

# **EARTHBAG HOUSING: STRUCTURAL BEHAVIOUR AND APPLICABILITY IN DEVELOPING COUNTRIES**

by

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A thesis submitted to the Department of Civil Engineering

In conformity with the requirements for  
the degree of Master of Science in Engineering

Queen's University

Kingston, Ontario, Canada

September, 2008

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## **Abstract**

Global awareness of environmental issues such as climate change and resource depletion has grown dramatically in recent years. As a result, there has been a surge of interest in developing alternative building techniques and materials which are capable of meeting our structural needs with lower energy and material consumption. These technologies are particularly attractive for housing. Much of the global demand for housing is currently being driven by economic growth in developing countries. Additionally, natural disasters such as the 2004 Indian Ocean tsunami have destroyed houses in many countries where limited economic wealth makes reconstruction a challenge. This has resulted in shortages of permanent housing in these areas.

This thesis explores the structural behaviour of earthbag housing under vertical compressive loading, in an attempt to broaden our quantitative understanding of this alternative building technique. Furthermore, this technique is assessed, along with other alternative construction techniques, for suitability in southern Sri Lanka, an area heavily damaged by the 2004 Indian Ocean tsunami.

It was determined that the compressive strength of unplastered earthbag housing specimens meets or exceeds the vertical compressive strength of conventional stud-frame housing technology using a variety of fill materials, with the greatest strength being observed for soil-filled bags.

Furthermore, the results of observational research from a site visit to Sri Lanka in 2006, combined with resource availability data and interviews with Sri Lankan citizens, suggest that earthbag housing is a very promising technique for housing construction in the southern coastal region.

## **Acknowledgements**

I would like to thank my supervisors, Dr. Kevin Hall and Dr. Colin MacDougall, for their help throughout my time as a graduate student. They provided a great deal of insight, support, encouragement, and an almost frightening amount of freedom, all of which was greatly appreciated.

The RESTORE Project partners were incredibly helpful in teaching me the realities of international development, as well as the finer points of the situation in post-tsunami Sri Lanka. In particular, Dr. Jana Janakiram (University of Guelph) and Dr. Brent Doberstein (University of Waterloo) were both very helpful.

The Civil Engineering department technical staff was also very helpful. In particular, Paul Thrasher and Dave Tryon were instrumental in getting the earthbag specimens fabricated and tested. I would also like to thank Steve Vardy for being a wealth of information on everything from straw bale houses to data acquisition.

I was very fortunate to have had the help of a number of research assistants, including Heather Munro, Jasper Boychuk, and Tommy Perley (whose inexhaustible work ethic helped keep the earthbag tests on track through their final days).

I would also like to thank the many great people at Queen's currently engaged in the discussion of humanitarian engineering, whose insights have greatly broadened my perspective on the issue.

Finally, I would like to thank my family, whose love and support has made my education possible.

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# **Chapter 1**

## **Introduction**

In recent years, environmental degradation has emerged as one of the most significant challenges facing global civilization. There are several drivers of this degradation, including greenhouse gas emissions due to fossil fuel consumption for energy and transportation (IPCC, 2007), and depletion of natural resources (Gordon et al., 2006). The construction industry accounts for a large portion of total global consumption (Roodman & Lenssen, 1994). This consumption has been estimated to be 50% of global material use, and 40% of global energy use (Price Waterhouse Cooper, 2008). Growth in this consumption is tied directly to global economic growth. Additionally, the current state of the world economy is such that growth in developing nations, especially in Asia, is driving global growth for the first time in modern history (Callen, 2007).

Economic growth can be beneficial in that it provides the means to develop and implement cleaner, more efficient technologies. Unfortunately, economic growth in developing countries is often initially pursued at the expense of the environment, until a point is reached where the accumulated wealth of a nation makes the implementation of more environmentally benign technologies feasible (Grossman & Krueger, 1995). Since many of the countries driving global economic growth have not yet reached this point, it is clear that there is significant potential for improvement of industrial practices in these countries.

Housing is a key component of the construction industry, and sustainable housing technologies have already experienced a surge of interest in developed nations such as

Canada and the United States. Exploration of techniques such as straw bale housing, bamboo, and earthen construction has led to improvements in understanding of material behaviour and construction practices, as discussed in Chapter 2.

These construction techniques are very well suited to application in developing countries for several reasons. First, they are all based on earthen materials which do not require significant industrial processing. This allows houses to be built with much less strain on global energy and resource supplies. Second, they all rely on materials which are locally available in a large majority of regions around the world, minimizing energy use due to transportation. Third, they are generally low- or intermediate-technology solutions which do not require specialized machinery or expertise to construct, and can be erected quickly when compared to conventional housing techniques.

These factors not only make alternative construction technologies attractive for developing countries in general, but also make them particularly well suited to post-disaster reconstruction, where access to conventional materials may be limited, as discussed in Chapter 3. The 2004 Indian Ocean tsunami damaged or destroyed hundreds of thousands of houses in countries such as India, Thailand and Sri Lanka. Reconstruction efforts have replaced some housing, but many residents of these countries were forced to live in temporary housing for several years after the disaster. Quickly erected, structurally sound housing, fabricated using alternative construction techniques and materials, may have the potential to avoid situations like these in the future.

Perhaps the biggest obstacles to widespread implementation of these alternative construction techniques are a lack of quantitative knowledge of structural performance,

and a lack of public awareness and acceptance. With this in mind, this thesis has three main objectives.

The first objective of this thesis is to gain insight into the compressive behaviour of earthbag housing through an experimental study of unplastered earthbag specimens fabricated with a variety of fill types, stack heights and bag sizes. In particular, the compressive behaviour of gravel-filled specimens are examined due to their suitability for use in below-grade applications (i.e. foundations), where their lack of fine particles makes them more resistant to moisture-related expansion and contraction, as discussed in Chapter 4. Soil is also investigated as a fill material due to its suitability for above-grade exposure conditions.

The second objective of this thesis is to develop the practice of earthbag testing. No standardized testing methodologies currently exist for earthbags. Such standardization will be necessary if earthbag housing is to be studied in a quantitative manner. The testing methodologies used in this thesis are based on existing standards for conventional materials such as masonry blocks, but these standards do not fully cover the preparation and testing of earthbag specimens. New practices have been developed where necessary, and have been based on accepted field practice for earthbag construction wherever possible. A discussion of these practices, and suggestions for further improvement of the practice of earthbag testing, is discussed in Chapter 7.

The third objective of this thesis is to investigate the state of post-tsunami housing in southern Sri Lanka in terms of existing building stock, material availability, and public

opinion in order to determine the suitability of alternative construction techniques for this area.

Chapter 2 presents a review of existing literature on the behaviour of alternative construction techniques, with a specific focus on straw bale, earthen and bamboo structural systems. This chapter focuses on structural performance in terms of strength, as well as resistance to the effects of several exposure conditions such as fire, earthquake and moisture damage. Furthermore, each construction technique is discussed with respect to ease of construction and material availability.

Chapter 3 presents the results of a field investigation of the state of housing in southern Sri Lanka, as well as some proceedings of the RESTORE Project, a collaborative post-tsunami reconstruction project incorporating both Canadian and Sri Lankan universities. Additionally, this chapter discusses some general opportunities and challenges for humanitarian engineering projects in the context of conflict, which were identified by the author's experience with the RESTORE Project.

Chapter 4 presents a detailed description of the test program and methodology used to examine the compressive behaviour of unplastered earthbag specimens. In addition, it outlines the details and methodology of the ancillary tests used to determine the material properties of the granular fill and polypropylene bags used to fabricate the earthbag specimens.

Chapter 5 presents the results of the test program outlined in Chapter 4. In addition, it presents a quantitative analysis of the effects of fill type, bag size and stack height as parameters affecting the compressive behaviour of earthbag housing.

Chapter 6 presents a discussion of the results of the earthbag testing program in the context of both alternative and conventional construction techniques. Additionally, it synthesizes the results of the earthbag testing program with the observations made in Chapter 3 to present an analysis of the suitability of straw bale, earthen and bamboo construction for use in post-tsunami reconstruction in southern Sri Lanka.

Chapter 7 presents the overall conclusions of this thesis with respect to the structural behaviour of earthbag housing, as well as the general suitability of alternative construction techniques for use in developing countries. This chapter also presents a discussion of potential areas for future investigation of the structural behaviour of the earthbag housing system.

In this thesis, “alternative construction techniques and materials” refers specifically to construction techniques which are suitable for one- or two-storey house structures, and which generally require fewer raw materials and less energy to fabricate than structures built with conventional construction techniques and materials such as timber frame, masonry, concrete and steel.

## **Chapter 2**

### **Literature Review**

The global trend towards increased environmental awareness has resulted in a surge of interest in ecologically friendly building materials and techniques. There is a wide variety of such materials and techniques, many of which have been used for hundreds of years with strong anecdotal performance records. The major advantages of these materials and techniques over conventional materials typically include a low embodied energy (often leading to reduced embodied greenhouse gas emissions), ease of construction, widespread availability and low cost. These properties make alternative housing technologies attractive not only for housing in the North American market, but also for use in humanitarian engineering projects in developing countries.

Humanitarian engineering is a broad term generally used to describe a school of thought, as opposed to a conventional engineering discipline. Many definitions of humanitarian engineering exist. It can be described as a philosophy which attempts to “balance technical excellence, economic feasibility, ethical maturity, and cultural sensitivity” (Colorado School of Mines, 2005). Alternatively, humanitarian engineering may be thought of as the practice of applying “science, mathematics and engineering skills for the purpose of improving the welfare of the less advantaged and to meet the needs of development” (Miller, 2008, p. 138). The underlying goal of humanitarian engineering is to increase equality and living standards worldwide, across all levels of income.

A desire for equality and high living standards around the world is a natural result of the innate human senses of empathy and justice. Despite the self-evident importance of humanitarian engineering, decades of attempts at eliminating poverty, inequity and low standards of living through international development projects have frequently been unsuccessful in achieving their stated goals (Hillman, 2000; Brooks, 2002). It should therefore be an explicit goal of any humanitarian engineering project not only to meet the short-term goals of the project (for example, building housing units, or supplying fresh water), but also to ensure that the benefits of the project can be sustained well after the project itself is complete. Some of the issues which complicate the task of ensuring long-term success of humanitarian engineering projects are discussed in Chapter 3.

The wide variety of alternative building materials and techniques (which will be discussed in more detail below) suggests that there will likely be many humanitarian engineering projects in which they might be useful. However, the very same magnitude of different materials and techniques that makes them flexible and applicable in many different situations can also confuse matters. With so many choices, and in light of the social challenges of humanitarian engineering projects, how is an engineer to choose the best possible option? This thesis will present a discussion of some of the most common alternative building materials and techniques, as well as the current state of knowledge with respect to their performance in structural applications. This basis of knowledge can then be used as a platform for considering the applicability of various alternative construction techniques for developing countries in a more informed manner, which will further be discussed in Chapter 6.

There is an extremely wide variety of alternative construction materials and techniques which are currently, or have been historically, used around the world. This paper will focus specifically on some of the most common of these materials, due to their popularity as well as the volume of research available on their behaviour. Natural materials such as earthbags, straw bales, rammed earth, clay brick (i.e. adobe) and bamboo have been some of the most popular alternative building materials due to their relatively high performance in structural applications and broad availability. There may also be benefits in terms of embodied energy, as discussed in Section 6.2. However, significant interest in studying natural building materials and techniques from a quantitative, research-based perspective has emerged only recently, and there are still significant gaps in the understanding of the behaviour of these materials in structural applications. Of these materials, earthbags have been discussed the least in engineering research literature, and as such there are many unanswered questions about the structural performance of earthbags, and how this performance varies with a number of parameters such as fill type, bag size and bag type.

The following section will outline the current state of knowledge with respect to the alternative construction materials mentioned above. Since humanitarian engineering projects are implemented across a broad spectrum of locations and cultures, it is useful to consider many construction technologies, as this increases the likelihood of finding a design solution to a given project which closely matches the objectives of environmental, social and economic sustainability.

## **2.1 Earthbag Construction**

Earthbag housing is a simple form of earth-based construction wherein large bags are filled with granular material, compacted and laid horizontally in a running bond to form the core of a wall system. Polypropylene bags are currently favoured by the earthbag building community for their strength, resistance to decay, and affordability, but natural materials such as burlap have also been used. Barbed wire is typically laid in between each course of earthbags to provide shear strength, as the friction between successive courses of bags is low, especially when polypropylene bags are used. After a wall is completely stacked, a plaster skin is applied to both the interior and exterior wall surfaces, to a thickness of several centimetres. This skin consists of several layers of varying composition, which can be either earth-, lime- or cement-based plasters (Hunter & Kiffmeyer, 2004). The purpose of the plaster skin is to protect the earthbags from environmental degradation, as well as to add strength and stiffness to the wall system. Some test structures have also been built using unplastered soil-filled cotton hoses (Minke, 2006), and though this test program did not use the term “earthbag”, the basic principles of the construction technique are largely identical to earthbag construction.

Bag size can vary, depending on manufacturer and builder preference, but the most common size for housing construction is approximately 457 mm wide and 762 mm long (nominally specified as 18”X30”). This particular size is sometimes colloquially known as a “50 Pound Bag” (Hunter & Kiffmeyer, 2004). This size has been accepted by the earthbag community as having an optimal balance of strength and workability, based

on construction experience. Bags are also available in larger dimensions such as 508 mm X 914 mm and 635 mm X 1016 mm.

Since soil composition can vary significantly from one site to another, there is some question about how the properties of earthbag structures vary with changes in the composition of bag fill. Soil particles are typically divided into clay, silt and sand based on particle diameter and composition. There are several different classification systems, but the Unified Soil Classification System is widely accepted, and is used for testing by the American Society for Testing and Materials. According to the Unified Soil Classification System (USCS), silt and clay particles are those with diameters less than 0.075mm, sand particles have diameters between 0.075 and 4.75 mm, and gravel particles have diameters between 4.75 and 76.2 mm (Das, 2005). This system does not differentiate silt and clay particles based on diameter, but rather on the minerals which make up the particles. Silt particles are generally quartz-based, whereas clay minerals are made up of complex aluminum silicates (Das, 2005). For all types of earthen construction, the fraction of soil made up of clay particles is particularly important since clay acts as a binding agent. Higher clay content results in higher cohesion, since clay particles typically have a net negative charge that attracts positively charged particles to their surface (Das, 2005). However, clay also displays certain properties which are undesirable for earthen construction. Specifically, it has a tendency to swell and shrink with high or low moisture contents, respectively. The amount of volume change between a saturated and dry clay can be anywhere from 100% to 2000%, depending on the specific clay minerals present (Hunter & Kiffmeyer, 2004). This volumetric instability

suggests that there is some upper bound for clay content, beyond which increases in cohesiveness are outweighed by high instability. Currently, the accepted optimal range for clay content in earthbag soils is between 5% and 30% (Hunter & Kiffmeyer, 2004), though very little quantitative testing has been done to verify this range.

Particle size distribution is important for its effects on cohesion and stability (and subsequently compressive strength) as mentioned above, but there are also serviceability concerns associated with the particle size distribution curve of a particular soil. Specifically, the amount and rate of deflection of an earthbag wall under service loads is likely to be affected by the relative fractions of sand and clay particles. In aggregate, sand particles are much less compressible than clay particles, and they typically reach maximum compressive deformation quickly upon being loaded. Clays, on the other hand, tend to be highly compressible, and deform much slower than sands under load (Terzaghi, 1923). In a structural context, this means clay-rich soils have the potential to exhibit greater deformations due to long-term dead loads than soils with leaner clay fractions. An examination of the effects of particle size distribution on the service behaviour of earthbag structures has not yet been conducted in any formalized manner. In order to bring earthbag construction into the mainstream for both developing and developed contexts, knowledge of service state behaviour is critical, since housing residents typically demand durable structures with a minimum of cracks, and are not likely to have confidence in a technology with poorly understood long-term response to loading.

Earthbag housing is a promising technology for a number of reasons. The two most significant reasons in the context of this thesis are its low cost and low-tech nature. Both of these properties are crucial in ensuring applicability in a development context as developing nations have, in almost all cases, limited access to financial resources and skilled labour. Unfortunately, while anecdotal knowledge on earthbag construction has been well developed over the past thirty years, this has not been matched by efforts to study the material in a quantitative fashion consistent with other structural engineering materials. As such, the practice of earthbag construction is currently based on many “rules of thumb” and unsubstantiated best practices which, while well meaning, may not result in the safest, most efficient use of materials.

To date, laboratory testing of earthbag technology has been virtually nonexistent. In terms of compressive strength, no peer-reviewed studies have been published, though the results of one testing effort, an undergraduate research project conducted at West Point Military Academy, have been published online (Dunbar & Wipplinger, 2006). This report presents the results of a series of compressive tests using polypropylene bags of an unspecified size, and three different fill materials described by the author as sand, dirt and rubble. This report found the average strength of the sand, rubble and dirt filled bags to be 0.30 MPa, 0.40 MPa, and 2.14 MPa, respectively. Average bag deformation values are not given, though the report does state that all specimens deformed by at least 30% before failing. These values are compared to the results of the tests conducted for this thesis in Chapter 6.

## **2.2 Straw Bale Housing**

Straw bale housing is currently one of the most well-known earth-based housing technologies in North America. It is a technology native to North America, with its origins in the Nebraska region of the United States around the beginning of the 20<sup>th</sup> century. From its inception, straw bale housing technology has existed to allow home builders to meet their housing needs within the resource limitations of their local environment; its origins in Nebraska are likely due to that area's relative scarcity of wood needed for conventional construction methods (Corum, 2005).

