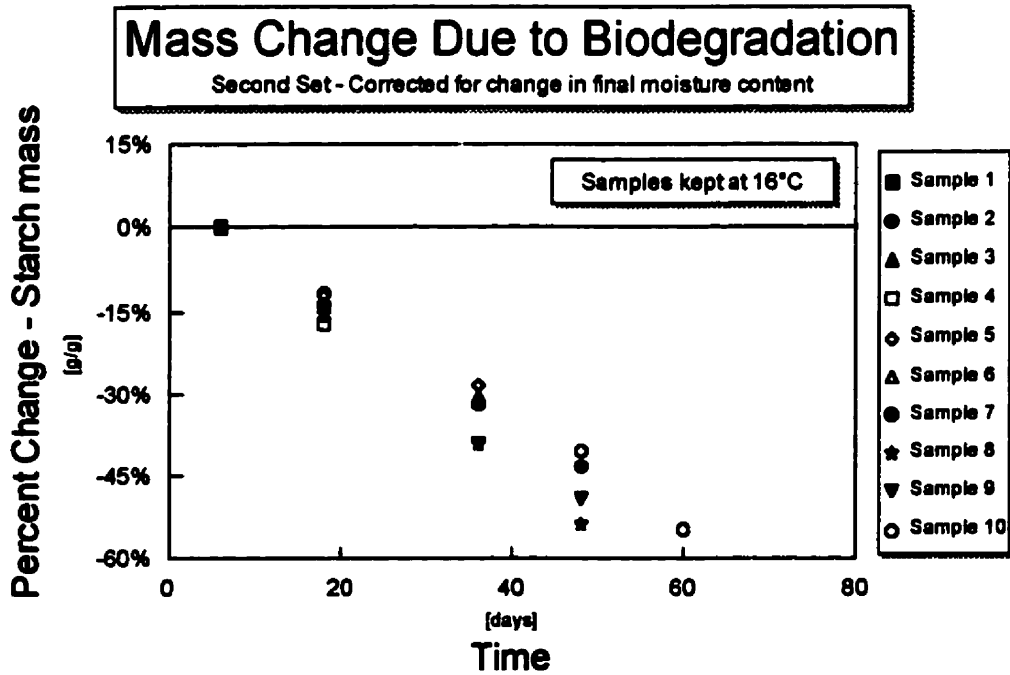


Figure 22 - Percent loss of starch over time for the second set.

samples being wrapped in polyethylene and the container being more air-tight than the one used in the first trials.

As a way of correcting the mass loss results, the moisture lost was deducted from the total mass lost. The resulting proportion of starch lost to total mass lost was assumed constant throughout the test and the intermediate results were scaled by the final proportion. This produced an approximation of the amount of starch lost at intermediate points during the testing based on overall changes in mass. The shortcomings of this approach are twofold. First, the assumption that the ratio of starch loss to water loss remaining constant seems reasonable but is not absolute. Second, there is doubt regarding the initial moisture content of the individual specimens. Moisture content samples were taken for each of the mixes prepared, but as seen in Figure 21, by the mass gain of sample A, which was in a closed system, the sample taken is not necessarily representative of the initial moisture contents of the individual specimens. Given these uncertainties, however, the figures do illustrate similar trends.

As mentioned earlier, the specimens in the second trial were initially placed directly on top of loose sand above water. This led to difficulties since some of the sand used for the base adhered to the bottoms of the specimens after being placed in the container. To counter this, mesh was placed over the sand to prevent further complications. As a way of correcting the results of the weight measurements, the weight of the specimens at the time of the first weighing was used as the initial weight. This is shown in Figure 22 and causes the recorded losses of starch to be lower than if the correction had not been necessary.

Comparing the two plots, it can be seen that there is greater variation among the specimens in the first set than in the second set. The increased variation may be attributable to the inoculum used for the first set. The inoculum had a low population of microorganisms, which decreases the likelihood that all specimens would be exposed to an aggressive starch hydrolyzing strain. The selectively cultivated organisms used to inoculate the second set of specimens would then account for the relatively more narrow band shown in Figure 22.

Figures 23 and 24 demonstrate the change in cohesive strength with time for the first and second trials respectively. Both sets reveal an increase in strength early on in the test. The most likely explanation for this trend is the retrogradation of the starch. As discussed previously, retrogradation is the increase in crystallinity of the starch molecules in the gel. This increased crystallinity causes a corresponding increase in the rigidity of the gel and would explain the observed trend. However, as degradation of the starch proceeds, strength loss follows. In Figure 24, the delay in strength loss is noticeably extended in

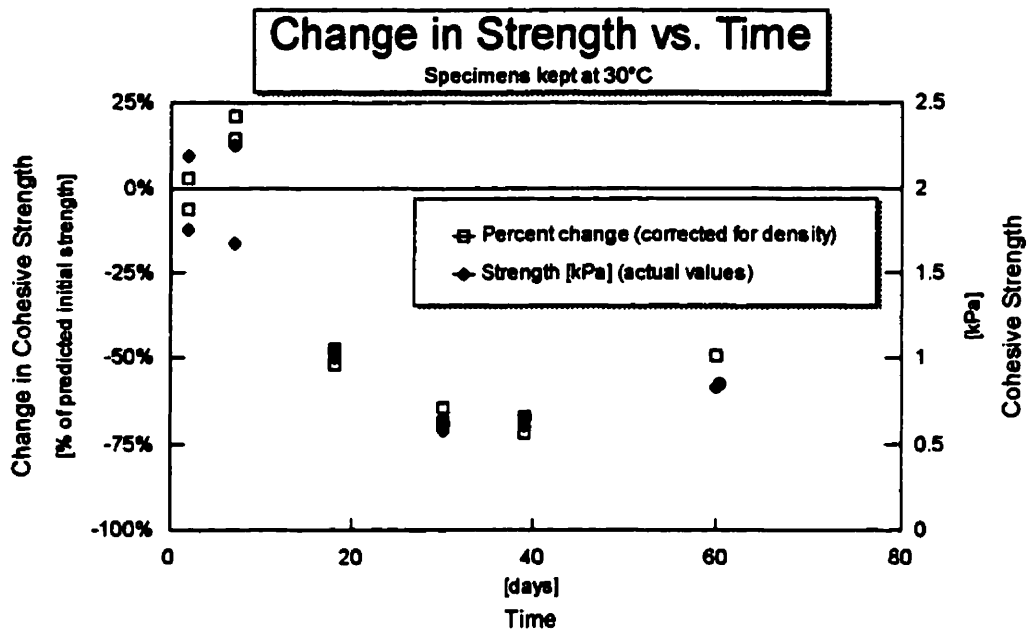


Figure 23 - Percent loss of strength over time for the first set. Strength was determined by uniaxial testing and the cohesive component then determined using Mohr's circle.

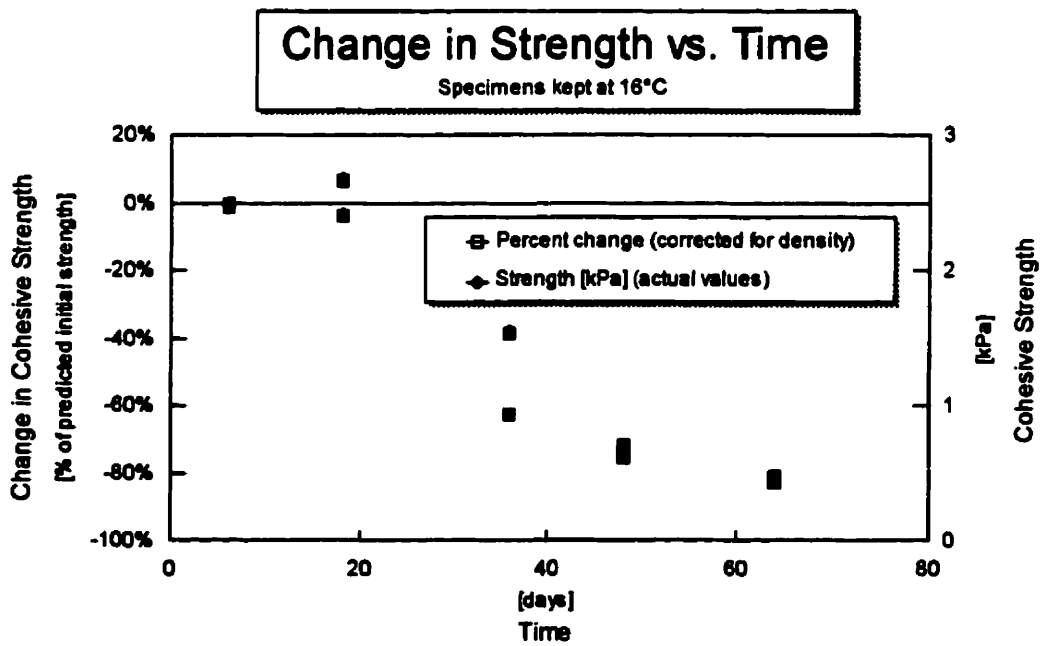


Figure 24 - Percent loss of strength over time for the second set. Strength was determined by uniaxial testing and the cohesive component then determined using Mohr's circle.

comparison to the length of delay shown by the first trial in Figure 23. The lower temperature is a reasonable explanation for the slower start shown by the second set. After 50 days though, the second set had lost strength to the same extent as was shown in the first set.

The seeming increase in strength shown at 60 days in Figure 23 is likely due to the low moisture content of the final specimen of the set, 7.6%, compared to 12.8% for the specimens tested at 40 days. Drying could account for the apparent increase in strength.

Figures 25 and 26 compare percent starch lost to percent strength lost. Again, the apparent gain in starch demonstrated in Figure 25 is attributable to the value of the initial moisture content used. Also, the scatter demonstrated in Figure 25 may be due to inconsistencies in the environmental conditions for the first set. The first set was kept in a container that was not as tightly sealed as the container used for the second set. While a fan was used to circulate the air in the container for the first set, the lack of tightness may have lead to relative humidities of less than saturation within the container. Thus, depending on the sample's position relative to the circulating air stream, the sample may not have been in a consistently saturated environment. This explanation is supported by the low moisture content measured in the final sample of

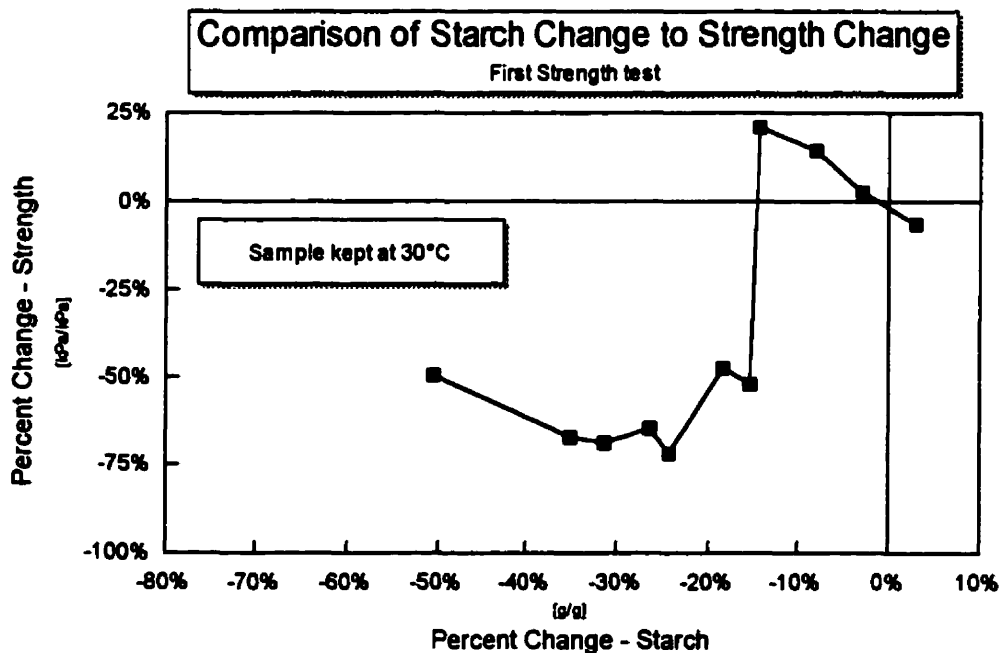


Figure 25 - Comparison of loss in starch to loss in strength for the first set.

the first set as noted above. Unsaturated environmental conditions would tend to dry the specimen, giving it greater strength.