When discussing straw bale houses, there are generally two structural support systems to consider. Load-bearing straw bale walls are essentially monolithic bale-and-plaster structures wherein the load from the walls and roof is carried entirely by the wall system. Alternatively, post-and-beam straw bale houses rely on a conventional timber frame for structural integrity, with straw bales acting as insulation and wall surfaces (King, 2000). In some cases, hybrid models may be constructed wherein the load is carried by timber door and window framing as well as the straw bales. The advantage of load-bearing straw bale walls over other types of straw bale construction lies in the fact that significant savings can be realized with respect to the amount of wood needed, with subsequent cost savings due to timber's relatively high cost compared to straw bales. Specifically, a load-bearing straw bale house can utilize up to 50% less timber than an equivalently sized timber frame house (CMHC, 2002). The disadvantage of load-bearing straw bale houses is that the structural behaviour of a load-bearing bale-and-plaster wall is considerably more complex than a simple post-and-beam structure. This can lead to

complex approvals processes, especially in areas where earthquake and/or snow loads are significant. Post-and-beam houses do not realize the same material savings as load bearing houses, but have the benefit of exhibiting much simpler structural behaviour. This can expedite the engineering and approvals process (King, 2000). In humanitarian engineering applications, it is not likely that straw bale houses will be constructed in regions with well-developed straw bale building codes and approvals processes. Thus, the regulatory advantages of post-and-beam structures would likely be counteracted by the increased cost of a post-and-beam structural system. As such, this paper will focus on load-bearing straw bale house issues.

The structural behaviour of a load-bearing straw bale wall is affected by many parameters. This section will attempt to cover these parameters in order of scale, beginning with the straw itself, then discussing the properties of bales and plasters, and finally addressing the behaviour of a plastered bale wall.

The term “straw” is used to denote the fibrous husk of many grain crops, such as wheat, barley, oats, rye and rice (King, 2006). It is important to differentiate between *straw* and *hay*, since hay contains seeds and other organic matter which is susceptible to rot, while straw has most (if not all) of the grain removed, making it more suited to house construction. Straw is essentially a biocomposite consisting of microfibrils of cellulose and hemicellulose bound together by a lignin matrix, with additional materials such as silica ash incorporated within the matrix. The percentage of silica ash content can significantly affect the rot resistance properties of the straw (higher silica ash concentrations result in higher rot resistance), which is an important consideration in

environments where straw rot is likely to occur. There does not appear to be significant variation between different varieties of straw from a structural perspective, with the notable exception that rice straw exhibits superior rot resistance and bale coherence due to its high silica ash content and barbed surface texture, respectively (King, 2006).

Moisture issues such as rot and fungal growth are of significant concern for straw bale houses, and are affected by many micro- and macroscopic parameters. As such, they will be further discussed alongside other large-scale issues.

Straw is converted from a loose agricultural waste product into a structural material through the use of baling machines. These machines take loose straw and compress it into rectangular bales of a specified dimension. Two bale size classifications have emerged as being popular for straw bale housing, referred to as “two-string bales” and “three-string bales”. The actual dimensions of these bale sizes vary slightly, but two string bales are approximately 350mm tall, 500mm wide and 800mm long. Three string bales are approximately 410mm tall, 600mm wide and 1160mm long (Vardy & MacDougall, 2006). In general, bales are laid flat (with the straw parallel to the ground) in a running bond, though bales can also be laid on edge (King, 2006).

Straw bale walls are typically constructed by laying several courses of bales on top of each other, and then coating the bales with plaster. The plaster itself is generally a mix of water and minerals such as sand, earth, straw, clay, lime, gypsum and cement. The properties of the plaster can vary significantly depending on the constituent materials. In general, plasters made from unprocessed materials such as earth, sand and clay are typically desired for their high vapour permeability, wide availability and low

environmental impact, while fired materials such as lime, gypsum and cement generally produce stronger plasters, at the expense of low vapour permeability and higher embodied energy. Additionally, earth plaster materials tend to be easier to apply, but since natural materials (such as clay) have higher variability than processed ones (such as cement), thorough testing of local materials is often required to obtain high-quality plaster mixes (King, 2006).

Structurally, a straw bale wall coated with plaster behaves as a composite member. Since the plaster is generally much stiffer than the bales, it carries the majority of the vertical loads acting on the wall. The straw, bonded to the plaster, acts as lateral reinforcement by preventing the plaster from buckling (King, 2006). Thus, the plastered straw bale wall exhibits superior structural performance than either the plaster or the straw would exhibit on their own. Despite a high degree of natural variation in the constituent materials, laboratory tests and anecdotal evidence strongly suggest that straw bale wall technology is a strong, durable construction technology from a structural mechanics perspective. Strengths for plastered bales with horizontal straw orientation have been observed in the range of 35-81 kN per metre of wall length, with strength strongly dependent on plaster thickness (Vardy & MacDougall, 2006). Full-scale wall tests have shown strengths in the same range, from 48-73 kN per metre of wall length (Grandsaert & Ruppert, 1999). In order to fully evaluate straw bale housing technology, however, one must also consider the behaviour of straw bale walls in response to phenomena such as moisture, fire, and seismic loads.

Moisture is a significant concern when constructing straw bale houses. The organic nature of straw makes it a candidate for decay, which causes loss of wall mass and could thus lead to structural failure (CMHC, 2000a). Additionally, moisture in straw bale walls may promote the growth of mould, which can adversely affect the health of a house's occupants (King, 2006). In order to discourage mould and rot issues, the generally accepted level of moisture content is 20% or less, as a percentage of bale saturation (CMHC, 2000a). Insect problems have also been associated with moisture. Anecdotal evidence has shown that straw bale walls are not likely to support insect populations unless excessive moisture is present, and also that insect problems tend to be self-limiting as the water is consumed (King, 2006).

Moisture content within a straw bale wall has been noted to increase rapidly in response to heavy rains which raises concerns about the suitability of straw bale housing in climates that regularly experience heavy rains such as seasonal monsoons. Encouragingly, however, it was also noted that excessive moisture levels were only observed when accompanied by multiple design and/or construction flaws (CMHC, 2000a). This suggests that careful attention to minimizing moisture infiltration during design and construction can prevent mould, decay and insect issues before they appear.

Fire resistance is a common concern for all building technologies. Straw bale housing is particularly prone to concerns about fire resistance due to the apparently flammable nature of straw, as well as due to the relative novelty of the technology. While it is true that loose straw is extremely flammable, laboratory tests have shown plastered straw bale walls to perform extremely well in standardized fire tests. The good

fire resistance of straw bale walls is derived partly from the tightly bound nature of the individual bales. The straw is compressed such that there is little room for oxygen to infiltrate and provide fuel for a fire (King, 2006). Furthermore, the addition of a plaster skin to a bale wall provides an incombustible surface that additionally inhibits the spread of flames to the straw bales themselves (Theis, 2003). In fire tests conducted in accordance with ASTM E119, plastered straw bale walls have been shown to readily meet 1-hour-wall criteria (King, 2006).

It is important to emphasize the flammable nature of loose straw, especially compared to the good fire resistance exhibited by plastered straw bale walls. Loose straw combusts extremely readily, which can be of particular concern on construction sites where it can also be plentiful, and where unplastered straw bale walls are likely to be present as well. In fact, one collection of reported straw bale house fires has shown construction activity prior to wall plastering to be a leading cause of fire damage to straw bale homes (King, 2006). The implications for straw bale housing in a humanitarian engineering context are clear. Wherever straw bale housing is under construction, careful attention must be paid to ensure all workers are properly educated on the fire hazard posed by loose straw, and the higher combustibility of straw bales prior to plastering. This effort at ensuring education and awareness is particularly important given the fact that many humanitarian engineering housing projects are conducted in developing countries. These countries are less likely to have access to skilled labour or workplace safety regulations which would otherwise provide for a minimum level of worker education (Koehn et al., 1995).

Seismic effects on straw bale houses can be either a minor or major issue, depending on the location in which the houses are being constructed. Formal research on the response of straw bale walls to seismic forces is limited, but some preliminary tests have been conducted, and some general recommendations formulated. Specifically, a straw bale vault structure was tested against seismic loads in California, and was found to perform well . Subsequently, several straw bale structures have been approved for construction under California's Zone 4 seismic design requirements (King, 2000), Zone 4 being the most severe seismic zone defined by the United States Geologic Survey (USGS, 2007). Additionally, it has been noted by other straw bale builders that connections and waterproofing details are most likely to become damaged due to seismic forces (King, 2006). Thus, straw bale housing built in areas of high earthquake risk should be detailed with specific attention paid to strengthening connections and ensuring the soundness of waterproofing.

These preliminary studies of the earthquake resistance of straw bale housing technology suggest that it is an excellent candidate for use in seismically active zones. In general, plastered straw bale walls have been observed to behave with much more ductility than conventional technologies such as reinforced concrete (King, 2006), indicating their potential suitability for earthquake-resistant design.

Straw bale housing technology is particularly attractive for humanitarian engineering projects due to its relatively low-tech construction techniques. Wall construction is labour-intensive, but simple enough that it can be undertaken by community members with little to no experience with conventional construction

techniques. Organizations such as Habitat for Humanity have noted that humanitarian projects have a greater degree of success when the future homeowners invest their own “sweat equity” (i.e. provide labour) in the project (Rank, 2006). In addition, straw bale house costs are skewed more towards labour than materials. A typical straw bale house cost ratio is roughly 40/60 (materials/labour), while conventional construction is roughly 60/40 (King, 2000). The result of this difference is that straw bale houses exhibit significantly greater cost savings when sweat equity is provided, as well as in developing countries where labour costs are typically much lower than in the developed world.

In light of the above considerations, straw bale housing appears to be an appropriate technology for locations where local straw is readily available and labour is plentiful. Its attractiveness is further enhanced in areas where conventional materials such as concrete and timber are scarce, or too expensive for widespread use. It also appears to be, with proper design and construction, very resistant against seismic damage, making it suitable for even the most severe seismic zones. Additionally, its excellent insulation value makes it a good choice for areas which experience cold winters. It is less attractive in areas with very high humidity and/or heavy rainfall patterns, due to moisture infiltration issues leading to rot and/or insect problems. However, these issues may be mitigated with careful design and construction.

### **2.3 Earthen Construction (clay bricks, rammed earth)**

Earthen construction is the oldest known construction technology used by humans, with archaeological evidence showing that it has been used for at least 9,000

years (Minke, 2006). Despite its ancient origins, earth construction continues to be one of the most prevalent forms of housing technology in the world, with approximately 30% of the world's population living in earth-based housing (Moquin, 2000). As with early straw bale housing in Nebraska, the historic prevalence of earthen construction throughout much of the world is due primarily to the widespread availability of soil, as well as the comparatively limited availability of other housing materials such as timber. Its availability, as well as its low cost compared to modern, heavily processed building materials (such as steel and concrete), has ensured its longevity as a building technology.

Earthen construction is a broad term which encompasses many different building technologies centred on the use of soil. The most common type of earthen construction is adobe brick housing. The term “adobe” can be used to denote a style of earthen construction, as well as to denote an individual brick made from clay-rich soil, typically formed and left to dry in the sun without compaction or additional baking. When soil is used to make bricks which are then mechanically compressed prior to construction, they are usually referred to as “compressed earth blocks”. Cob walls are a type of structure formed by mixing clay-rich soil with fibrous material such as straw, forming the resultant material into clumps (“cobs”), and packing them together to form a monolithic wall. Finally, rammed earth is another system which dispenses with modular soil units in favour of one monolithic soil structure. This is achieved by constructing forms to enclose the wall volume, and then filling the formwork with soil one layer at a time, with each layer being tamped before the next one is poured.

Despite the variety of ways in which earth can be used as a construction material, the structural behaviour of earth housing is generally governed by a few key material properties. The most important property of soil, from a structural perspective, is its grain size distribution. A soil's relative percentage of clay, silt, sand and gravel greatly affects the mechanical strength of the soil. As a structural material, soil can be thought of as being roughly analogous to concrete, with clay particles acting as the binder (cement), and silt and sand acting as the aggregates. Earth is further analogous to concrete insofar as it is capable of achieving significant compressive strength, but can carry essentially no tensile loads (Minke, 2006). In general, the strength of a soil being considered for use in earthen construction is proportional to its clay content, and inversely proportional to its silt content (Moquin, 2000). This is due to the microscopic structure of clay particles, which consists of many thin plate-like particles with strong inter-particle binding forces. As soils become richer in clay, they become stronger due to an increase in these binding forces. However, after a certain point, increases in clay become detrimental to a soil's structural suitability, as swelling and shrinkage cracking increase with clay content (Minke, 2006). In general, clay contents of around 20-30% are desirable, with higher clay content being likely to result in excessive swelling and cracking, and lower clay content likely to result in insufficient compressive strength (Moquin, 2000). Silt, however, is detrimental to a soil's strength at any percentage, and thus the most desirable soils for construction purposes are soils with very low silt content. Soils with acceptable clay content and little silt can obtain compressive strengths in the range of 0.49MPa to 5.52MPa (Moquin, 2000; Minke, 2006). Furthermore, the compressive strength, tensile

strength, binding force (i.e. the inter-particle force that holds the soil together) and shrinkage tendency of a given soil may be altered through the addition of admixtures such as linseed oil, cellulose, gelatine, starch and asphalt (Minke, 2006). Asphalt, in particular, has been noted for its ability to act as an excellent stabilizer in adobe bricks by reducing water permeability and, subsequently, erosion.

Earthen construction does not face the same moisture related decay issues as straw bale housing, since soil is essentially inorganic (with the exception of humus-rich topsoils, which are unsuitable for earthen construction). However, moisture and wind can cause degradation of earthen construction over time, and are important factors to consider when designing for long-term durability. Erosion of exterior wall surfaces by water can significantly increase the required frequency of maintenance and reduce the lifespan of an earthen structure. In areas with low to moderate rainfall, this erosion can be minimized by providing large roof overhangs to prevent rainwater from running down the exterior walls of a structure (Minke, 2006). However, in areas with heavy rainfall and/or frequent windblown rain, further protection of exterior surfaces may be needed.

There are several methods whereby earthen walls may be protected from moisture- and wind- based erosion. Minke (2006) presents a comprehensive overview of several techniques, materials and considerations related to erosion protection. The simplest and most common method is to consolidate the soil on the exterior face of any earthen structural elements. Consolidation can be achieved by rubbing a trowel across a surface while it is moist, until the surface appears shiny and smooth. More complex methods of weather protection can involve the application of paint and/or plaster to

prevent erosion. When using paints, the most important consideration is the vapour permeability of the paint, since earthen houses perform best when their internal moisture content is allowed to fluctuate in response to environmental moisture levels. With plasters, the most important considerations are durability and ductility. Earth-based plasters degrade just as readily as earthen walls, and are thus not recommended for exterior finishes. Cement-based plasters are typically much stronger than earth plasters, but also exhibit very brittle behaviour which can lead to cracking and subsequent water infiltration. Lime plasters are a good candidate for an exterior wall finish due to their combination of durability and permeability, but these plasters can require several days and diligent upkeep to cure properly (Moquin, 2000). Aside from paints and plasters, there are a variety of other wall coatings which have been shown to improve the durability of earthen construction. These coatings include organic compounds such as linseed oil, oxblood, and cellulose glue paint, as well as mineral compounds such as siloxane. The list of traditional water repellents is quite extensive, with a variety of treatments based on locally available materials, such as banana leaf and agave juice (Minke, 2006). Siloxane is a particularly attractive water repellent coating, as it has been observed to virtually eliminate water absorption without negatively affecting vapour permeability (CMHC, 2000b). This should be taken into account when determining which treatment to use; higher laboratory performance does not necessarily indicate the best choice of treatment. A traditional treatment may be a better choice than a synthetic or proprietary product depending on such things as local expertise and preference, as well as transportation costs and embodied energy.

Earth-based buildings are particularly attractive from a fire-resistance perspective. Earthen walls are typically quite massive, with large thermal storage capacity, which suggests their ability to transmit excess heat in the case of a fire would be low. In addition, earth-based walls do not burn readily, further suggesting that if a fire were to start in an earth-based house, it would not propagate quickly, if at all. Very few studies have been conducted on the fire resistance of earthen walls, probably due to their extremely incombustible nature. However, studies commissioned by Rammed Earth Constructions, an Australian housing contractor, have shown a 250mm thick rammed earth wall to have a 4-hour fire resistance rating based on Australian testing standards (Rammed Earth Constructions, 2007). This meets the most stringent fire resistance rating requirements specified for non-combustible firewalls in the National Building Code of Canada (CCBFC, 2005). Since adobe is similar in composition to rammed earth (using modular blocks instead of monolithic volumes), it can be assumed that it exhibits similarly good fire performance. Cob walls are somewhat different than rammed earth and adobe walls, since the straw mixed with earth to form cobs is combustible. In addition, instances of cob houses collapsing during a fire have been observed (Ley & Widgery, 1997), which would seem to reflect negatively on cob's suitability for fire resistance. However, in instances of structural failure during a fire, the cause can usually be traced to the failure of timber members in the building, or the saturation of the cob by water in an effort to quench the fire, resulting in increased wall plasticity. Nevertheless, it has been observed that cob walls can achieve fire resistance ratings of two hours (Ley & Widgery, 1997). It may thus be deduced that all forms of earthen construction have

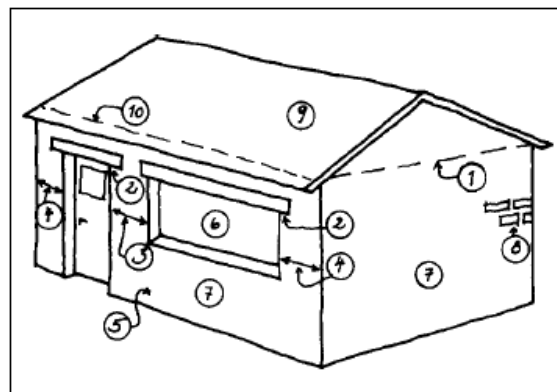
adequate fire resistance for use in dwellings, and in some cases may vastly outperform the requirements specified in local or national fire codes. Thus, earthen construction is particularly attractive in areas where fires are likely, or where high dwelling density has the potential to make fire propagation particularly disastrous.