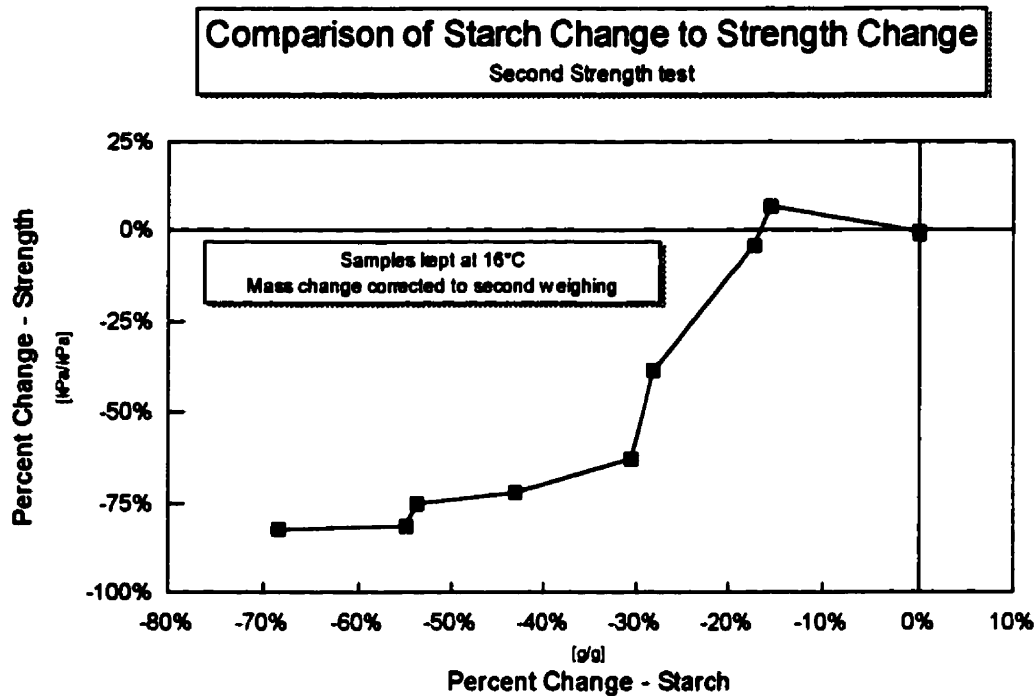


Figure 26 - Comparison of loss in starch to loss in strength for the second set.

3.4 Half-size Model

Scale often significantly affects the behaviour of materials. Small samples may be unrepresentative of the behaviour present in larger specimens. Defects present in a small specimen may be exaggerated by the effect of flaws. An example of this might be comparing the presence of a knot in a piece of lath board to the same knot in a plank. The strength of a lath board may be significantly reduced by a knot, while the same knot in a plank may have minimal impact. Conversely, large flaws are likely absent in small specimens. To use a similar comparison, knots are usually not found in toothpicks since the toothpick is too small to hold a knot. In this last case, the toothpick would be proportionately stronger than the board from which it was made. For this reason, a large scale test was done.

3.4.0.1 Method



Figure 27 - Application of the barrier material to the half-size wall.

Two concrete slabs measuring 600 mm square were joined together by dowels and mortar forming a small wall 1.2 m high. This wall was dampproofed with the solvent based asphalt compound used in the other tests and trials.

Initially an attempt was made to use a stucco sprayer to apply the sand/paste mixture. The lack of nozzle pressure and a nozzle opening that was too small, precluded effective use of the device. Therefore, the barrier was applied using the simulated shot-creting gun mentioned above.

Dampproofing of the wall was done a number of days before the test to ensure that it was dry. The 16 l of paste required, was prepared approximately 18 hours prior to testing. Immediately before application of

the material, the paste and sand were effectively mixed in a paddle-type concrete mixer. Shooting of the barrier was done in the middle of the day.

3.4.0.2 Results

Figure 27 shows the barrier being shot into place. The application of the barrier proceeded without problems initially. Once the barrier had been applied in a thick layer, a steel ruler was plunged into the barrier to measure the depth of material placed. Shooting proceeded and depth checks continued periodically.

At the point when the barrier material was almost uniformly 100 mm thick, a large section sloughed off from the middle of the wall. The failure is shown in Figures 28 and 29.

As can be seen in Figure 28, the failure occurred immediately below the point where the ruler had been used to measure depth. The probing of the ruler may have contributed to the failure by creating localized stresses in the displaced material. A further reason, and perhaps the more significant one that underlies the failure, is identified in the close-up photograph in Figure 29. Large glossy areas can be seen in a number of locations over the failure surface. This gloss is indicative of an adhesion failure at the interface between the barrier and the dampproofing. As discussed in the adhesion section of Chapter 2, the barrier system is a type of pressure sensitive adhesive. Since the dampproofing is the component providing the 'wetting', the paste binder must be brought into intimate contact with the dampproofing. Such intimate contact can only be practically accomplished with this system if the barrier material has sufficient velocity when it leaves the nozzle of the gun. It is presumed therefore, that the lack of sufficient air pressure supplied to the nozzle was the reason for the failure.

In addition to reducing the adhesion at the interface, the reduced pressure in the nozzle, and consequent low nozzle velocity, would have led to a reduction in the density of the barrier material placed. The reduced barrier density would result in decreased shear strength within the barrier, which is a relationship shown in Figure 18. This reduction in barrier strength would place greater reliance on the adhesive interface since the resistance to sloughing would be provided to a greater proportion by the cohesive component of the barrier. This is to say, that decreased density reduces the ability of the frictional resistance to carry the force that resists the tendency to slough; this is known as the active earth pressure in geomechanics. With a decrease in the frictional strength of the barrier, the active earth pressure must

be resisted and carried by the cohesive component, which is already poorly connected to the wall.

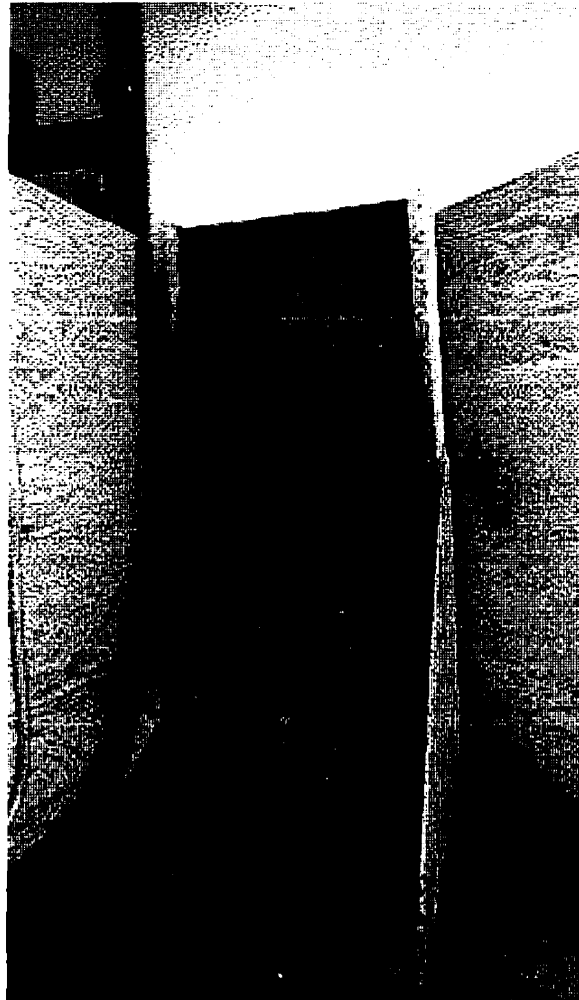


Figure 28 - Sloughing failure of barrier.

This failure demonstrates the importance of nozzle velocity to the success of the starch binder system. Nozzle velocity determines the amount of impact force exerted by the barrier particles when they hit the wall, creating the crucial wetting contact that is needed for adhesion. Nozzle velocity also determines the density of the barrier and consequently the barrier's initial strength. The greater the strength in the barrier material initially, the less reliance it must place on the adhesive interface to provide support.

In addition to increasing the nozzle velocity in the application of the barrier material, it may also be possible to increase adhesion by increasing the roughness of the interface. If sand particles were incorporated into the dampproofing, mechanical interlocking could occur at the adhesive interface. The

dampproofing itself would carry some of the shear of the interface, therefore reducing the total reliance on intrinsic adhesion to carry the shear. For such an approach to be effective, the dampproofing material would need to be capable of carrying this shear even when heated due to insolation. The thickness of the dampproofing layer is one factor affecting its shear strength, thus, a thick coating of dampproofing should be avoided. If increased nozzle velocity does not adequately resolve the difficulty of adhesion at the interface, the addition of sand to the dampproofing should be considered. Trials should be done using various sizes of sand particles to determine the optimal particle size that would create the highest degree of interlocking while at the same time minimizing the thickness of the dampproofing layer.



Figure 29 - Close-up of the failure surface.

3.5 Adhesion

Subsequent to the failure of the half-size model, a semi-qualitative investigation was done to compare the adhesion of the barrier material when applied under low nozzle velocities to that applied under high nozzle velocities

3.5.1 Method

The test method used sudden impact to create a shearing force between the block and the barrier material. In this way, both the adhesive interface and the matrix of the barrier material itself were tested simultaneously. The device used for this purpose consisted of a frame supporting two pulleys. For testing, the block was attached to a wire rope running over the pulleys. At the other end of the rope, a hanger was attached for supporting masses. Mass was added to the hanger until the block was balanced; the block neither rising nor falling under its own power. The block was then raised until the hanger rested on the floor. A piece of wood was placed underneath the block to absorb some of the impact. The height of the block above the wood was measured. Mass was removed from the hanger and the hanger was then quickly released, allowing the block on the other end of the rope to fall and impact against the wood. If no failure was noticed, more mass was removed from the hanger, the hanger was brought back to the floor, and the block again allowed to fall. This sequence was repeated until the barrier material became detached from the block.

Two concrete blocks were coated with dampproofing on one face and allowed to dry. The first block had barrier material applied mid-day when the available air supply energy supplied to the laboratory was low. This resulted in a low density sample of barrier material. The block was tested immediately after shooting to prevent the influence of any drying effects and minimize the effects due to retrogradation of the paste.

The second block had the barrier material applied in the evening when the available air supply energy was relatively higher. This resulted in a more densely placed barrier material that was also tested immediately following application.

3.5.2 Results

The weights and heights used along with the corresponding work provided to the block immediately prior to impact are summarized for each block in Table 12.

	Trial 1			Trial 2		
Energy of Air Supply	Low			High		
Impact	Mass	Height	Work	Mass	Height	Work
1	18.4 kg	135 mm	24.4 J	19.3 kg	127 mm	24.0 J
2	-	-	-	16.1 kg	172 mm	27.2 J
3	-	-	-	16.1 kg	172 mm	27.2 J
4	-	-	-	16.1 kg	172 mm	27.2 J

Table 12 - Summary of results from impact tests used to qualitatively compare adhesion.



Figure 30 - First block after first impact



Figure 31 - Second block after second impact



Figure 32 - Second block after third impact



Figure 33 - Second block after fourth impact

The final result of testing for the first block is shown in Figure 30. A picture of the second block after the second, third, and fourth impacts are shown in Figures 31 through 33.

For comparison of results, work was chosen as the measure of comparison because it represents the energy of the block immediately prior to impact. Since both blocks impacted upon the same piece of wood, the energy prior to impact is a reasonable quantity to use to compare results.

The first specimen, having the barrier material applied when the available air supply energy was lower, failed on the first impact as shown in Figure 30. In comparison, the second specimen, which had the barrier material applied when the available air supply energy was higher, showed no signs of damage after the first impact. The second impact for the second specimen caused a crack to form near the top of the block and a portion to dislodge from the bottom as shown in Figure 31. The result of the third impact on this second block, pictured in Figure 32, was an opening of the crack to about 4 mm in width. The fourth impact finally caused the ultimate failure of the barrier material shown in Figure 33.

Comparing the results of the two blocks, the effect of nozzle velocity or force used to place the barrier material is obvious. The first sample sustained only one impact at the low energy level. In contrast, the second specimen was able to sustain the same amount of energy without demonstrating any visible signs of damage. For the more densely placed specimen, three additional impacts at a higher energy level were required to cause a failure in the barrier material.

These observations confirm the hypothesis that this barrier material was acting as a pressure sensitive adhesive. Thus, if sufficient nozzle velocity is imparted to the barrier material by the shotcreting gun, the barrier material will be able to create the pressure needed to come into intimate contact with the dampproofed surface causing adhesion to occur. Also, the density of the barrier material is higher when increased nozzle pressure is used, resulting in an increase in the barrier's in situ strength.

These results also support the hypothesis explaining the failure of the mid-size test. The same half-size test should have been successful if shooting of the barrier material had occurred when the gun had been supplied with air of greater energy.

3.6 Summary

The series of laboratory investigations outlined above provide a number of insights into the behaviour and properties of the barrier material. A summary of some of these properties is shown in Table 13.

Property	Relationship Type	Constants
% starch loss - (g lost/ g starch)	$y=mx+b$	$m= 0.84\%/day$ to $0.63\%/day$ $b= 4.1\%$ to -3.7%
% Change in strength	$y=mx+b$	$m=-1.64\%/day$ to $-1.74\%/day$ $b=15.4\%$ to 2.2%
Rate of Drying	$W=bt^a$	$a=0.55$ to 0.67 $b=1.9$ to 8.4
Permeability	sand Barrier material - initial Barrier material - eventual	$k=3.0$ mm/sec to 5.3 mm/sec $k=0.13$ mm/sec to 3.2 mm/sec $k=0.35$ mm/sec to 0.52 mm/sec

Table 13 - Summary of barrier material properties.