In contrast to its excellent fire resistance, earthen construction is highly vulnerable to earthquake damage. Adobe in particular, classified as unreinforced masonry, is extremely susceptible to damage as a result of seismic forces (Tolles et al., 2000). However, it is possible to design earthen structures to minimize susceptibility to seismic forces. A thorough discussion of the seismic behaviour of earthen structures is presented by Minke (2001), along with design guidelines which aim to reduce the risk of seismic damage. The guidelines are summarized into three distinct strategies for designing the structural system of a house, each of which follows a different approach to ensuring seismic resistance:

1. Walls and roof should be stiff, heavily reinforced and strongly connected to ensure that no deformation occurs as a result of seismic forces.
2. Walls and roof should be well connected, but also ductile enough to deform under seismic loads. This deformation absorbs seismic energy without causing failure. This strategy requires the use of a “ring beam” which caps the wall system and must have wall-to-beam and beam-to-roof connections of adequate strength.
3. Walls are designed with a ring beam as in strategy #2, but roof is supported by columns which are structurally independent of the wall system. This allows

the wall system and roof system to vibrate independently in accordance with their different resonant frequencies.

In addition to the above strategies, construction detailing can also contribute significantly to a structure's seismic resistance. Figure 2.1 presents a house schematic along with 10 common design detailing errors which can lead to structural damage in an earthquake.



1. Ring beam is lacking.
2. Lintels do not reach deeply enough into masonry.
3. The distance between door and window is too small.
4. The distance between openings and wall corner is too small.
5. Plinth is lacking.
6. The window is too wide in proportion to its height.
7. The wall is too thin in relation to its height.
8. The quality of the mortar is too poor, the vertical joints are not totally filled, the horizontal joints are too thick (more than 15 mm).
9. The roof is too heavy.
10. The roof is not sufficiently fixed to the wall.

4-7 Typical design mistakes which might lead to the collapse of the house

**Figure 2.1: Schematic diagram of simple earthen house with common causes of structural damage indicated (Minke, 2001).**

Minke (2001) also notes that site selection can play an important role in determining a house's susceptibility to seismic damage, especially where construction is taking place near slopes. Specifically, houses should be built on flat ground, with a minimum of 3 metres separating the house from the nearest slope. Placing the house too close to a rising slope increases the risk that the house will be damaged by materials

falling down the slope. Alternatively, placing it too close to a descending slope increases the chance that the house will itself slide down the slope in the event of seismic activity.

Much like straw bale houses, earthen houses are an attractive design solution in areas where labour is plentiful, but conventional building materials are scarce and/or prohibitively expensive. Earthen construction can often be constructed from materials gathered on-site (Minke, 2006), which lowers the cost of acquiring and transporting building materials. In addition, earthen houses (adobe structures in particular) can be constructed relatively quickly (Moquin, 2000). Unfortunately, earthen construction does suffer from a poor image in some areas, with some criticisms going so far as to call adobe houses “hovels fit only for the destitute” (Moquin, 2000, p. 95). While these criticisms are largely unfounded in the light of modern research on the capabilities of earthen construction, it is still important to take local preference into account during the materials selection phase of any housing design project.

## **2.4 Bamboo**

Bamboo is widely used as a construction material around the world, with an estimated 800,000 people currently living in bamboo structures (DeBoer & Bareis, 2000). In addition to housing, it is also commonly used to make access scaffolding in Southeast Asia (Chung & Yu, 2002). There are several reasons why bamboo is an attractive material for construction. Specifically, its mechanical properties, growth characteristics, and availability all make it well suited to housing applications in developing countries, particularly those located at latitudes where it is commonly found. However, there are

several factors which may inhibit bamboo's suitability for design, depending on context. This section will discuss the strengths and weaknesses of bamboo as a structural material, specifically in a housing context.

Bamboo is a type of giant grass which produces a woody stem, called the culm (Ghavami, 2005). The culm itself is a biocomposite. In general, natural fibrous materials are composed of strong ligno-cellulosic fibres surrounded by a matrix of hemicellulose and lignin (Mohanty et al., 2002). The difference in mechanical properties between the fibrils and the matrix leads to strongly orthotropic material behaviour, which will be discussed below.

Bamboo species are generally found between 40° northern and southern latitudes (Daiglis, 1999). In its native habitat, it grows extremely quickly, often reaching its maximum height in only a few months, with maximum mechanical strength typically obtained after 3-6 years, depending on species (Chung & Yu, 2002). It is prized as a material with a relatively low environmental impact, mostly due to this high growth rate and its renewable nature. However, given its somewhat limited geographic distribution, the environmental impact of transportation should be considered when using bamboo. In some cases, shipping costs and environmental impacts may completely offset the environmental benefits of using bamboo over more conventional building materials.

Structurally, there are two ways in which bamboo can be utilized. It may be left whole or flattened for use as a structural member in and of itself (Chung & Yu, 2002, DeBoer & Bareis, 2000), or it may be used as fibrous reinforcement in composite materials (Ghavami, 2005; Li et al., 1995; Daiglis, 1999).

Whole bamboo is geometrically well-suited to being used as a structural member, due to the fact that it grows in relatively straight culms. Additionally, the circular, hollow geometry of bamboo culms means they obtain a higher moment of inertia than would be achieved if the same amount of material were arranged in a solid mass. This is analogous to the benefits of hollow structural sections (HSS) commonly used in steel design and construction.

Bamboo culms are highly orthotropic. The behaviour of bamboo is roughly analogous to that of structural timber, with high strength parallel to the direction of the longitudinal fibres, and lower strength perpendicular to these fibres (Ghavami, 2005).

In quantitative terms, bamboo compares favourably with the conventional structural materials of wood, steel and concrete. Chung and Yu (2002) conducted a series of compression and bending tests for two common species of bamboo, namely *Bambusa pervariabilis* (Kao Jue) and *Phyllostachya pubescens* (Mao Jue), with the intent of determining characteristic values for bamboo strength in bending and compression. In total, 364 compression tests and 91 bending tests were conducted to determine average strength values and their standard deviations. These data were then used to obtain the fifth percentile value for strength in each case, which is then subject to a material safety factor of 1.5. This adjusted value is then presented as a design value for strength. A summary of the strengths determined is presented in Table 2.1.

**Table 2.1: Bamboo strength in compression and bending (Chung & Yu, 2002).**

Proposed mechanical properties<sup>a</sup> for *Bambusa pervariabilis* (Kao Jue) and *Phyllostachya pubescens* (Mao Jue)

| Bamboo species                           |  | Characteristic strength (at fifth percentile) |     | Design strength ( $\gamma_m=1.5$ ) |     | Design Young's modulus (Average value) |      |
|--|--|---|-----|------------------------------------|-----|--|------|
|  |  | Dry   | Wet | Dry                                | Wet | Dry                                    | Wet  |
| <i>Bambusa pervariabilis</i> (Kao Jue)   | Compression $f_{c,k}$ (N/mm <sup>2</sup> ) | 79  | 35  | $f_{c,d}$ (N/mm <sup>2</sup> )     | 52  | $E_{c,d}$ (kN/mm <sup>2</sup> )        | 10.3 |
|  | Bending $f_{b,k}$ (N/mm <sup>2</sup> )     | 80  | 37  | $f_{b,d}$ (N/mm <sup>2</sup> )     | 54  | $E_{b,d}$ (kN/mm <sup>2</sup> )        | 22.0 |
| <i>Phyllostachya pubescens</i> (Mao Jue) | Compression $f_{c,k}$ (N/mm <sup>2</sup> ) | 117   | 44  | $f_{c,d}$ (N/mm <sup>2</sup> )     | 78  | $E_{c,d}$ (kN/mm <sup>2</sup> )        | 9.4  |
|  | Bending $f_{b,k}$ (N/mm <sup>2</sup> )     | 51  | 55  | $f_{b,d}$ (N/mm <sup>2</sup> )     | 34  | $E_{b,d}$ (kN/mm <sup>2</sup> )        | 13.2 |

<sup>a</sup> Dry condition m.c.<5% for both Kao Jue and Mao Jue. Wet condition m.c.>20% for Kao Jue, and m.c.>30% for Mao Jue. Linear interpolation is permitted for mechanical properties with moisture contents between dry and wet conditions.

The values presented in Table 2.1 are well within the range required for housing-scale structures, with compressive strength (23-78 MPa) comparable to that of concrete. Its bending strength (24-54 MPa) is significantly superior to the bending strength values of timber given by the Canadian Wood Council (2001), which specifies bending strengths of 3.9-19.5 MPa, depending on grade and species. It is important to note the effect of moisture on the strength and elastic modulus of bamboo. As noted in Table 2.1, an increase in bamboo moisture content significantly lowers its strength in compression and bending, as well as its elastic modulus.

The high tensile and bending strength of bamboo is offset by its very low strength in shear. It has been noted that even though some bamboo species have theoretical tensile strengths of 200-300 MPa, it is shear failure that commonly governs performance (Daiglis, 1999). This is due to the relatively weak hemi-cellulose and lignin matrix which binds the plant's fibres together. As such, bamboo is not likely to be an ideal design solution for structural applications where high shear stresses are expected.

When used as fibrous reinforcement in composite materials, the mechanical properties of the resulting composite are heavily dependent on the configuration of the composite in question. Ghavami (2005) discusses some of the issues surrounding the use of bamboo as tensile reinforcement in concrete beams. Untreated bamboo “splits” (fractions of bamboo culms split longitudinally into strips) were observed to behave poorly as concrete reinforcement due to their tendency to absorb water, and subsequent changes in volume. The splits absorb water and expand when the concrete initially sets, releasing it slowly and shrinking as the concrete cures. By the time curing is complete, the result of the volume change is voids surrounding the bamboo splits, leading to poor bond strength and a lack of force transfer from the concrete to the bamboo. It is noted that bond strength can be improved with a variety of surface treatments. However, given their reliability on epoxies and similar petrochemicals, this process is likely to be too expensive for use in affordable housing developments. In addition, the use of synthetic petrochemical-based products to treat bamboo is counterproductive if a housing project’s goal is to minimize environmental impact. Finally, bamboo has a modulus of elasticity less than 10% as stiff as that of steel, suggesting that bamboo-reinforced concrete beams would experience very large deflections (Daiglis, 1999).

Alternative approaches to the use of bamboo as fibrous reinforcement in composites has focused on the use of bamboo fibres and/or splits in polymer resins to form products similar to engineered wood products such as plywood and fibreboard.

Plybamboo is a product composed of bamboo splits, coated in resin and pressed together into sheets. Daiglis (1999) presents a summary of several different plybamboo

manufacturing techniques which produce sheets with modulus of rupture (MOR) values ranging from 68 MPa to 129 MPa, depending on thickness, resin type, and press time. This strength compares very favourably to that of plywood, which has typical MOR values of 20.7 MPa to 48.3 MPa (Forest Products Laboratory, 1999). It can thus be assumed that, from a strength perspective, plybamboo is a feasible alternative to plywood for structural applications.

However, it is further noted by Daiglis (1999) that plybamboo requires a “long and complicated” manufacturing process. This process typically involves a combination of high pressures (1.5 MPa to 3 MPa) and high temperatures (50°C to 135°C) to achieve the strengths listed above. The resources required for this type of process, such as industrial presses and plentiful electricity, suggest that manufacturing may not be possible in rural or infrastructure-poor areas. Also, Daiglis (1999) notes that plybamboo production factories are rarely successful, even where technically feasible and located close to a ready supply of bamboo. Finally, the plybamboo products discussed were all manufactured with either urea formaldehyde (UF) or phenol formaldehyde (PF) resins. UF is cheaper than PF, but is also considerably more hazardous to human health due to its tendency to emit more formaldehyde gas than PF resin. Soy-based polymers have been shown to emit fewer volatile organic compounds than petrochemically-derived resins such as UF and PF (Mannari & Massingill, 2006), and as such may be a more suitable choice for structural bamboo composites.

Bamboo culms can also be broken down and mixed into a resin matrix to form various bamboo composite sheets. This process allows waste bamboo from both

structural and non-structural applications to be recycled for use in structural sheeting. The strength of the resulting composite material is dependent on a number of factors, including resin type, fibre size, mix ratio and fibre-resin bond interface. The three most common types of composite sheets are (in descending order of particle size) waferboard, fiberboard and particleboard.

One commonly reported problem with bamboo composite products is the tendency of bamboo fibres to form poor interfacial bonds with polymer matrices, leading to debonding at relatively low stresses (Lee & Wang, 2006; Saxena & Gowri, 2003; Daiglis, 1999). Surface treatment of the bamboo fibres with an interfacial coupling agent has been shown to improve this bond quality. Saxena & Gowri (2003) reported an improvement in flexural strength of 15-36%, with similar increases in tensile strength and modulus of elasticity. The interfacial agent used in this study was polyester amide polyol. While surface treatments such as this significantly improve mechanical properties, it should be noted that a synthetic interfacial agent such as polyester amide polyol may not be a realistic surface treatment product in developing countries where access to such products is limited.

The strength values for engineered bamboo products such as those mentioned above are similar to the values observed in their conventional wood-fibre counterparts. For example, Daiglis (1999) reported modulus of rupture (MOR) values for bamboo particleboard in the range of 13.8 MPa to 24.7 MPa, which compares favourably with typical wood particleboard MOR values of 5.0 MPa to 16.5 MPa (Forest Products Laboratory, 1999). This suggests that when the necessary raw materials and

manufacturing equipment are available, engineered bamboo products may be a mechanically viable product for housing construction. Non-structural uses for bamboo in housing situations are abundant, such as bamboo mats for use as curtain walls (Liese, 1987).

Moisture-related issues can be of concern for bamboo construction. Due to its organic nature, it is susceptible to degradation by several different mechanisms such as fungi, insects and rot (Brown, 2004). Its low natural resistance to such mechanisms has been described as a “major shortcoming” (Liese, 1987, p. 202) with regard to structural applicability. In addition, the outer layer of bamboo culms is high in silica, which inhibits the ability of preservatives to infiltrate the bamboo via simple immersion. Rather, as described by Daiglis (1999), more complicated methods of preservation are required. One such process, the Modified Boucherie Method developed by Walter Liese, involves the forcing of preservative longitudinally through the bamboo by means of pressurized preservative application at the cut end of a culm. This process is described as “long and complex” (Daiglis, 1999, p. 72), and thus not likely to be of use in a developing context. Traditional bamboo preservation methods described by DeBoer & Bareis (2000) are much simpler, and have been anecdotally shown to significantly decrease the risk of rot, fungus and insect problems. One such method, developed in Japan, involves air-drying bamboo culms for several months, followed by one to two weeks of direct sunlight to finish the drying process, followed by five minutes of smoke-curing above a charcoal pit. Uncured bamboo structures in tropical locations typically last only 3 to 5 years before needing replacement. Data from the direct comparison of

uncured bamboo decomposition to that of cured bamboo in an identical environment are currently lacking, but anecdotal evidence from Japan has shown that smoke-cured bamboo can last hundreds of years if properly cured and used for interior (i.e. dry) exposure conditions (DeBoer & Bareis, 2000).

Structural design can play an important role in ensuring the longevity of bamboo as well. The ideal design for a bamboo structure features large roof overhangs, as well as a brick or stone foundation to minimize contact with the soil (Gutierrez, 2000). This acts to minimize moisture levels in the bamboo, as well as preventing attack from microbes or compounds in the soil that may accelerate the deterioration of bamboo members.

Research on the fire performance of bamboo structures is very limited. Anecdotally, bamboo is reported as having a very poor fire resistance (Daiglis, 1999). In particular, the natural fibres used for the traditional lashed connection technique are prone to rapid combustion, leading to early and catastrophic structural failure. While the International Standards Organization has proposed a model building code for bamboo, it does not provide any guidance on fire safety for bamboo construction beyond stating that “Fire resistance rating shall be determined in accordance with applicable national standards” (ISO, 2004). A lack of published fire test results indicates a significant need for more research in this area.

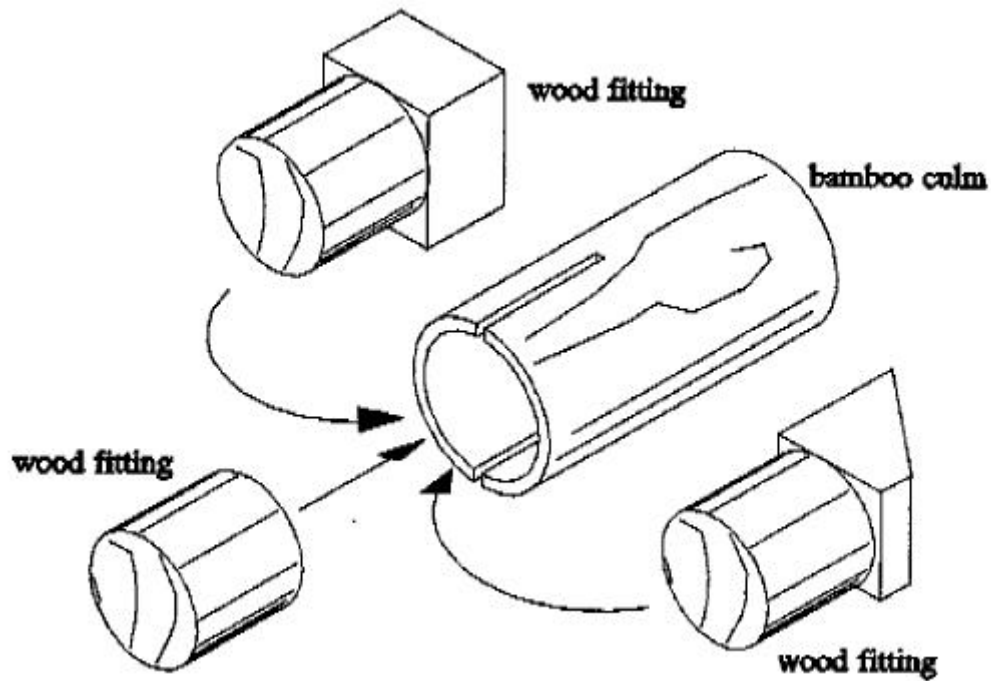
The performance of bamboo structures under seismic loading has been the subject of several studies. One such test led by Jayanetti (2004) examined the seismic resistance of a 2.7m x 2.7m bamboo-framed model house, using a wall infill of bamboo strips with a mortar cover of 50mm. The study tested the house on a shaker table at forces

equivalent to a Richter scale rating of 7.8. This is also equivalent to a Zone 4 earthquake according to the Bureau of Indian Standards IS 1893, which is the most severe earthquake rating in the subcontinent. Post-test inspections of the model house revealed that all connections remained intact, and no cracks were observed in the bamboo-and-mortar infill. Post-earthquake field tests noted by DeBoer & Bareis (2000) reinforce these findings by observing that many bamboo structures with masonry infill survived an earthquake of magnitude 7.5 in Costa Rica. The underlying cause of this high performance is the fact that the shear provided by the mortar infill holds the building together, while the light weight of the bamboo results in relatively low lateral forces. Additionally, even bamboo-framed housing without masonry infill has been anecdotally reported to perform better than solid masonry housing, due to bamboo's ability to sustain large deflections without inelastic deformation (DeBoer & Bareis, 2000).