The laboratory investigations provide a basic level of verification that the barrier material will perform as theoretically predicted in Chapter 2. To achieve a greater level of certainty about the feasibility of the barrier material and the efficacy of shotcreting, a full scale field trial needs to be performed. The next chapter will discuss the issues that a field test could resolve and outline details for such a test.

4 PROPOSED DEMONSTRATIONS

Theory suggests that the aggregate barrier system should work well, and the laboratory investigations support what theory suggests. There are still aspects of the system though that require demonstrations to prove that the system does indeed work. These demonstrations should occur in two stages. The first stage would be set of field studies to verify those aspects of the system that were not treated by the laboratory testing. The second stage would be the implementation of the system on a group of test homes, moving the system from the prototype stage, and demonstrating the viability of the system.

The field testing should focus on two aspects. First, the effectiveness of the system to act as a termite barrier should be verified. Secondly, the method of application should be refined. The house trials should show that the system could form an integral part of a broader basement design approach. Some design considerations for the implementation will be discussed below. Finally, a comparison of costs for different approaches is included.

4.1 Field Testing

The field test should demonstrate the following two aspects:

1. the ability of a standard shotcrete machine to efficiently place the barrier material; and,
2. the ability of the barrier system to exclude foraging termites from the basement in both a cracked and uncracked state.

4.1.1 Methods of Application

Two possible approaches for applying the barrier material need to be evaluated. Each of these approaches could be demonstrated within the same field trial. The first approach would use the same paste material as was used in the laboratory investigations; this paste, mixed with the sand, would then be applied using a dry-mix shotcrete machine. The second approach would create the paste as part of the application process; a partially uncooked starch slurry, combined with the sand, would be mixed with steam at the nozzle to complete the cooking of the starch.

For the first approach, preparation of the paste requires some additional planning. If the paste is to be made on-site, a kettle must be used that has specialized stirring equipment since the paste becomes

extremely viscous once it reaches the gelatinization temperature. In order to prevent burning, the paste must be stirred until gelatinization is complete. The cooked paste must then be transferred to a separate mixer to be incorporated into the termite sand. Once the barrier material is mixed, it would be transferred to the hopper of the shotcrete machine for application.

If the paste is prepared off-site, difficulties in the transporting and handling of the gelled binder would occur. The amount of binder required to install the barrier around a 10 m by 10 m by 2m high basement wall would be about 850 litres or almost 4 oil drums. This could make the installation of the barrier system undesirably labour intensive.

In the second approach, the gel would be made at the time of application, thereby avoiding some of the complications posed by the first approach. It is worth noting that this second method for preparing a starch paste was not found in the literature. The barrier material would be created in a series of steps. To start, a thin consistency 3% corn starch carrier paste, would be cooked on site. This thin paste could be pumped to a mixer where the remaining uncooked corn starch, approximately 21.25% by mass of the carrier, would be added and mixed with the sand. This partially cooked mixture would be fed to the hopper of the shotcrete machine. At the nozzle, pressurized steam would cook the remaining uncooked portion of the corn starch to complete the binder. If the layer of slurry coating the sand is thin, and the temperature of the steam is high, the rate of gelatinization would be increased (Lepoutre and Inoue 1993). Turbulent mixing within the nozzle should assist in the uniform gelatinization of the paste. The proportions of the corn starch in each fraction are an adaptation of a TAPPI "carrier type" recipe (Lepoutre and Inoue 1993).

Should it prove to be successful, this second approach would have a number of advantages over the first method. The binder could be easily made on-site in the amounts required using more standardized equipment, i.e. a standard kettle and steam generator. The production of the barrier material would be less labour intensive since there would be no handling of the binder.

In these application trials, the influence of adding sand to the dampproofing layer should also be studied. As mentioned earlier, sand incorporated within the dampproofing would increase the roughness of the dampproofing surface, allowing some mechanical interlocking to occur within the dampproofing/starch paste interface. This interlocking would enhance the adhesion of the barrier system to the dampproofed layer. A caution, mentioned above, regarding the addition of sand to the dampproofing should be reiterated. If sand is added to the dampproofing, the mechanical interlocking will transfer more of the

shear force to the damproofing layer. If the damproofing layer is too thick, the damproofing layer itself may experience a shear failure, particularly if the damproofing is heated due to insolation.

4.1.2 Termite barrier verification

The termite barrier aspect of the system would also benefit from a demonstration of performance. While the sand used in the barrier system is known to act as a termite barrier, this ability should be verified when combined with the binder. Two separate functions should be tested. First, the barrier should demonstrate its ability to prevent foraging through the interstices of the sand. Second, the ability of the barrier system to prevent foraging along the sand/wall interface, as well as interfaces between service connections and the sand, should be verified. A possible test method is outlined below.

The test site should be chosen in an area of known termite activity. Stakes made of white pine could be located throughout the test area to determine areas of termite activity (Grace 1989). For the tests, a 300 mm wide by 600 mm deep by about 1.7 m long trench should be excavated in an area determined to have significant termite activity. Testing done in this manner would be similar to the exposure methods used in Australia for demonstrating the effectiveness of stainless steel mesh as a termite barrier (Lenz and Runko 1994).

A series of four test panels, measuring 300 mm by 300 mm and 12 mm thick should be made from decaying ship-lapped white pine. One of the panels could be used to verify the ability of the barrier system itself to prevent the passage of termites. Two other panels could be used to study the effect of a gap or crack occurring in the barrier. These two panels could be covered with sheet metal leaving a vertical 10 mm strip of exposed pine board. This gap in the sheet metal would be offset by a vertical gap in the barrier material of either 50 mm or 100 mm. The last of these panels could demonstrate the effectiveness of the barrier system around service connections that penetrate the barrier. Capped pipes of the size of water and sewage connections could be glued to the pine panels at locations offset from one side of the panel to the other. The panels should be shot with barrier material to a thickness of 50 mm on one side and 100 mm on the opposite side, then lowered into the trench. Prior to backfilling the trench, a layer of kraft paper or cardboard should be placed on each side of the coated panels to further encourage termite activity. The arrangement of these panels can be seen in Figure 34. Once the backfill has reached the top of the panels, a 100 mm layer of barrier sand should be placed over the trench to ensure the panels are attacked from the barrier face. A layer of fencing, or other material could then be placed over the sand

to avoid disturbance due to the digging of dogs as was encountered by Myles (Myles 1994b). Finally, the backfilling could be completed, filling the trench.

The effectiveness of the barrier sand to protect service connections penetrating the floor slab can also be demonstrated in this test. Sealed pipes could be pushed into the floor of the testing trench and barrier sand placed around the pipes. A piece of decaying white pine could be placed around the pipes and then another layer of barrier sand used to cover the pipe and pine board. This arrangement is also shown in Figure 34.

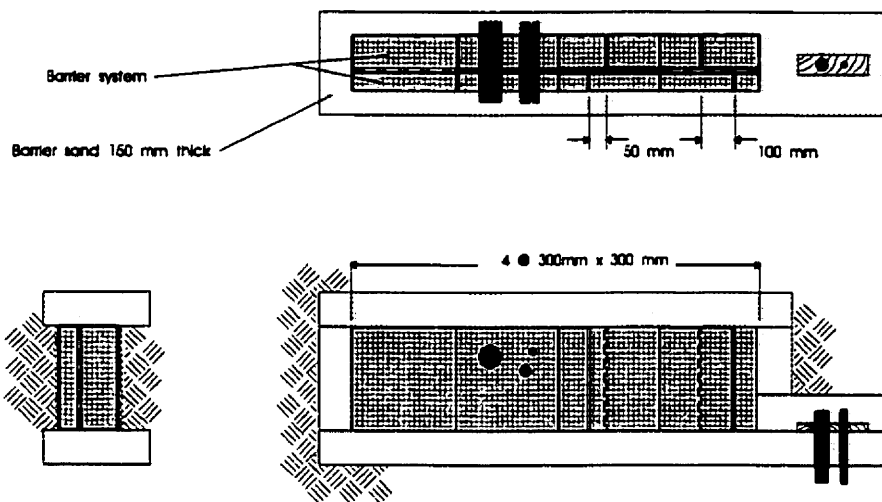


Figure 34 - Arrangement of panels for proposed field test.

After a year of exposure, the test site could be carefully excavated and the various panels visually inspected for signs of termite attack. Once all monitoring results have been obtained, the data should be carefully examined to ensure consistency with the predicted behaviour. Any difficulties should be resolved before further development proceeds.

4.2 House Trials

If the field tests clearly demonstrate the effectiveness of the barrier material, trials on residential housing should proceed. In this second phase, ease of implementation and the effect on construction sequencing should be demonstrated.

It may be possible to incorporate exterior insulation into the barrier system. Exterior insulation of the basement is the preferred approach since it keeps the basement wall warm, reducing the condensation difficulties encountered with a cold basement wall (Timusk et al 1995).

Other arrangements of exterior insulation may be possible, but attention should be paid to ensuring:

1. The insulation is not short-circuited by seepage of ground water;
2. Foraging at the basement wall is prevented; and,
3. No alternate routes of possible entry by termites into the structure are provided by the above-ground details.

The first requirement can be satisfied by placing the drainage layer on the outer side of the insulation. Satisfying the second requirement places a contradictory condition on the system, requiring the barrier material to be placed next to the basement wall. Finally, the third requirement may be resolved with the use of appropriate flashing details.

One method of implementing exterior insulation that satisfies all three requirements could involve sandwiching the insulation between layers of barrier material. The outer layer of barrier material would act as a drainage layer, while the inner layer would serve as a second line of defence, preventing foraging along the basement wall in the event of a breach in the outer barrier. The insulation could be installed by impaling it on anchors adhered to the basement wall.

4.3 Cost

Cost is a significant consideration in the housing industry. Increased building cost is undesirable since it may decrease the number of sales for builders and decrease affordability for consumers.

A comparison of some options for providing a drainage layer and termite protection is shown in Table 14.

Approach	Cost
Termicide treatments - per application, reapplied every 5 yrs.	\$1,200
DrainClad - 19 mm mineral fibre insulation	\$730
Hand backfilling with termite barrier sand - 100 mm layer	\$2,100
Backfilling whole excavation with termite barrier sand	\$6,000
Proposed Barrier System - 50 mm layer	\$1,400
- 100 mm layer	\$1,900

Note: Estimates based on a 10 m by 10 m house with a basement wall 2 m high.

Table 14 - Comparison of costs for various drainage layers and termite protection measures.

4.4 Summary

The field and house demonstrations should verify the effectiveness of the barrier system. In addition, if the cost of the system were to remain within the estimates given above, its use would certainly make economic sense in termite prone areas because the added cost would be returned to the owner simply by avoiding the need for a single treatment of termicide. Refinements made to the application procedure may help to reduce the cost of installation, thereby further enhancing its appeal as a building system.

These final demonstrations, if successful, will establish the effectiveness and viability of the barrier system as a solution to the problems posed by termites and water leakage.

5 CONCLUSIONS & RECOMMENDATIONS

5.1 Conclusions

Two significant problems that can afflict basements are water leakage and termite infestations. Both of these problems can be costly to repair or control after the basement has been built. A solution to these problems that uses a uniform sand and corn starch binder to provide a combination drainage layer and termite barrier has been outlined in this thesis. This barrier material can be easily installed by shotcreting it into place.

The sand of the barrier material has a demonstrated ability to exclude the foraging of termites. The sand also possesses desirable characteristics as a filter and drainage layer. The sand would successfully protect all but the very finest of silty or dispersive clay soils and has a draining ability sufficient to prevent hydrostatic pressure from existing against the foundation wall.

Under laboratory conditions, the binder for the barrier material used to aid in the installation of the barrier, was found to lose over 80% of its initial strength within 2 months. Also, the products of degradation were seen to be innocuous and normally occurring within the soil. This binder is a form of pressure sensitive adhesive and was successful in adhering the barrier material to the wall if the material was applied with sufficient force.

While further demonstrations are needed to develop this prototype into an implementable product, the system appears to be a feasible preventative measure to combat the problems of basement water leakage and termite infestation.

5.2 Recommendations for further research

1. A full size test should be done to demonstrate the effectiveness of this barrier system and uncover and resolve any unforeseen difficulties.
2. Further permeability studies on the barrier material are advisable. These studies should investigate the influences that the following factors have on permeability of the barrier material: density of the placed material; biodegradation with time using tap water and distilled water; and,

exposure to various distributions of silt sizes and the potential for clogging. Also, side inflow tests should be done on the material to determine compliance with CCMC requirements.

- 3. Further refinement to the composition of the binder material may enhance the rate of degradation in the soil environment. Investigations into the culturing of bacteria best suited to degrading the binder should be done and a method developed for selecting native organisms for use in each region where the barrier material may be used.**
- 4. Further study should address the delivery or application of the material. Adaptations to existing shotcrete technology may ease the use of the system. Methods that are able to produce the binder continuously on site should receive particular attention.**
- 5. The impact on site work scheduling should be investigated to optimize the sequencing of processes in house construction.**
- 6. Investigations into the response of the barrier material to imposed strains, due to settlement of the basement wall, should be done. These studies should examine the change in porosity in response to the applied strain and the strain required to allow passage of termites through the interstices of the sand. This study should also be done for different stages of starch degradation.**

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Appendix A

Listing of wax binders investigated

Trials for various wax formulations.