Where mortar is not used as infill, it is important to design the structural system such that lateral forces can be resisted by the structure's connections. DeBoer & Bareis (2000) notes that bolted bamboo connections can be very strong in compression, but may pull apart under tension depending on connection detailing. This necessitates the use of redundant truss members to carry opposing forces during loading cases such as roof uplift or seismic forces.

When considering constructability, it is important to note that bamboo structures are possible across a broad range of complexity. Perhaps the most significant construction detail in determining a structure's overall quality is the connection method. Traditional bamboo structures make use of lashed joinery, wherein culms are tied

together at joints using a natural fibre such as jute. Detailed descriptions of traditional bamboo construction techniques are presented by Daiglis (1999). While these connections are attractive due to their simplicity, they are seldom capable of developing the full strength of bamboo culms, and thus will govern failure at much lower loads than are theoretically possible (Daiglis, 1999). To fully utilize the potential strength of bamboo, several efforts have been made to develop improved connection methods. Arce (1993) presents a summary of several traditional and modern connection methods. The author notes that more effective joints are typically more expensive, but also notes that since stronger joints can reduce the amount of bamboo needed (by allowing it to develop its full mechanical strength), the effect of joint selection on cost is complex. Figure 2.2 shows a connection system designed by Acre (1993) which was reported to perform well in laboratory testing.



**Figure 2.2: Schematic diagram of a proposed bamboo connection method (Acre, 1993).**

The main obstacle discussed by the author is the need to fabricate wood cylinders to a specific diameter to match the culms being used on a member-by-member basis. However, the author proposes that this shortcoming may in fact prove beneficial in that it may provide an opportunity for livelihood generation within the community, thus enriching the local economy.

For high performance bamboo joinery, the method of choice is currently one developed by Simon Velez wherein culms are bolted together (DeBoer & Bareis, 2000). In order to reduce stress concentrations at the bolt which could lead to splitting, the culm is filled with mortar around the bolt in order to produce a more uniform stress distribution. Bamboo structures designed with this connection method are capable of

very large spans and complex geometries, as can be seen in Figure 2.3, a bamboo arch bridge designed by Simon Velez and constructed in China.



**Figure 2.3: Bamboo arch bridge (Velez, 2008).**

While the joinery methods pioneered by Simon Velez are capable of pushing bamboo structures near the theoretical limits of the material, the complexity of the connection method makes it an unlikely candidate for use in housing development situations. Fortunately, the dimensions of a typical dwelling in developing countries are much smaller than the extreme spans attempted by Velez, thus suggesting that simpler, lower-performance connection methods will be adequate.

## 2.5 Comparison of Known Material Properties

In order to make informed choices about material and technology suitability for engineering projects, direct comparisons should be made between the many alternative building technologies available. Direct, quantitative comparison is a complex task, given that straw bale, earthen and bamboo construction vary significantly in their form and function. However, relative comparisons can be made which can inform the material selection process. Table 2.2 presents a comparison of straw bale, earthen and bamboo construction with respect to six key material properties and design considerations – compressive strength, moisture and rot resistance, seismic resistance, fire resistance, complexity, and material availability. Numerical values are used for compressive strength, but for subjective parameters such as “complexity” (the amount of specialized knowledge and skill required for construction), a relative rating of *very low*, *low*, *medium*, *high* or *very high* was given based on existing research as outlined in the literature above.

**Table 2.2: A comparison of material and construction properties for the three main types of alternative building technologies outlined above.**

| <b>Material Type</b> | <b>Compressive Strength</b>                                  | <b>Moisture and Rot Resistance</b>                  | <b>Seismic Resistance</b>   | <b>Fire Resistance</b>   | <b>Complexity</b>   | <b>Material Availability</b>                            |
|----------------------|--|---|---|--|---|---|
| <b>Straw Bale</b>    | 35-81 kN/m<br><i>Strength given per metre of wall length</i> | Medium  | High  | High<br><i>Plastered</i><br>Very Low<br><i>Unplastered loose straw</i> | Low-Medium  | High  |
| <b>Earthen</b>       | 0.49-5.52 MPa  | Medium-High<br><i>Requires periodic refinishing</i> | Low<br><i>No seismic detailing</i><br>Medium<br><i>With seismic detailing</i> | Very High  | Low-Medium<br><i>Cob, Adobe, Earthbag</i><br>Medium-High<br><i>Rammed Earth</i> | Very High   |
| <b>Bamboo</b>        | 23-78 MPa (whole)<br>68-129 MPa (MOR, plybamboo)             | Low<br><i>Untreated</i><br>High<br><i>Cured</i>     | High  | Low  | High  | Low<br><i>Widely available only in tropical regions</i> |

## 2.6 Summary

The above sections provide a general overview of some of the most common, and most thoroughly researched, alternative building materials currently in use around the world. The above information is by no means comprehensive, but rather outlines the general characteristics and behaviour of straw bale, earthbag, earthen and bamboo wall systems with respect to several considerations of particular interest for the context of housing in both the developing and the developed world. In general, the alternative

technologies discussed display an attractive combination of low cost, low complexity, and environmental benefit. From a structural performance perspective, the two most significant barriers to widespread adoption of these materials include moisture and rot issues, as well as nonexistent research in several key areas such as fire and seismic performance. However, these issues do not appear to be severe or insurmountable, and as such, there is significant promise for the use of alternative building materials in a developing context. Further discussion of the applicability of these technologies, in the context of the RESTORE Project in Sri Lanka, is discussed in Chapters 3 and 6.

## **Chapter 3**

### **The RESTORE Project - Opportunities and Challenges for Humanitarian Engineering in the Context of Conflict**

As discussed in Chapter 2, many alternative building materials and techniques are particularly well suited to use in marginalized communities, as these areas often have an abundance of labour but, in general, lack the financial and manufacturing resources necessary to take advantage of high-performance, high-technology building materials. Additionally, since many alternative building techniques such as rammed earth, adobe and earthbag construction are designed to take advantage of local materials (sometimes from the construction site itself), they are excellent candidates for use in areas where natural disasters have disrupted infrastructure such as transportation and power distribution networks.

Natural disasters can place further strain on conventional building techniques by damaging or destroying large numbers of households, which subsequently places a large strain on the capacity of conventional building material industries to meet the demand for replacement housing. As can be seen in Figure 3.1 there were still many emergency tent camps occupied by villagers almost two years after the Indian Ocean tsunami of December 2004.



**Figure 3.1: Emergency tent shelters erected in December 2004, in use as of September 2006 (all pictures in Chapter 3 were taken by the author).**

### **3.1 The RESTORE Project**

The Indian Ocean tsunami did extensive damage not only to housing and transportation infrastructure, but also to coastal fisheries and ecosystems. With this in mind, four Canadian universities (Queen’s University, University of Waterloo, Guelph University, and University of Manitoba) partnered with three Sri Lankan universities (Ruhuna University in Matara, Eastern University in Batticaloa and Southeastern University in Akkaraipattu) to undertake a large reconstruction project in southern Sri Lanka, focusing specifically on coastal areas that suffered the most damage in terms of ecosystem, livelihood and housing loss. “The RESTORE Project: Environmental and Livelihood Restoration and Development in Tsunami-affected Coastal Areas of Sri Lanka” was chiefly funded by the Canadian International Development Agency (CIDA)

who contributed \$1.75 million, with the four Canadian partner universities contributing a total of \$195,000. This chapter presents a discussion of the author's involvement in the project from the perspective of a graduate student in engineering. Given the recent growth in interest in developing a humanitarian engineering curriculum as a sub-discipline, the insights gained through the author's RESTORE Project experience may help inform future attempts at humanitarian-focused graduate engineering research. From this experience, a general discussion is presented of the hazards of humanitarian engineering projects when undertaken in a foreign context, followed by strategies for project design which may minimize these hazards.

The overarching goals of the RESTORE Project were to remediate the coastal environment damaged by the tsunami, as well as to assist in building the capacity of the citizens of coastal Sri Lanka to engage in productive, sustainable livelihoods. In order to meet these goals, the project activities were divided into a number of target areas, with a portion of the funding set aside for "new technologies". This set of activities was intended to encourage technology transfer to Sri Lankan villagers in a way that would enhance economic opportunities as well as ecosystem conservation and restoration, while also minimizing the risk of future natural disasters. A summary of the activities within this target area, which was produced during the project meeting and site visit in 2006, can be found in the New Technologies Action Plan, presented in Appendix A. It should be noted that this activity summary was written before the escalation of conflict discussed below in Section 3.5: Problems Arising due to Conflict. As such, the actual implementation of these activities did not follow the outline developed in this action plan.

In light of the project's overarching goals, it was recognized that inadequate housing supply was a significant barrier to the establishment of new, sustainable livelihoods for many coastal villagers. This thesis was originally intended to address this issue by examining local material availability and traditional structural vernacular, analyzing existing alternative construction techniques, and designing a housing solution that would address the structural and cultural constraints of the Sri Lankan context in an environmentally low-impact manner. The intended goal of this activity was to directly improve the problem of insufficient housing supply, while also building the capacity of the local construction industry to meet further housing shortages in an environmentally responsible fashion.

A two-week site visit to southern Sri Lanka was completed in September, 2006 in order to meet with the project partners, set out a timeline for the project (then estimated to be completed by the end of 2008) and visit several sites along the southern coast to conduct observational research on both the damage done by the tsunami as well as local preference in terms of architectural style and material use. This preliminary visit was intended to be followed in 2007 by a longer stay of several months in order to coordinate and supervise the execution of the activities associated with the housing restoration portion of the project. Unfortunately, unsafe circumstances arising due to the long-standing conflict between the Sri Lankan government and the Liberation Tigers of Tamil Eelam (LTTE, commonly referred to as the Tamil Tigers) prevented the completion of this return trip, and thus the original scope of this thesis was altered from that of a case study of alternative building material applicability in a specific development context.

Instead, as mentioned in Chapter 1, the scope has been modified to be a more general study of the structural behaviour of these materials (earthbags in particular), supplemented with a discussion of some of the issues surrounding the applicability of alternative building materials in humanitarian engineering projects.

### **3.2 Results of Observational Research**

The main objective of the author's observational field research in Sri Lanka was to gain an understanding of the typical housing materials and structural configurations favoured by the residents of the south coast of Sri Lanka. Original structures which survived the tsunami were observed, as well as damaged and destroyed structures, and rebuilt structures, which have been constructed specifically to replace houses destroyed by the wave.

Original structures were almost entirely constructed of either non-engineered concrete (i.e. cement-water-aggregate mixtures mixed on-site, with or without reinforcing steel, with no analysis done to determine the adequacy or efficiency of reinforcement), or plastered brick (see Figure 3.2). In discussing these materials with villagers in these areas, it was determined that they were favoured due to a cultural preference for concrete. Further discussions indicated that houses built with these materials were perceived as being in line with modern western housing, and thus a symbol of affluence.



**Figure 3.2: Typical concrete and masonry house near Matara, Sri Lanka.**

Of the damaged and destroyed houses that were still observable in 2006, all were non-engineered concrete or masonry. Additionally, all were within several hundred metres of the coast line, and there was significantly more damage done to walls which were perpendicular to the direction of travel of the wave (see Figure 3.3).



**Figure 3.3: Masonry wall oriented parallel to direction of tsunami, left standing with rest of house destroyed near Matara, Sri Lanka.**

Reconstructed housing was also almost entirely concrete and masonry. No timber or bamboo frame housing was observed at all, despite the fact that the southern region of Sri Lanka contains both timber and bamboo resources. Bamboo is used in the construction industry in this area, but its use is limited to temporary shoring poles (see Figure 3.4) and scaffolding.



**Figure 3.4: Post-tsunami concrete frame housing with masonry infill and bamboo shoring poles near Matara, Sri Lanka.**

Many houses were constructed on land reclaimed from former house sites, though some housing projects funded by non-government organizations were deliberately constructed several kilometres inland in order to avoid the risk of future tsunami damage. These housing reconstruction projects heavily favoured concrete and masonry materials.

In terms of structural configuration, virtually all of the single-family dwellings in the area studied were one-storey structures with rectangular dimensions, one door, two windows and sloping roofs covered with a variety of materials of significantly varying quality, such as terra cotta roof tiles or scrap sheets of tin.

### **3.3 Potential Problems Associated with Development from “Outside”**

The motivation for undertaking humanitarian projects is almost always a desire to improve the quality of life for people living with significant hardship. However, this desire is not enough, in and of itself, to ensure that humanitarian projects will improve a given situation in reality. The definition of a successful project varies depending on the goals of the project, but in general it can be said that project success involves improving the lives of all stakeholders involved in the project. However, since there can be many stakeholders in humanitarian projects, both direct and indirect, and since the notion of “improvement” is itself a subjective term, there are many complex factors that influence the outcome of a humanitarian project.

The dualistic potential for humanitarian development (and technology in general) to do harm as well as good has been extensively discussed in the literature of the arts and social sciences, such as philosophy and development studies (Anderson, 2000; Selinger, 2007), and this notion can be readily applied to the work of engineers (Miller, 2008). The work of an engineer in a humanitarian context has the potential to do harm, good, or both. With this in mind, the potential problems discussed here will focus on those problems most likely to occur in a construction-type project where physical infrastructure is being provided to people who would not otherwise have access to it. The issues discussed here were identified in the process of group discussion between the Canadian and Sri Lankan project partners, and can be summarized as dependence, imbalance, irrelevance and disconnectedness.

### **3.3.1 Dependence**

One of the most significant potential problems with humanitarian construction projects, and indeed all humanitarian projects, is the danger of creating dependence. Many, if not all, construction projects require maintenance or replacement parts once completed. If the necessary skills to perform this maintenance or to fabricate these parts are not held by the community or region in which the project is completed, that community becomes dependent on foreign expertise to maintain their infrastructure. While there may not be any inherent danger in having interconnected economies, maintenance costs can be prohibitively expensive for some complex construction projects, thus limiting the ability of the community to benefit from the project in the long term. In addition to physical dependence in the form of maintenance, there is also the less quantitative possibility of creating a culture of dependence. Depending on the specifics of local culture, dependence on an outside body may be seen as less preferable than to receive no aid at all. In the words of a Sierra Leonean aid recipient, “Isn’t a dignified death preferable to continued life dependent on the uncertain generosity of the international community?” (Anderson, 2000).

### **3.3.2 Imbalance**

Beyond the issue of dependence, humanitarian construction projects also carry with them the danger of creating social imbalances. This is especially true of subsidized or externally funded housing projects. Since these projects directly benefit a specific, limited segment of the population, it can lead to feelings of resentment or unfair treatment in those who do not directly benefit from the project. This problem is

particularly difficult to avoid given that humanitarian construction projects often have limited budgets and can rarely provide resources to everyone who is in need, instead focusing on a group of individuals decided on the basis of some designated selection criteria.

Humanitarian projects can also imbalance local economies. In general, humanitarian construction projects are designed to satisfy unmet needs. However, satisfying unmet needs is also the main driver for economic activity. As such, if humanitarian construction projects are meeting local needs using external funding, it reduces the opportunities for local communities to meet their own needs through conventional economic channels. Humanitarian projects are virtually always limited in their scope, which makes them inherently inferior to a healthy economy which can meet the needs of its members over a much longer time frame. In the case of housing, it is the construction industry which is at the greatest risk of being imbalanced.

### **3.3.3 Irrelevance**

Irrelevance is a problem which can plague humanitarian engineering projects which are well intended but poorly researched. It is easy to assume that a community in an impoverished region would appreciate a new school, but it may well be that there are other needs, such as clean drinking water, which rank much higher on the community's priority list. Engaging in irrelevant projects may not actively be harmful, but it risks misplacing limited resources for improvement.

### **3.3.4 Disconnectedness**

Finally, humanitarian construction projects face the danger of creating a feeling of disconnectedness between the project stakeholders and the project's output. When humanitarian aid is given for free, it can be more difficult for the recipients of the aid to place value on it. This lack of "buy-in" to the project may make the recipients less likely to use or maintain it. Additionally, a feeling of disconnectedness between project and recipient can occur when the project is designed and built in conflict with the actual wishes or culture of the recipients. In Indonesia, for example, there have been many efforts to build suburb-style housing developments for those currently living in squatter villages. However, many of these developments go completely unused, with local citizens eschewing them in favour of housing styles more consistent with their cultural heritage (Lindquist, 2000). This form of disconnectedness differs from irrelevance in that it addresses an identified need, but in a manner that does not result in recipient satisfaction.

### **3.4 Strategies for Increasing the Likelihood of Project Success**

In order to address the challenges presented above, several strategies were adopted in order to optimize the design and implementation of the housing construction activity.

It was decided that the most effective way to address housing shortages, while also rebuilding local capacity and generating livelihoods, would be to build a small number of "model structures". These structures would be built to act as community

centres and disaster shelters (a local priority after the tsunami). By building the model structures to serve a communal purpose, the project would avoid the issues surrounding unequal distribution of benefits, as discussed above. At the outset of the project, the author had envisioned and prepared for the construction of houses, but a discussion with the Sri Lankan project partners illuminated the issue of imbalance that this would create in the social structure of the villages. This highlights the importance of flexibility when planning and executing humanitarian engineering projects.

The design, placement and construction of the structures was to be determined by collaborative work between the project managers and the community members and groups. This strategy is consistent with the principles of participatory action research (PAR), an ideology which aims to maximize the involvement of local people in meeting their own needs. The goal of PAR is to conduct research to improve the lives of those affected through direct action. Participation of the affected community members is encouraged and sought out to the greatest degree possible, from as early in the research process as possible. The input of local people thus helps guide the research methods and goals to maximize the relevance of the project to their own needs (Hagey, 1997). This represents a philosophical break from the ideology of the “expert researcher”, which implies that the knowledge and research techniques of an expert are superior to the indigenous knowledge of individuals and groups in developing nations, and that the expert should maintain control over all research activities (Greenwood et al., 1993).

By adopting the philosophy of PAR, it was hoped that several of the problems discussed above could be avoided. The participation of villagers helps avoid

disconnectedness in favour of “militancy (fighting for change)” (Hagey, 1997).

Additionally, by involving representatives from the local construction industry in the actual construction and maintenance of the project, issues of dependence on outside knowledge for maintenance can be minimized. The application of PAR to the RESTORE Project was accomplished by designing a Participatory Rural Appraisal (PRA, not to be confused with PAR), which is a form of needs assessment in which the villagers themselves are responsible for conducting the assessment. This form of needs assessment is particularly well suited to humanitarian development projects since it increases project buy-in while also avoiding any modification in natural behaviour that may occur when villagers are being observed by outsiders. Additionally, the PRA model is well suited to gathering information for humanitarian engineering projects, as engineers are typically untrained in observational research methods and thus may be susceptible to a variety of cognitive biases, such as outgroup homogeneity bias, which is the tendency of observers to underreport variability in groups with which they do not self-identify (Messick & Mackie, 1989).

In addition to reducing the probability of dependence, involving the construction industry in the building of structures using alternative materials may promote technology transfer and capacity building. Transfer of alternative building materials technology is desirable for several reasons, both economical and environmental, as mentioned in the introduction and literature review. Capacity building is important in light of the RESTORE Project’s stated goal of livelihood generation. A construction industry that has experience with a greater suite of construction materials will be able to satisfy a

greater range of construction needs, thus increasing the amount of livelihoods the industry is able to support.

### **3.5 Problems Arising Due to Conflict**

As well as suffering the effects of the 2004 Indian Ocean tsunami, Sri Lanka is also burdened with a history of ethnic conflict. Most Sri Lankans belong to one of two ethnic groups: the Sinhalese or the Tamil. The Sinhalese make up a significant majority of the country's population at 73.8%, with Tamil residents of Sri Lankan and Indian descent comprising the single largest minority group, at 8.5% of the population ("Sri Lanka", 2008). Since the 1970's, a small fraction of the Tamil minority, the Liberation Tigers of Tamil Eelam (also known as the Tamil Tigers), have waged a protracted militant campaign to establish an independent state, Tamil Eelam, in the northern regions of Sri Lanka. This conflict was initially confined to the disputed northern regions, but has increased in intensity and spread to the eastern, south eastern and southern regions of the country since 2006. This escalation of violence presented several obstacles to the successful completion of the RESTORE Project in general, and the alternative building materials construction activity in particular.

In terms of logistics, a significant barrier to Canadian participation in the RESTORE Project came when the Department of Foreign Affairs and International Trade Canada (DFAIT) issued an advisory against all non-essential travel to Sri Lanka in the fall of 2006. Queen's University policy on international travel does not allow for student travel to countries where DFAIT advisories are in effect, and thus the advisory effectively

eliminated the possibility of future site visits. Additionally, the situation in southern Sri Lanka grew significantly more dangerous shortly after the first site visit, with bombing of civilian targets and kidnapping of aid workers and university staff occurring in several of the areas selected for project activities. This tragic turn of events highlights the importance of maintaining a high level of awareness of the political situation in any country where humanitarian engineering projects are being planned, though it should be noted that rapid changes in political climate and levels of danger are not always possible to predict.

It is an unfortunate paradox of conflict that it creates and exacerbates human needs, while also limiting the ability of people to safely address those needs.

### **3.6 Discussion and Lessons Learned from the RESTORE Project**

Despite the fact that the original plan for the RESTORE Project was rendered unfeasible as a result of conflict, several general lessons can be synthesized which may be of use for the planning of future humanitarian engineering projects.

The importance of observational research prior to the actual design and construction phase of a project cannot be overstated. During the planning stages of the RESTORE Project, for example, the original intent of the author was to construct several houses using straw bale, adobe brick or bamboo technology. The reasoning behind this intent was that housing shortages were a key problem in Sri Lanka, and the reconstruction of such a large portion of the country's building stock, if done in a sustainable fashion, could have a significant impact on the country's ecological footprint.

However, observational research and discussion with local villagers and academics led to the conclusion that the construction of several houses for select villagers was not the optimal way to structure the project from the perspective of maintaining social equity. Additionally, conversations with villagers highlighted the fact that concrete is preferred due to a high perceived quality, and a cultural association with affluence. This suggests that construction materials such as bamboo would be unsuitable in this application, due to a significantly different aesthetic. Instead, if a desire for more sustainable buildings was identified at the village level through the PRA, adobe, earthbag or straw bale techniques would probably be best suited to the context, since these techniques all involve a plaster finish which is similar to the aesthetic of a plastered masonry or non-engineered concrete structure.

This experience also highlights the importance of understanding the nature of the conflict situation in a given context, as violence arising due to conflict can severely impact the ability of a humanitarian engineer to personally work in an area, and can also hamper effective communication with local partners. While conflict-affected areas often have significant infrastructure needs, safety and logistics concerns dictate that humanitarian engineering projects should be pursued only in areas where significant conflict is not probable.

Based on the results of the field research discussed above, it was decided that earthbag housing is a promising housing technology for use in southern Sri Lanka. A detailed discussion of the thought process leading to this conclusion can be found in Section 6.3. However, since earthbag housing is also one of the least understood

alternative housing technologies from the perspective of structural performance, it was decided to conduct an experimental study of the structural performance of earthbag housing in order to assess its general suitability as a housing material. This study is discussed in detail in Chapters 4 and 5.

A transcription of the author's field notes from the 2006 site visit is presented in Appendix B.

## **Chapter 4**

### **Test Program and Methodology**

Due to the relatively recent development of earthbag housing techniques, as well as the informal manner in which most earthbag construction has been performed to date, there exists no commonly accepted standard for testing earthbag assemblies. As such, the methodology used in this study is the result of combining specimen construction techniques developed for use in real world earthbag applications with commonly accepted materials testing practices. The intent of this combination of field and laboratory practice is to obtain results which are both scientifically valid and consistent with the behaviour that would be expected in real world earthbag construction. International standards have been used where applicable, specifically for the tensile testing of polypropylene textile samples and for soil grain size distribution analysis.

#### **4.1 Testing Program**

A testing program was designed which consists of three main sets of tests. The first set (“part 1”) is a series of compressive tests of earthbag assemblies intended to determine the load-deflection characteristics of earthbags, as well as how these characteristics change with respect to bag size and soil properties. The second set of tests (“part 2”) aimed to characterize the granular materials used to fill the bags in part 1. The

third set of tests (“part 3”) involved characterization of the ultimate strength and load-deflection characteristics of the polypropylene textile used in the bags tested in part 1.

This testing program was designed to have two main goals:

1. To provide information on the compressive strength and load-deformation characteristics of unplastered earthbags, as the foundation for future full-scale earthbag wall testing.
2. To develop the tools and techniques used for testing earthbags in a laboratory setting.

The results of this testing program are presented in Chapter 5.

## **4.2 Experimental Methodology**

### **4.2.1 Compressive Tests of Unplastered Earthbags**

In order to obtain an estimate of the unplastered strength of earthbag assemblies in compression, bag sample specimens were assembled wherein three earthbags of a given size were stacked on top of each other, with a large load distribution plate placed on top in order to ensure uniform application of compressive load. This configuration is based on the only other laboratory-based earthbag test program (Dunbar & Wipplinger, 2006), which was in turn based on a modified version of ASTM E 447.

In order to characterize the effects of fill type on bag strength and stiffness, three different types of fill were selected for investigation. The first material investigated was

crushed granite with a nominal diameter of 12.7 mm, screened of all fine particles (also referred to as a “clear stone”) obtained from a quarry near Willowdale, Ontario. Crushed granite was selected for testing due to its increasing popularity as a fill material for earthbag foundations. This increase in popularity is due to the fact that, once the fines are removed from crushed stone, it is largely unaffected by the presence or absence of moisture. Conversely, soils (particularly clay-rich soils) have a tendency to swell and shrink significantly depending on moisture content (Minke, 2006). Since foundations must typically resist below-grade moisture exposure, crushed granite has been increasingly popular as a fill material for earthbag foundations.

Topsoil from the Kingston, Ontario region was also tested. Common field practice recommends against using topsoil due to its high percentage of organic content. This organic material decomposes over time, and would likely lead to a decrease in wall strength over the life of an earthbag building. However, clay-rich soil from below the topsoil layer was unavailable in the Kingston area during the testing phase of this thesis, and it was reasoned that, for short-term strength and stiffness tests, decomposition of organic material would not significantly affect the behaviour of earthbag prisms. However, it is possible that the existence of this organic matter in a non-decomposed state may affect the performance of topsoil-filled earthbags, which highlights the need for future testing which examines the behaviour of earthbags with a wide variety of fill types.

Anecdotal evidence and all existing earthbag literature suggest that increasing sand content would measurably decrease bag strength and stiffness. With this in mind,

the third material selected was a mixture of the Kingston topsoil and masonry sand, mixed in a 4:1 ratio by volume (soil : sand) using a portable mixer (Figure 4.1). This was done to determine if a 20% increase in sand content would produce measurably different earthbag behaviour. Masonry sand, whose composition is governed by ASTM C 144, was used as the sand additive. See Appendix C for the specified particle size distribution of masonry sand according to this standard.

Throughout this thesis, these two soils will be referred to as “topsoil” and “sandy soil” for the sake of brevity, though it should be noted that the particle size analysis presented in Chapter 5 shows that both soils are composed of more than 50% sand particles, and as such would be classified as sandy soils.



**Figure 4.1: Portable mixer used to mix masonry sand and topsoil.**

Polypropylene bags were obtained from the Lloyd Bag Company of Chatham, Ontario in three different nominal sizes: 457 mm X 762 mm, 508 mm X 914 mm, and 635 mm X 1016 mm (hereafter referred to as the “small”, “medium” and “large” bag sizes). In order to fill the bags, folding bag stands were fabricated out of hollow steel sections and used to hold the bags upright while they were filled by shovel, as shown in Figure 4.2.



**Figure 4.2: Folding “C”-shaped metal bag stand, with empty bag.**

In order to simulate field construction techniques as detailed in Hunter & Kiffmeyer (2004), fill was added until it was approximately 150 mm from the top of the bag stand based on the judgment of the author. This was done to gain some idea of the amount of variation in bag mass and volume that is likely to occur under field conditions. Once filled, the bags were removed from the stands and sealed by folding the top 50mm of the bag down, then folding that 50mm fold down again. Once this was done, three 50 mm spiral screws were used to “pin” the bag shut at the edges and in the centre of the fold, shown in Figure 4.3. This pinning step was improvised for these tests, since the prism test configuration does not provide adjacent bags for the specimen to abut against. In real world earthbag construction, the excess length of bag above the fill line is simply folded under the bag as it is laid down, and the adjacent bag in the course abuts against the folded end to keep the bag from opening (Figure 4.4). It was assumed that as long as the prism specimens did not fail due to failure of the pinned end, the overall behaviour of the pinned bags would be similar to the behaviour of bags with folded ends.



**Figure 4.3: Folded and pinned bag closure.**



**Figure 4.4: Unplastered earthbag wall, with folded bag ends abutted by adjacent bags (OK OK OK Productions, 2008).**

For the topsoil and sandy soil filled bags, filling was performed while the soil was moist to aid in compaction, though the exact moisture content was not determined. Once the bags were filled, they were laid flat and compacted by repeated blows from a length of 38mm X 89 mm lumber. Again, this does not perfectly simulate the field practice suggested by Hunter & Kiffmeyer (2004), which incorporates the use of concrete tampers (which are more ergonomic than a two-by-four), but the flat profile and rounded edges of a 38mm X 89 mm piece of lumber (which minimize the danger of ripping the bags) make it well suited to achieving the same results as a concrete tamper for small amounts of tamping. Once the bags were compacted to the point where additional blows did not visibly compact or deform the specimens, they were stacked and left to air dry for one month. Since the granite material was screened of fines, compaction was not an issue, and the bags were simply filled and stacked without tamping.

After filling the small, medium and large bags with granite, it was noted that the large bags were extremely difficult to manipulate, even with two people per bag. A representative bag was weighed, and was determined to have a mass of 89.2kg. Given that the intended purpose of this thesis is to explore building materials and techniques which are easy to construct with minimal specialized equipment or skill, it was decided that the large bags could be eliminated from the testing program given their lack of practical constructability. This confirms the colloquial description of bags larger than 508 mm X 914 mm as “way-too-big bags” (Hunter & Kiffmeyer, 2004).

After filling the bags, load distribution plates were constructed to ensure flat, uniform bearing surfaces on the top and bottom of the test specimens (as much as is possible given the irregularities of granite as a fill material). Both steel and wood were investigated as possible bearing plate materials, and wood was selected as the optimal material due to cost and weight advantages versus steel. As discussed in Chapter 5, the wood bearing plates did meet their intended purpose, but their performance suggests that steel may be a suitable choice for future earthbag tests at higher ultimate compressive loads, or for larger testing programs where durability will be a more significant concern.

The plates were designed to resist the compressive forces expected in these tests based on the maximum capacity of the testing machine (840 kN) and the material properties of hemlock lumber (Canadian Wood Council, 2001). This resulted in a section comprised of four 140 mm X 140 mm hemlock beams, with 19 mm plywood facing on top and bottom (see Figure 4.5 for detail). The hemlock beams were connected laterally with 19 mm threaded rod inserted through holes drilled at the neutral axis, at the midpoint and approximately 100 mm from each end (3 rods total).

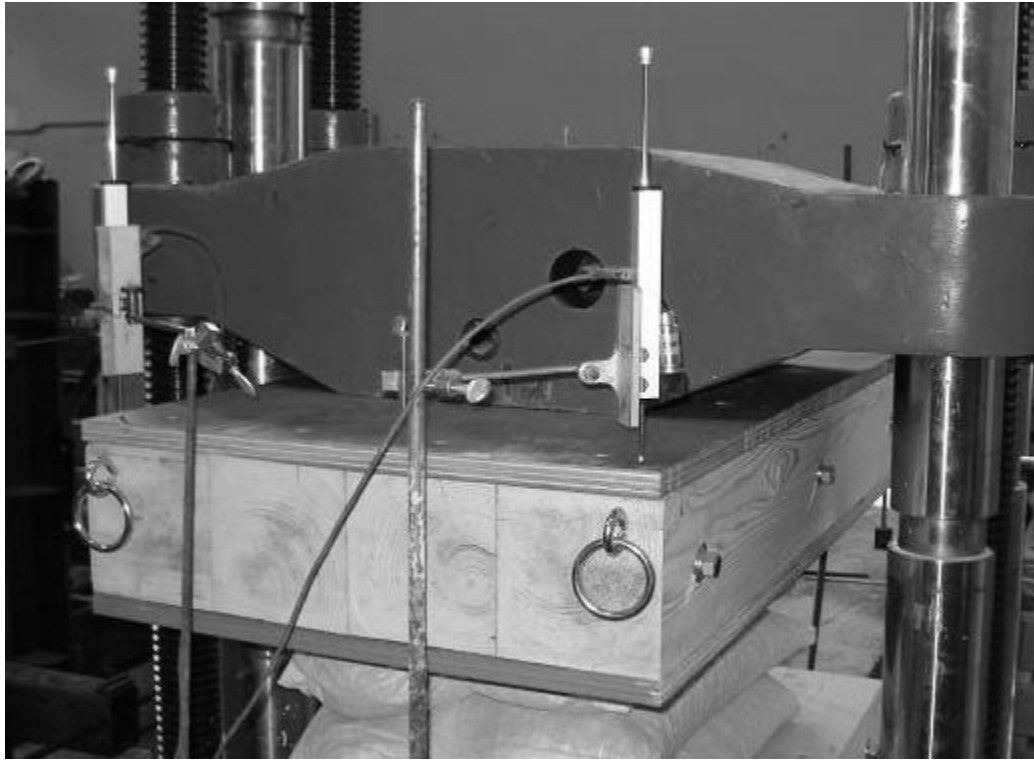


**Figure 4.5: Earthbag specimen MG1, with hemlock loading plates on top and bottom.**

The specimens were tested in a Riehle tension/compression testing machine rated to a maximum load of 900 kN, using stroke control to apply a constant rate of compression. The first test was run at a relatively slow stroke rate of 2 mm/min in order to gain some perspective on the load/stroke relationship for earthbags without risking quick, violent failure. Once it was determined that the specimens would deform a substantial amount before failure, and that this failure would not likely be sudden or

violent, the stroke rate was increased to 4 mm/min for the rest of the granite filled bags, and 8 mm/min for the soil-filled bags. At the maximum stroke rate of 8 mm/min, the time between starting the test and failure was in the range of 10-20 minutes.