Batch ID	Formulation	Adhesion	Tack	Consistency	Drying/Setting rate
727B	20% wax 2281	excellent	none - all sand rebounded		moderate-slow
728	20 % wax 5714	"	high	shot in clumps	good
729A	20% wax 5818	"	good		
729B	19% wax 2281 7.5% wax 5714	"	more sand adhered		
729C	20% wax 5714	"	high	good	good
729D	20% wax 2281	"	as before		
804	5% wax 2281 15% wax 5818	"	good	low rebound	good

Notes:

Percentages are per mass of barrier material mixed. If two waxes were used in a trial they were weighed out and mixed in a molted state prior to combining with the sand.

Wax 2281 - Crude scale wax.

Wax 5714 - High molecular weight microcrystalline wax.

Wax 5818 - Moderate molecular weight microcrystalline wax.

All waxes were provided courtesy of IGI International Waxes Ltd

Appendix B

Listing of Corn Starch Binders Investigated

Trials for various corn starch formulations. Hydroxyethylcellulose is included in these trials as a possible gel-forming substance.

Batch ID	Formulation	Adhesion	Tack	Consistency	Drying/Setting rate
628A	2% HEC	poor	low	thick/plastic	slow
628B	4% KOH 20 % CS			thick	
629A	2%KOH 20% CS				
629B	30% CS in 40g tepid water added to 30g water at 100°C	marginal*	moderate	good	
629C	20% CS with cellulose	good*	good	good	
629D	10% HEC with cellulose	marginal*		thick gel	slow
705A	10% Found'n Coat (by mass sand)	good	poor - thin	sloppy	still drying days after application
705B	30% CS 50% hot water 50% tepid water	poor	low		
705C	As in 705B with mineral spirits added	worse than in 705B			
705D	30% CS 1.5% borax	good	moderate	good	moderate
706A	10% CS 1% borax 3.6% HEC 1.5% NaCl	only if block prepasted	poor		
706B	15% CS 1% borax 3.4% HEC 0.5% NaCl	poor			
708A	30% CS 1.5% borax 0.75% NaCl 0.1% soap				
708B	13% CS 8.7% borax 4.3% NaCl	good if prepasted	moderate	very thick	slow

Batch ID	Formulation	Adhesion	Tack	Consistency	Drying/Setting rate
712A	30% CS 0.75% CaCl ₂			slurry	
712A-2	22g 10% KOH added to 200 g slurry	poor		thin gel	
712A-3	added 1.5g borax	moderate	moderate	thick	
712B	30% CS 10% CaCl ₂ 1.5% borax			slurry	
712C	30% CS 5% CaCl ₂ 10% MgCl ₂			slurry	
713A	20% CS 4% KOH 4% borax			rubbery mass	
713B	15% CS 1% KOH			Gravy-like sol	
713C	15% CS 1% KOH borax			rubbery mass	
715A	16% CS 2% KOH 2% borax			slurry	
715B	20% CS 3% KOH 2% borax	Moderate	High rebound	moderate	
719A	20% CS 2.8% KOH 3.2% borax			curdled	
719B	20% CS 5.6% KOH	moderate	low rebound		moderate
720A	25% CS	good†	little rebound best if in thin layers		
720B	Large batch of A	good†			
721A	20% CS 20% flour	moderate†	poor - sloughed after 10 min.		

Batch ID	Formulation	Adhesion	Tack	Consistency	Drying/Setting rate
725A	20% CS 5.8% NaCl	moderate†		forms slurry - salt must be added after gelling	better than in 720A
725B-1	as above				
725B-2	as above mixed with 2% gypsum	moderate†			better than B-1
726A	20% CS 1% HCl	moderate†	good	good	skins quickly - better than 720A
726B	as in A 7.2% NaCl				moderate
726C	as in A 7.2% NaCl 5% gypsum			thick	moderate
726D	as in A 4% borax sprayed over surface				best - dry to touch in 1 hr.
727A	15% pregel Duragel™	none	only when dry		
803A	20% CS 1% HCl	moderate†			
803B	as in A 6% borax sprayed	moderate†			good
803C	20% CS 5.6% KOH 6% borax	moderate†		turns to rubbery mass	
803D	as in C no borax	moderate†			

Notes:

Percentages are per mass of liquid.

*- applied to bare concrete block

† - soap applied to dampproofing layer prior to shooting

For trials with KOH or Duragel no cooking was involved. Also, no cooking was involved in batches 712B, and 712C.

CS - Purified food powder corn starch

KOH - Potassium Hydroxide

Borax - $\text{Na}_2\text{B}_4\text{O}_7 \cdot 10\text{H}_2\text{O}$

CaCl_2 - Calcium chloride

NaCl - Sodium chloride

MgCl_2 - Magnesium chloride

flour - bleached white all purpose wheat flour

gypsum - depapered pulverized wall board

HCl - hydrochloric acid

Appendix C

REPORT

DETECTION AND CHARACTERIZATION OF STARCH HYDROLYSING BACTERIA IN A SAND-STARCH PASTE DEVELOPED TO ACT AS A TERMITE BARRIER.

Prepared by;
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April 3, 1996

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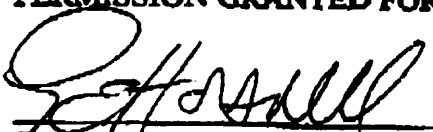
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DETECTION AND CHARACTERIZATION OF STARCH HYDROLYSING BACTERIA IN A SAND-STARCH PASTE DEVELOPED TO ACT AS A TERMITE BARRIER.

INTRODUCTION:

Many bacteria, which require an organic source of carbon for growth (heterotrophic), have the ability to produce the enzyme amylase to hydrolyse starch. Amylase may be excreted from the cells into the surrounding environment. This provides a mechanism by which starch may be broken down into glucose which can be shunted into the cells and utilised as a source of energy during metabolism. Aerobic, anaerobic and facultatively anaerobic bacteria are included in this group. Bacteria capable of starch hydrolysis include species of the following genera;

- | | |
|-------------------|-----------------|
| * Actinomyces | Fusobacterium |
| Aeromonas | Gardinerella |
| * Bacillus | Gemella |
| Bacteriodes | Lactobacillus |
| * Clostridium | * Pseudomonas |
| * Corynebacterium | Streptobacillus |
| Eikenella | * Streptococcus |
| * Flavobacterium | Vibrio |

- * May be isolated from soil. The remainder are unlikely to be isolated from soil, although Aeromonas species are common in surface water and tap water.