In order to capture the load/stroke relationship, as well as to ensure uniform deflection of the top bearing plate (which would suggest uniform distribution of load to the earthbags themselves), instrumentation consisted of the load and stroke values from the Riehle machine as well as four linear potentiometers (LPs) placed on top of the top bearing plate (shown in Figure 4.6). It should be noted that, due to equipment limitations, only two LPs were used on the tallest specimens (G9). Data from all sensors was obtained using DT Measure Foundry data acquisition software.



**Figure 4.6: Specimen in testing machine from above, showing LP instrumentation.**

This initial testing program is summarized in Table 4.1, which also shows the two-letter naming convention used for each combination of bag size and fill, wherein the first letter signifies bag size (S – small – 457 mm X 762 mm, M – medium – 508 mm X 914 mm) and the second letter signifies fill type (G – granite, T – topsoil, S – sandy soil). Thus, test SS2 signifies the second test performed on small bags filled with sandy soil. Note that 5 tests of each bag size were done for granite-filled bags, while only two of each size were done for topsoil- and sandy soil-filled bags. It was initially intended to perform 5 tests on each combination of bag size and fill type, but it was recognized during testing that the available compressive testing machinery was capable of failing the

granite bags, but not the soil-filled bags. The motivation behind performing 5 tests was to obtain an average ultimate failure load for the bags. Since this was not possible with the soil-filled bags, it was decided to reduce the number of tests to 2 tests per size/fill combination, as this would give some idea of the variability of the load-deflection relationship for each combination while also making most efficient use of scarce equipment time. It should be noted, however, that this small sample size does limit the validity of statistical inferences made from the resultant data.

**Table 4.1: Initial Compressive Testing Program.**

|                                    | <b>Crushed Granite</b> | <b>Topsoil</b> | <b>Sandy Soil</b> |
|------------------------------------|------------------------|----------------|-------------------|
| <b>Small Bags (457mm X 762mm)</b>  | SG (5 tests)           | ST (2 tests)   | SS (2 tests)      |
| <b>Medium Bags (508mm X 914mm)</b> | MG (5 tests)           | MT (2 tests)   | MS (2 tests)      |

It should also be noted that, as discussed in Chapter 5, the first two granite bag tests (SG1 and SG2) were not run to failure, but were only run up to approximately 250 kN to ensure that the testing apparatus was behaving as expected. Two additional small granite-filled bag tests were run as part of the second testing program to compensate for this.

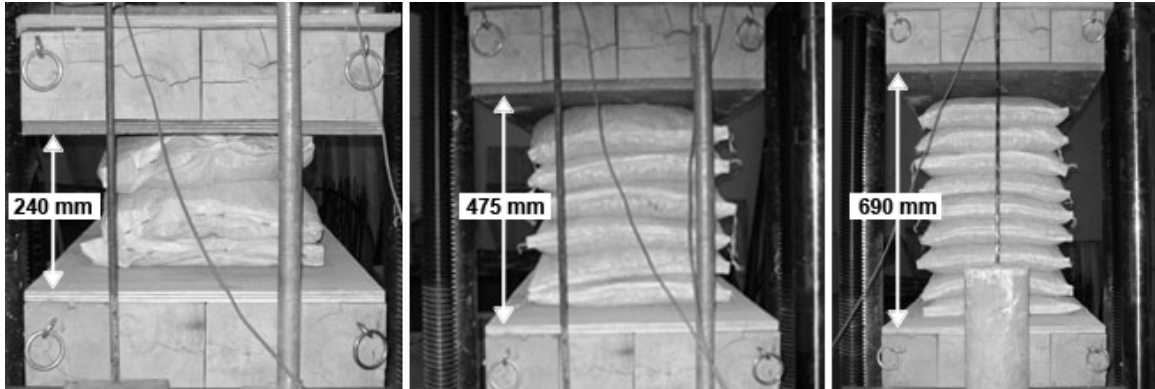
After the initial testing program was completed, it was decided to supplement the results with a second testing program focusing specifically on granite-filled bags. This is due to the fact that, as discussed in Chapter 5, granite-filled bags have substantially lower

ultimate strength values than soil-filled bags, and thus represent, of the materials tested here, the “worst-case scenario” for bag fill material. Thus, a deeper understanding of the range of ultimate loads for granite-filled bags may assist engineers in determining design values and safety factors for earthbag strength. The second compressive testing program is similar to the first in terms of testing apparatus and instrumentation, but rather than testing only specimens of three bags, additional specimens were constructed using three bags, six bags, and nine bags. These configurations were chosen to determine the effect of stack height on compressive strength of earthbag prisms (for the six- and nine-bag stacks). Table 4.2 shows the testing matrix and naming convention for this second round of compressive tests. The naming convention for this set of tests is slightly different. The first letter for all tests is G, since all bags in this program were filled with granite. The second character represents the height of the stack (3, 6 or 9). For each of these configurations (except G3) 3 tests were run to gain some idea of the variability of the ultimate load. Note that the G3 tests were fabricated with the same configuration and methodology as the SG tests from the first testing program. Only 2 G3 tests were run to compensate for tests SG1 and SG2, as mentioned above.

**Table 4.2: Second Compressive Testing Program.**

|                        | <b>3 Bag Stack</b> | <b>6 Bag Stack</b> | <b>9 Bag Stack</b> |
|------------------------|--------------------|--------------------|--------------------|
| <b>Gravel Fill (G)</b> | G3 (2 Tests)       | G6 (3 Tests)       | G9 (3 Tests)       |

Figure 4.7 shows a visual comparison of the stack height of 3-, 6- and 9-bag specimens, shown with long bag axis into the page. Approximate height values are given based on the average pre-compression height of SG, G6 and G9 specimens.



**Figure 4.7: Visual comparison of 3-, 6- and 9-bag specimens (not to scale, height values approximate).**

#### **4.2.2 Soil Characterization**

In order to gain a greater understanding of how the compressive behaviour of earthbags varies with the type of fill, particle size analysis tests were conducted for the crushed granite, topsoil and sandy soil. Unlike determining the compressive strength of earthbag specimens, soil particle size analysis is well understood, and all granular materials were analyzed according to the provisions in ASTM D 421, as well as ASTM D 422. These tests involve two types of analysis. First, mechanical sieving of a representative quantity of soil is done by passing the soil through a series of sieves with openings of decreasing size. The mass retained on each sieve can then be weighed and compared to the initial sample weight to give a percentage of soil particles with diameters

larger than the sieve on which they were retained, but smaller than all sieves above the one in question. This is straightforward for large particles, but a second method of analysis is used for particles smaller than 2 mm due to the difficulty in effectively sieving small particles.

Hydrometer analysis involves the dispersion of soil particles in a column filled with a solution of water and dispersing agent. For these tests, Calgon (a commercial water softener) was used as a dispersing agent since it consists of powdered sodium hexametaphosphate. The sodium ( $\text{Na}^+$ ) ions react with polyvalent cations (such as  $\text{Ca}^{++}$ ) which normally form interparticle linkages between clay particles. By breaking down these linkages, the dispersing agent ensures that no large flocs form that might otherwise skew the particle size analysis. Once the soil is dispersed in the water-dispersing agent solution, a hydrometer is used to measure water density at a series of intervals over the course of 24 hours. As soil particles settle to the bottom of the column, water density decreases and the hydrometer is less buoyant. Readings from a calibrated hydrometer can then be used to calculate the percentage of soil left in suspension at a given time. The amount of time taken by the soil particles to settle can then be used to determine the diameter of particle smaller than the percentage determined using the hydrometer. This is based on the principles of Stokes' Law, which states that the settling velocity of particles in a fluid is proportional to their diameter. It should be noted that since the crushed granite fill was clear stone (i.e. no fine particles), it was possible to determine the particle size distribution with mechanical sieving only, and no hydrometer analysis was necessary. Full hydrometer analyses were completed for the topsoil and sandy soil.

The results of these tests can be found in Chapter 5. Since soil particle size distributions can vary greatly from one location to another, these two soil tests alone do not represent a large fraction of the soil particle size distribution spectrum. However, if future earthbag testing efforts also include soil particle size analysis as part of their testing program, it may one day be possible to derive an empirical relationship between particle size distribution and earthbag strength and/or stiffness. This would be of great significance for engineers working with earthbag technology, as particle size analysis could be done at an early stage of the project to inform the structural design process.

#### **4.2.3 Tensile Testing of Polypropylene Bag Fabric**

Since failure of unplastered earthbag prisms occurs when the bags themselves rupture, the tensile strength and load-deflection behaviour of the polypropylene bags were investigated. The bags are fabricated from a woven polypropylene textile, and as such, initial testing was done under the requirements of ISO 13934-1. However, as discussed in Chapter 5, the tests showed evidence of grip slippage, as well as a tendency to fail due to stress concentrations at the grips, underestimating the true strength of the fabric. In order to obtain a more representative value for the tensile strength of the textile, further specimens were tested according to ASTM D 4595. While not sold as a geotextile, the woven polypropylene bag material is similar in construction to woven polypropylene geotextiles, and as such, it was decided to test the material under this standard, as it tends to give more representative material property values than narrow strip tests. Narrow strip testing such as that prescribed by ISO 13934-1 can yield ultimate

strength and elongation values which are not characteristic of the material's true values due to the influence of edge effects along the sides of the strip, which have a tendency to bow inwards as the material elongates due to severe Poisson's ratio effects (Koerner, 1997). The advantage of the wide-width strip method is that, due to the wider width of the specimens (200 mm, as opposed to 50 mm in ISO 13934), the influence of edge effects are minimized. Additionally, the wide-width grips used for this test are fabricated in such a way so as to reduce slipping and grip failure of polypropylene textiles. These tests were conducted by an independent laboratory, CTT Group, located in Saint-Hyacinthe, Quebec. A summary of test results along with average strength values are given in Chapter 5 in terms of kN per metre width, which is a more practical means of reporting strength for textiles versus ultimate stress, since the thickness of thin woven textiles can be difficult to accurately determine.

## **Chapter 5**

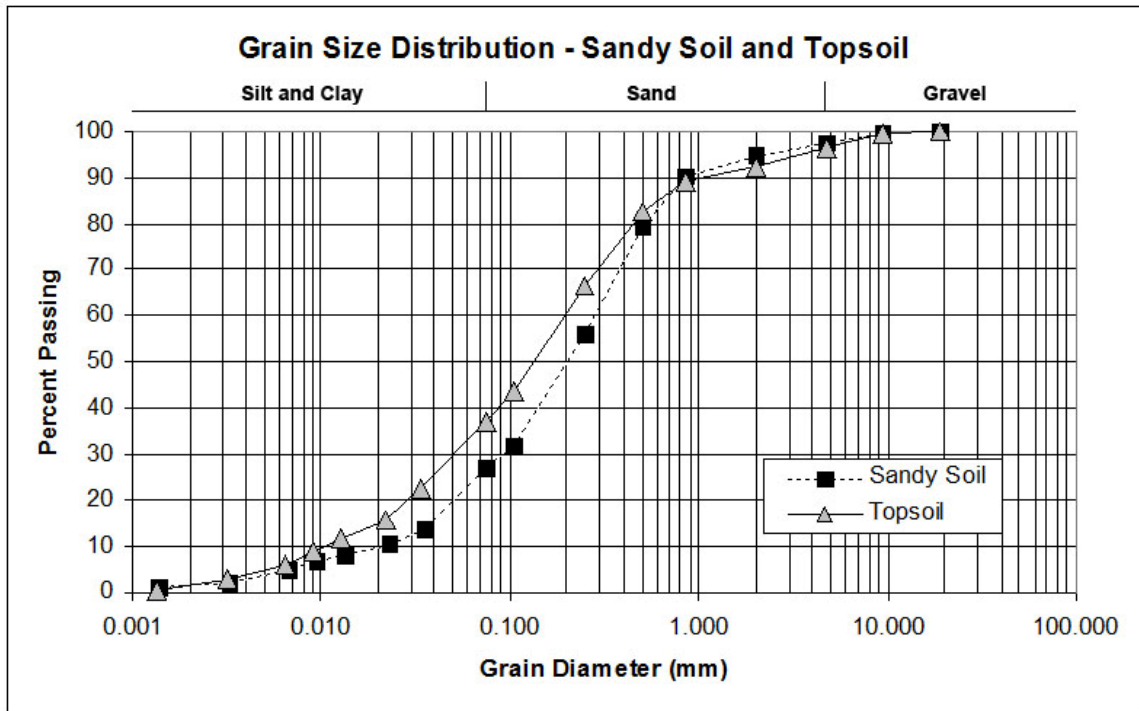
### **Results and Analysis**

This chapter presents the results of the testing program described in Chapter 4. Section 5.1 describes the results of the particle size analysis conducted on the granite gravel, topsoil and sandy soil materials (as defined in Chapter 4). Section 5.2 describes the corrective measures which were used to compensate for experimental error in the earthbag testing program. Sections 5.3, 5.4 and 5.5 describe the results of the compressive tests conducted on granite-filled, topsoil-filled and sandy soil-filled earthbag specimens, respectively. Sections 5.6, 5.7, and 5.8 present an analysis of the effects on specimen strength and stiffness of fill type, stack height and bag size, respectively. Section 5.9 presents the results of tensile tests conducted on the polypropylene textile used to fabricate the bags used for the tests discussed in Sections 5.3, 5.4 and 5.5.

#### **5.1 Ancillary Tests - Soil Particle Size Analysis Results**

Particle size distribution plots were constructed for the sandy soil, topsoil, and granite gravel. For both soils, less than 5% of the material by mass can be classified as gravel or larger. The composition of the remaining fraction varies between the topsoil and sandy soil, as was expected given the addition of masonry sand to the sandy soil. Figure 5.1 shows the particle size distribution for both the sandy soil and the topsoil. It should be noted that, given that particle size varies over several orders of magnitude, the

x-axis of the graph is plotted using a logarithmic scale. The numerical results of the particle size analyses of both soils are presented in Appendix C.

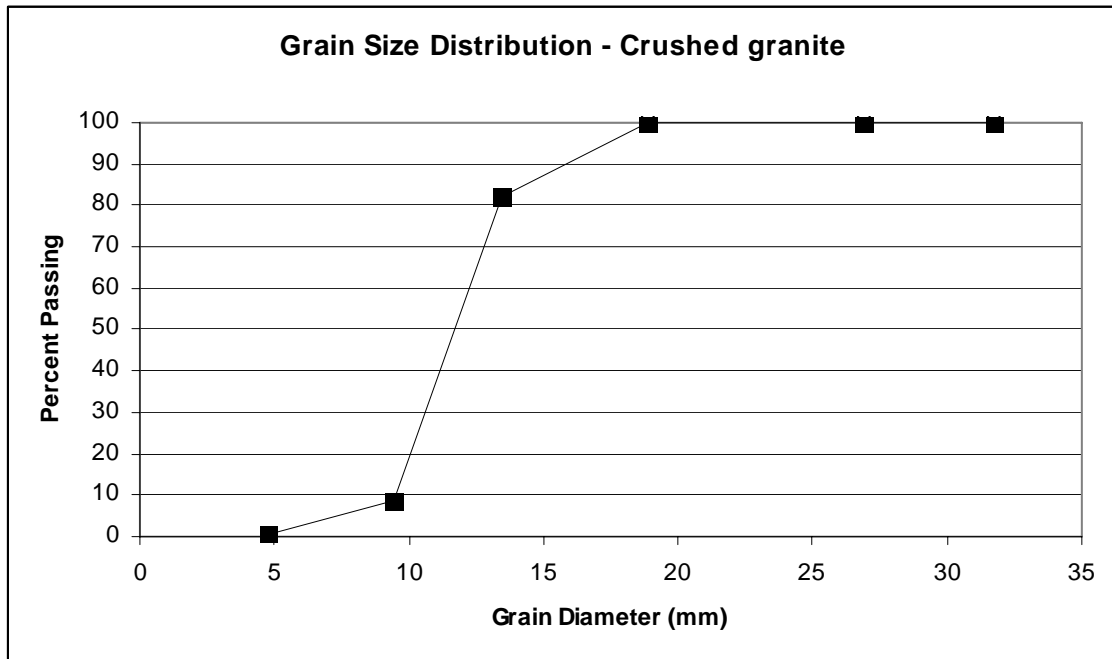


**Figure 5.1: Grain size distribution curve results for sandy soil and topsoil.**

The results confirm that the topsoil contains a higher proportion of clay and silt particles than the sandy soil, which is to be expected given the addition of sand particles to the sandy soil. The topsoil is composed of 37% silt and clay particles by mass, whereas the sandy soil is 27% silt and clay particles. The results further show that the sandy soil is composed of 70.5% sand particles by mass, whereas the topsoil is composed of 59.2% sand particles.

Results for the crushed granite are presented in Figure 5.2. These results show that the material is largely (>70%) composed of particles with diameters between 9.4 and

13.4 mm, which agrees with the material's nominal diameter of 12.7 mm ( $\frac{1}{2}$ " ) as specified by the material supplier. It should be noted that, since the granite particle sizes vary much less than the soil particles, the grain size distribution is not presented using a logarithmic x-axis as above.



**Figure 5.2: Grain size distribution curve for crushed granite.**

## 5.2 Correction of Earthbag Test Results

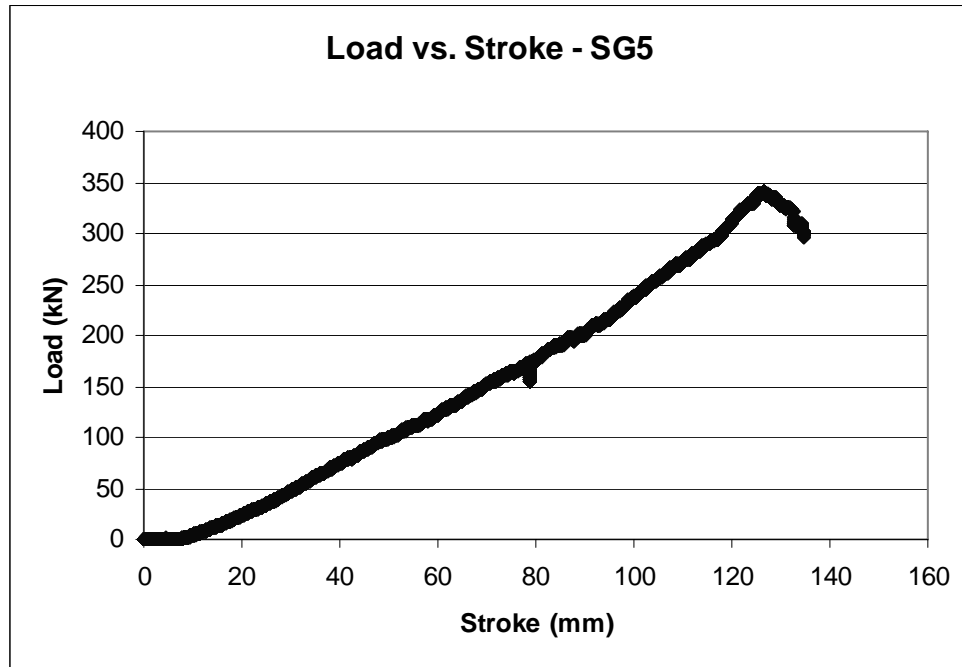
This section describes corrections applied to the raw load-deflection plots in order to account for non-uniform load application and deformation of the timber top-plate.

One general observation from the results of the earthbag tests concerns the behaviour of these specimens upon initial loading. The load-stroke plots for all tests initially show very low or even flat load-displacement curves for a period of time before

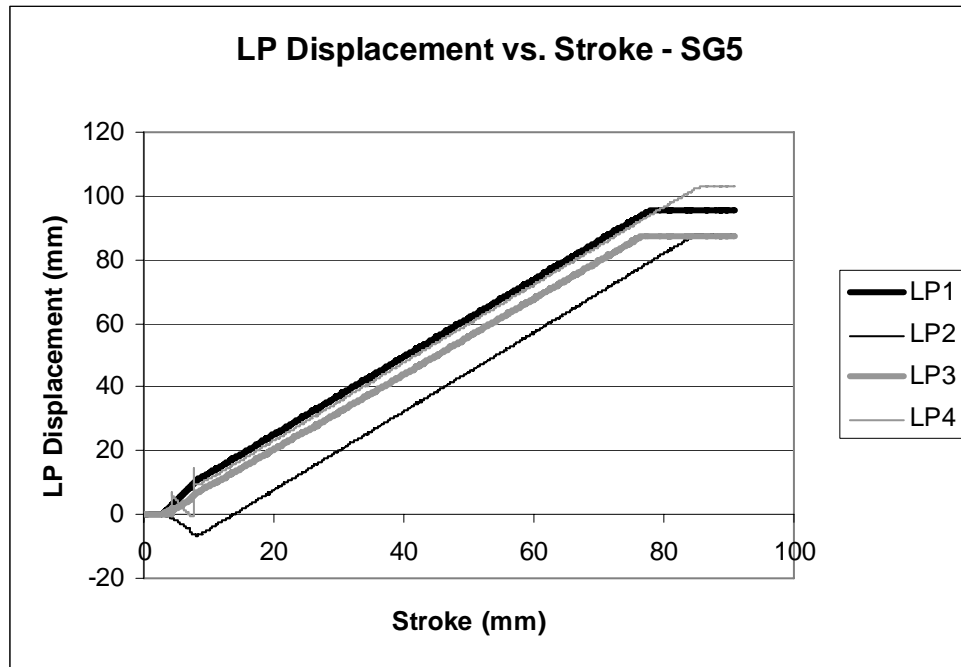
the measured load starts to increase with further stroke. This can be seen in Figure 5.3, which shows the load-deflection plot for specimen SG5, a typical small granite-filled specimen. This initial load response is not representative of material behaviour, but is due to the fact that the top loading plate was tilted at the beginning of every test. This was minimized as much as possible, but the irregular geometry of the bags (and in particular the gravel-filled bags) made this unavoidable. As such, initial displacement of the loading head first served to level the loading plate. Once the loading plate was level and in contact with the entire surface of both the loading head and the earthbag specimen, it began displacing downwards in a uniform manner.

Four linear potentiometers (LPs) were used to measure the deflection of each corner of the top-plate to determine whether uniform displacement of the top-plate was occurring. The plot of displacement (as measured by the LPs) versus machine stroke for specimen SG5 (a typical SG specimen) presented in Figure 5.4 shows that once the top-plate is leveled by the cross head (at about 8 mm of stroke), all four LPs displace downward at the same rate, indicating uniform plate displacement. Figure 5.4 also indicates that LPs 2 and 4 initially measured negative displacement due to the fact that, upon contact with the loading head, the lower side of the top-plate rose while the higher side fell, until the plate was level. This also explains the fact that the rates of displacement measured by LPs 1 and 3 are higher from 0 to 8 mm of machine stroke, as this was the amount of stroke required to level the top-plate. The flat region of the stroke-displacement plots indicates the point at which the LPs ran out of travel. Each of

the LPs ran out at a different value due to the fact that there were small differences in the initial displacement of the LPs as they were set up.



**Figure 5.3: Load versus stroke plot for specimen SG5, showing approx. 10 mm of machine stroke before full contact between loading head and top-plate.**



**Figure 5.4: LP displacement versus machine stroke, specimen SG5.**

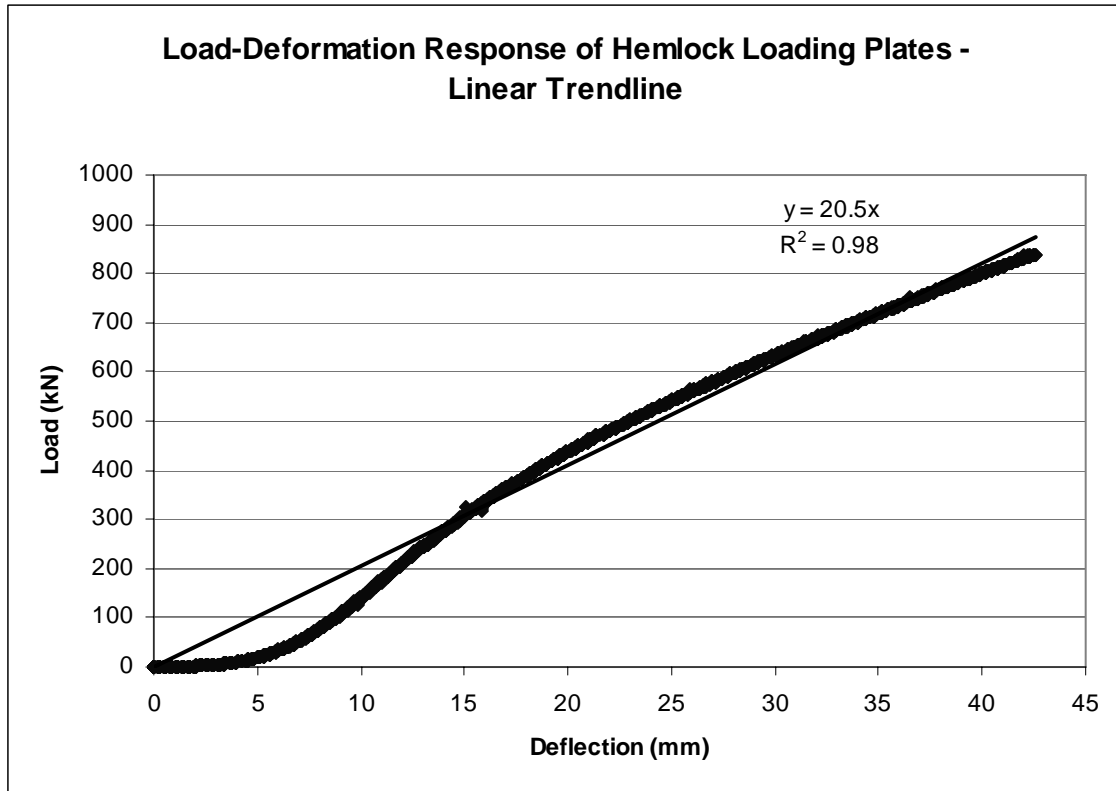
Due to the compressible nature of the hemlock loading plates used to ensure an even distribution of load, it was necessary to apply a correction factor to the stroke value recorded from the testing machine's output. In order to do this, it was first necessary to determine the load-deformation response of the loading plates. This was accomplished by running a compression test on the loading plates in the same configuration as was used in the earthbag tests, but with a steel plate substituted in place of earthbags. The steel plate chosen had dimensions roughly similar to the earthbags tested, though due to resource limitations the actual dimensions are slightly longer and narrower than the small and medium earthbags, at 939 mm x 389 mm. The compression test yielded a plot of load vs. machine stroke. The strain in the steel plate was calculated based on the stress resulting from the applied load and a modulus of elasticity of 200 GPa (CISC, 2004).

This strain was then multiplied by the steel plate's thickness of 40 mm in order to determine the compression attributable to the steel plate. This was calculated at each time step recorded by the data acquisition system, and then subtracted from the corresponding machine stroke value to determine the deformation of the hemlock loading plates. At the testing machine's maximum load of 840 kN, the deformation of the hemlock plates was 42 mm.

Figure 5.5 shows the load-deformation curve for the loading plate. Theoretically, wood is a linear material, and thus it was determined that the small slope observed up to about 5 mm must be attributable to the fact that this curve was obtained after running 28 tests using the hemlock plates. As such, it was assumed that the plywood facing on top of the upper plate must have been crushed, resulting in low stiffness until the load became high enough to mobilize the full stiffness of the plates.

In order to correct the measured load-displacement curves of the earthbag specimens, it was necessary to find an appropriate trend line equation for the hemlock load-deformation curve. Two trend lines were produced using the automated trend line calculator in Microsoft Excel 2003, which is based on the least squares method. The first is linear, which approximates the load-deformation response of the plates assuming they behave in a perfectly linear fashion. It was found by plotting the load on the plates as a function of deformation and finding the line of best fit for the data, and forcing this line through the origin, since at a load of zero there should be no deformation. The plate deformation could then be found at any load by dividing the load value by the slope of

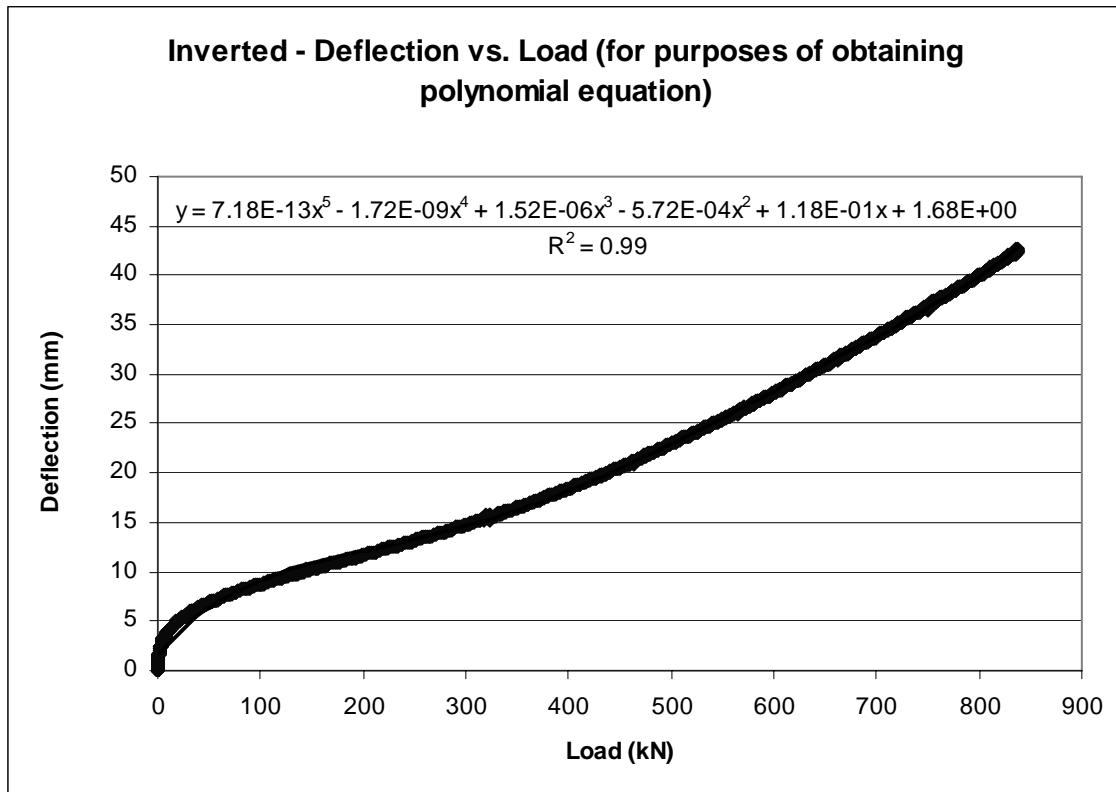
the resultant trend line, which was calculated to be 20.5 mm/kN. The load versus deformation plot for this trend line is shown in Figure 5.5.



**Figure 5.5: Load versus deformation plot for hemlock plates, with linear trend line.**

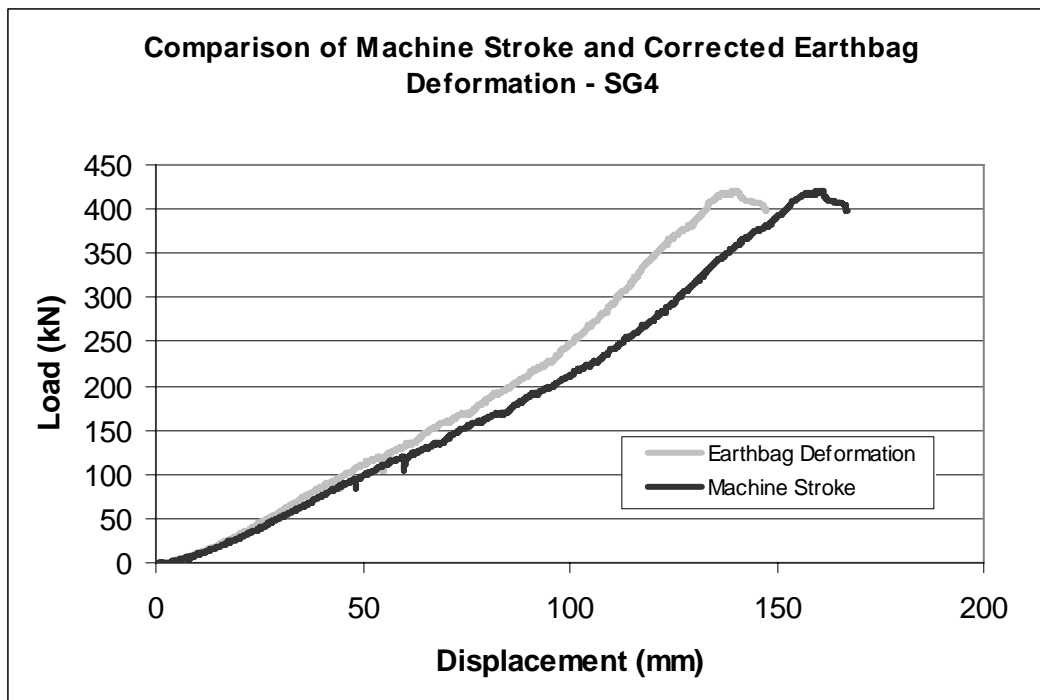
The second trend line is a fifth-order polynomial which captures the variation in the slope of the load-deformation response from low to high loads. Since the nonlinear behaviour of the plates was assumed to be the result of plywood crushing, it was decided to use the linear trend line equation to correct the first ten tests, of which all but one were run below the testing machine's full capacity. The polynomial trend line equation was used to correct all subsequent tests, since these tests exceeded the maximum capacity of

the machine several times, resulting in the crushed plywood. To determine the polynomial trend line, deformation was plotted as a function of load, such that the resultant trend line equation could be used to directly calculate the deformation of the plates at any load. It should be noted that the equation of the polynomial trend line, displayed in Figure 5.6, has been truncated for clarity, and as such would not accurately reproduce the trend line if plotted as written. In order to obtain a trend line whose shape closely matches the measured load-deformation curve (i.e. with an  $R^2$  value of 0.9 or higher), it was necessary to use a fifth-order function and carry the coefficients to additional decimal places. The full equation is given in Appendix D.



**Figure 5.6: Load versus deformation plot for hemlock plates, with polynomial trend line.**

Figure 5.7 shows the load-stroke and corrected load-deformation plot for a typical small gravel-filled specimen, SG4. This figure shows the magnitude of the correction factor for a typical gravel-filled specimen. While the machine stroke overestimates the deformation of the earthbags by approximately 20 mm at ultimate load, the general features of the plot remain the same, and show evidence of strain hardening before failure.