In addition, certain fungi are also capable of starch hydrolysis.

A paste consisting of a mixture of sand, starch and water has recently been developed at the University of Toronto. In theory, the paste can be applied to the exterior foundation of a building. When the excavation is backfilled, bacteria from the soil should hydrolyse the starch causing the sand to become permeable to water for good drainage while leaving the sand in place to provide a barrier against termite invasion.

A sample of paste, inoculated with soil, was provided to the Ministry of Environment and Energy, Laboratory Services Branch, Microbiology Unit for analysis.

PURPOSE:

The analyses were designed to;

- 1) isolate, from the paste, any heterotrophic bacteria capable of growing in air and capable of hydrolysing starch,

- 2) characterize and identify those bacterial strains capable of hydrolysing starch.

METHODS:

An agar culture medium (mHPC agar), typically used to recover heterotrophic bacteria from water, was modified. The pH indicator (bromocresol purple) was removed and soluble starch was added to the formulation at a 2% concentration.

One gram (gm) of termite barrier paste was aseptically transferred to a dilution blank containing 99 millilitres (mL) of sterile, phosphate buffered water. The suspension was homogenized and dilutions of the suspension were prepared by transferring 11 mL of the original suspension to a second 99 ml dilution blank, 11 mL from the second to a third dilution blank and so on. Amounts of 0.1 ml from the original suspension and each dilution were spread over the surface of separate culture plates containing the starch culture medium in an attempt to obtain bacterial growth which would produce in the range of 20 - 100 colonies on a plate from one of the dilutions. Duplicate culture plates were prepared from the original suspension and each dilution.

One set of culture plates was incubated aerobically at 35°C. The second set of culture plates was incubated aerobically at room temperature (approximately 22°C). The culture plates were observed each day over a period of two weeks for evidence of clear zones (starch hydrolysis) around or under any of the bacterial colonies growing on an otherwise opaque agar.

A small amount of growth from each unique bacterial colony type showing evidence of starch hydrolysis was transferred aseptically to a fresh starch agar plate and streaked for purity. Pure cultures of bacteria capable of starch hydrolysis were subjected to a series of tests to characterize and identify the bacterial strains.

In addition, the count of bacteria capable of starch hydrolysis and the total bacterial count per gram of paste were calculated.

RESULTS:

Table 1 presents the bacterial counts per gram of material. Table 2 presents the reactions of bacteria capable of starch hydrolysis and their identification.

Very few bacteria capable of starch hydrolysis were detected using the method outlined. Recovery rates of bacteria capable of starch hydrolysis ranged from 0.027% (room temperature) to

0.54% (35°C) of the total aerobic, heterotrophic bacterial population per gram. Hydrolysis occurred more rapidly at the higher temperature. Only 3 colony types were observed among those capable of starch hydrolysis. Further tests revealed that these were representative of only 2 genera. Not all strains hydrolysed starch equally well. Starch hydrolysis ranged from moderate to good based upon the size of the zone of clearing around the colonies and the degree of clearing.

All of the bacterial strains isolated, which were capable of starch hydrolysis, were gram positive. Due to limitations in the ability of the laboratory to identify gram positive bacteria, the bacteria capable of starch hydrolysis could only be identified to genus level. Four bacterial strains were tested. Three of the four strains were species of the genus Bacillus. Two of these strains appeared to be identical species (type 1). Both strains had moderate but slightly different abilities to hydrolyse starch. The third strain was a different species of Bacillus (type 2) but it was the best starch hydrolyser. It revealed a very clear, 2-3 millimetre zone of hydrolysis in the agar around its colonies. The fourth bacterial strain could only be categorized as being a member of a group of bacteria referred to as the Actinomycetes. It had moderate ability to hydrolyse starch.

All of these strains could hydrolyse starch at both temperatures but all performed better at 35°C. Hydrolysis took about 3 days at 35°C but took 7 days or longer at room temperature. Those bacteria with moderate ability to hydrolyse starch revealed hydrolysis only directly underneath the growth. They did not produce a zone of hydrolysis extending sideways into the agar beyond the colonies.

CONCLUSIONS:

Analysis revealed that bacteria capable of starch hydrolysis were present in the termite barrier paste submitted. The low recovery rate and limited variation in the types of bacteria which were isolated and able to hydrolyse starch, may have occurred for the following reasons. Recovery was limited by the aerobic incubation technique to only aerobic and facultatively anaerobic bacteria. Strictly anaerobic bacteria (e.g. Clostridium species) could not grow. The type of soil used for inoculation of the paste may have had a limited initial bacterial population. The age of the material used to inoculate the paste and bacterial competition for nutrients may have caused a reduction in the variation of bacterial types. Bacteria capable of producing spores (e.g. Bacillus spp. and Actinomycetes) would have had a better chance to survive any adverse conditions.

Many starch hydrolysing fungi and bacteria, including

Actinomycetes and Bacillus species (spp.), may be found in soils throughout the world. Therefore, it would appear feasible that the system will work in a field trial situation regardless of location. However, soils will likely differ in the levels and types of starch hydrolysing bacteria. Therefore, to ensure that sufficient levels of bacteria able to hydrolyse starch are present and that hydrolysis will proceed at some optimum rate, it may be prudent to consider spraying a light mist of a liquid suspension containing spores of bacteria, known to hydrolyse starch effectively, over the paste before the soil is backfilled into the trench around the foundation.

Table 1: Bacterial Counts Per Gram of Termite Barrier Paste			
35°C, 3 days		Room Temperature (22°C), 7 days	
Total	Starch +	Total	Starch +
370,000	2000	370,000	100

Table 2: Characterization of Bacteria Capable of Starch Hydrolysis Isolated from Termite Barrier Paste							
Isolate	Colony Type	Gram	Cell Shape	Cell Arrangement	Spores	Motile	Tentative Identification
1	Round Rough	+	Rod	Chains	Yes	Yes	<u>Bacillus</u> spp. (type 1)
2	Round Rough	+	Rod	Chains	Yes	Yes	<u>Bacillus</u> spp. (type 1)
3	Round Smooth	+	Rod	Chains	Yes	Yes	<u>Bacillus</u> spp. (type 2)
4	Round Hard Compact	+	Filamentous		Not Seen	No	Actinomycete

Ability to hydrolyse starch;

Bacillus species, type 1 - moderate

Bacillus species, type 2 - good

Actinomycete - moderate