**Figure 5.7: Load versus machine stroke and load versus earthbag deformation, specimen SG4.**

It should be noted that, since the post-cracking behaviour of wood is inelastic, the load-deformation response curve during unloading would not be identical to the curve measured during loading. Additionally, since the earthbag specimens undergo stress

relaxation when the stroke is held constant, these correction equations are not valid for the response of the specimens when loading is paused. With this in mind, the figures in this chapter which display earthbag specimen test results are displayed using machine stroke rather than earthbag deformation in order to graphically represent stress relaxation and unloading behaviour. The corrected numerical values for specimen strength and stiffness are used in the quantitative analysis of the effects of fill type, stack height and bag size in Sections 5.6, 5.7 and 5.8, respectively.

A summary of ultimate load, corrected values for earthbag deformation at ultimate load, as well as deformation at 50, 100, 200 and 300 kN are presented in Appendix E. Additionally, the nominal bearing areas of the small and medium bags were used to calculate a nominal stress value which, while approximate, allows for a comparison of the relative strength of the small and medium bag sizes. Nominal stiffness of the bags was calculated by dividing ultimate strength by earthbag deformation at ultimate. Finally, the length of the bags was used to calculate the capacity of the specimens in terms of kN per metre of wall length. This figure is compared with the values for other alternative construction materials and conventional construction configurations in Chapter 6.

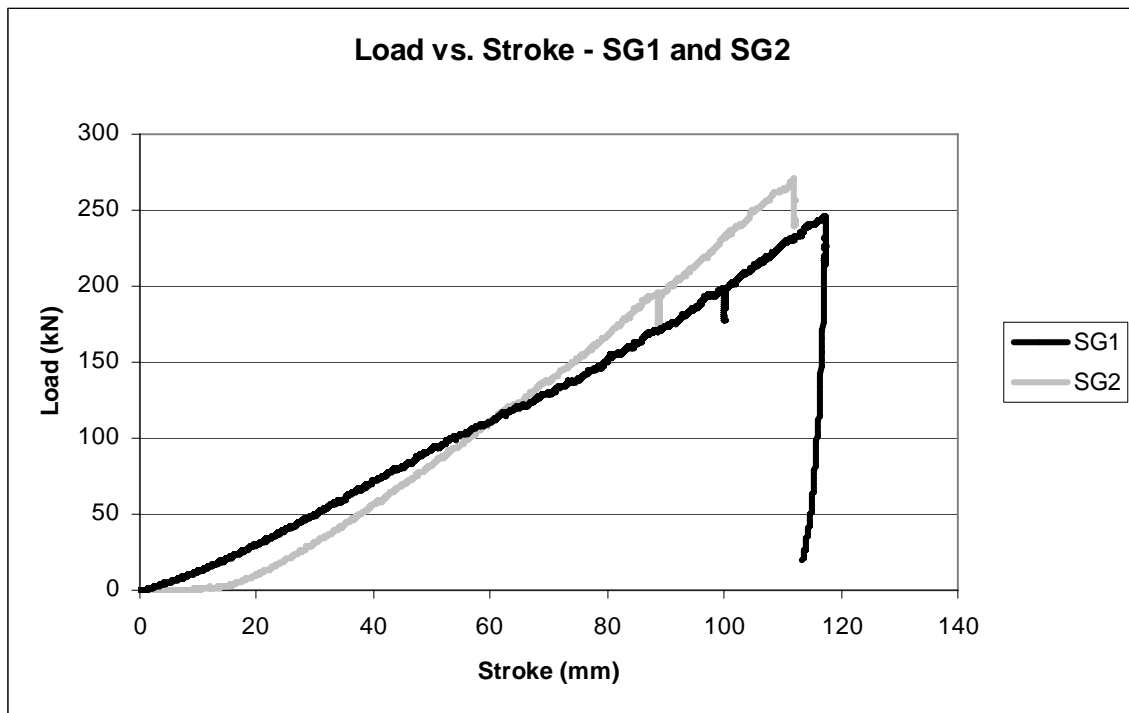
## **5.3 Granite-filled Earthbag Results**

### **5.3.1 Small Granite-filled 3-Bag Stacks**

It was necessary to define a failure criterion for earthbags, as a standard definition does not currently exist. It was decided to use the term “failure” to denote the point at

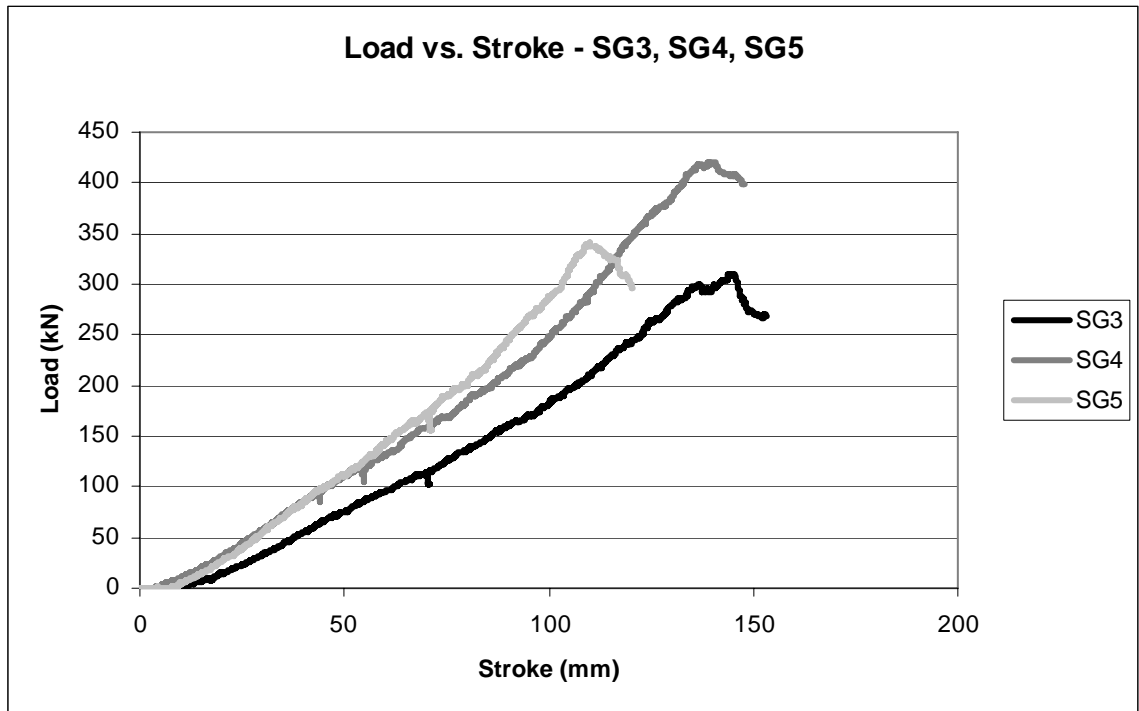
which the polypropylene bags have ripped enough to cause a loss of fill material, leading to a sudden decline in load when loading the specimens in stroke control. As can be seen in Figure 5.9 (particularly in test SG3), this point is sometimes followed by a further increase in load as the stones shift following the initial loss of fill, but this is followed by total failure of the specimen shortly thereafter, once a large amount of fill has been lost.

Small (457 mm x 762 mm) gravel-filled bags were tested first. Five specimens were tested as part of the first testing phase, with two additional specimens tested during the second phase. Of the first set, the first two tests were not run to failure, but rather were used to ensure the adequacy of the testing machine, specimen and loading plate configuration. The results from these tests are presented in Figure 5.8. The portion of the curve after peak load for specimen SG1, which was unloaded immediately at a load of 250 kN, shows extremely inelastic unloading behaviour. As well, both SG1 and SG2 show evidence of stress relaxation, as evidenced by the decrease in load under sustained stroke.



**Figure 5.8: Load versus stroke, specimens SG1 and SG2 (not tested to failure).**

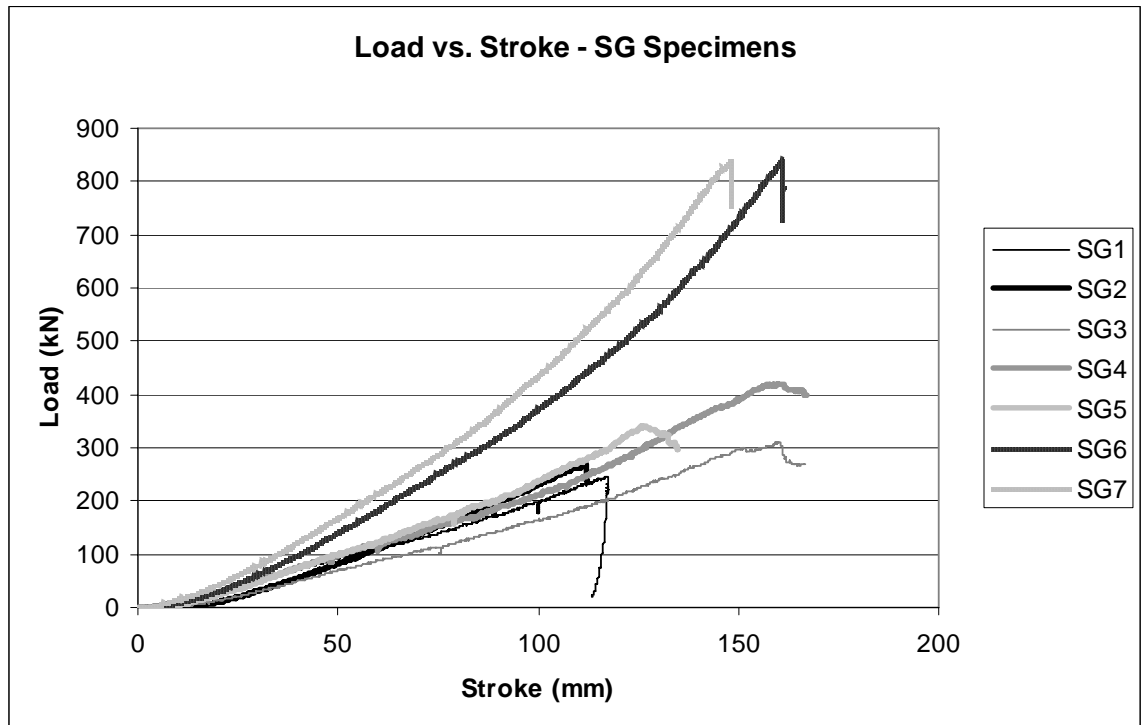
Once it was determined that the testing configuration had the capability to apply a uniform load to the bags, tests SG3, SG4 and SG5 were run to failure. The results of these tests are presented in Figure 5.9. The load vs. stroke response is approximately linear at low loads, with some strain stiffening as the load approaches failure. No failure of the pinned bag closure or bag seam was observed. The variation in ultimate load and stiffness for these samples is likely due to the heterogeneous nature of the fill material as well as imperfections in bag fabrication and stacking, though these fabrication imperfections were minimized through the use of a standardized fabrication procedure as discussed in Chapter 4.



**Figure 5.9: Load versus stroke, specimens SG3, SG4 and SG5.**

Two additional small granite-filled 3-bag specimens were tested five months after tests SG1-5, in order to obtain a larger sample size. These tests (SG6 and SG7) exhibited significantly different behaviour than tests SG1-5. Figure 5.10 shows the load vs. stroke plots for tests SG1-7 (i.e. all small 3-bag gravel specimens tested). Test SG6 was run at a stroke rate of 8 mm/min, rather than 4 mm/min (at which all other granite bag tests were run), and displayed significantly stronger and stiffer performance than the first round of tests. It did not fail within the loading range of the testing machine, though it did show signs of failure when the test was stopped at machine's maximum load of 840 kN. In order to determine if the change in loading rate was responsible for the change in bag behaviour, test SG7 was run at the original loading rate of 4 mm/min. However,

specimen SG7 displayed similar behaviour to test SG6 in terms of both strength and stiffness, which suggests that the effect of the higher loading rate was insignificant.



**Figure 5.10: Load versus stroke, all SG specimens.**

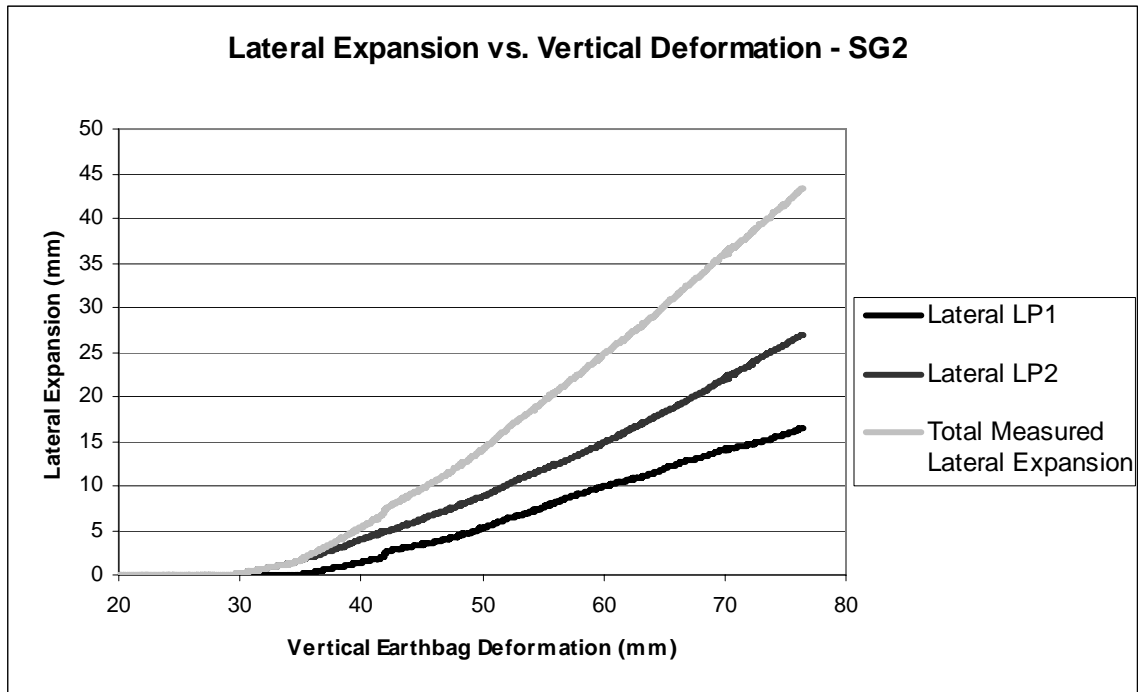
A statistical analysis was performed to determine the statistical significance of the values for SG6 and SG7 relative to specimens SG3-5. The U test, also known as the Wilcoxon, Mann-Whitney, or rank-sum test, is an appropriate test for determining whether two samples are likely to have come from the same population, without requiring that the populations be normally distributed. Since it is not known if the populations in question are normally distributed, this test was selected for use here. In this case, it would be useful to determine if the measured ultimate loads for SG6 and SG7 are likely to have come from the same population as those measured for specimens SG3-5.

Unfortunately, the U test requires that each sample have a minimum of three values in order to determine the critical value at significance levels of 0.05 or smaller (Devore & Peck, 1993). Since the sample group of SG6 and SG7 has only two values, an alternate approach was taken. Specifically, the values for SG6 and SG7 were examined to determine their statistical significance in accordance with ASTM E 178, assuming a normal distribution of ultimate load values for small gravel-filled earthbag specimens. As stated previously, it is not known if the populations in question are normally distributed, but the assumption is made here to allow for the application of ASTM E 178. The results of this analysis verify the null hypothesis that the values for SG6 and SG7 come from the same normal population as the values for SG3, SG4 and SG5 with a significance level of greater than 10%. As such, it is possible that the large values for specimens SG6 and SG7 represent the large variability of earthbag specimen strength. However, it is the opinion of the author that there is likely an underlying physical cause for the difference in strength between specimens SG3-5 and specimens SG6 and SG7 which, if identified and controlled, would reduce the variation in specimen strength. In either case, it is clear that design values for earthbag compressive strength should be based on a conservative interpretation of specimen test results. Further discussion of the strength of earthbags in the context of housing design is presented in Chapter 6.

One possible factor which may have contributed to the anomalous behaviour of specimens SG6 and SG7 is specimen age. The specimens used for the first round of tests were filled and stored for a period of one month before testing, while the specimens used for round two were filled and tested within a one-week period. It is possible that the bags

from round 1 were weakened by the longer storage time, though the exact mechanisms for this weakening are not clear. The bags were stored indoors, so ultraviolet radiation (which can degrade polypropylene) was not a significant factor. As well, all bags were inspected for tearing prior to testing to ensure no damage occurred during storage. It is possible that the polypropylene may have undergone creep after being stacked for one month, and this may have weakened the bags. If this is true, it indicates the need for future tests to examine the effects of specimen age on strength and stiffness. Additionally, it is possible that variability in terms of textile strength may have influenced the results. Unfortunately, the manufacturer was unable to provide information on the control of bag quality during manufacturing.

In addition to ultimate load and vertical deformation, tests SG2 to SG5 were run with instrumentation to measure the lateral deformation of the middle bag of each specimen. A sample plot of lateral expansion versus vertical deformation for specimen SG2 is presented in Figure 5.11. The lateral LPs were set up such that there was a small gap between the instrument tip and the side of the specimen, hence the initially flat instrument response as the specimen expanded enough to make contact with the instruments. As such, the first 20 mm of machine stroke, showing zero lateral LP response, have been omitted from Figure 5.11.



**Figure 5.11: Lateral expansion versus vertical earthbag deformation, specimen SG2.**

Since the relationship between lateral expansion and vertical deformation appeared to be linear, it was possible to estimate the ratio of lateral deformation to longitudinal deformation for each of these specimens. This was calculated by summing the deformation measured from each of the two lateral LPs to obtain the total lateral expansion of the specimen for each time step, plotting these values against the vertical deformation of the earthbags, and fitting a linear trend line to the data. The results are presented in Table 5.1 which gives the slope of the trend line (i.e. the ratio of lateral expansion to vertical compression) and the  $R^2$  value (coefficient of determination) for each trend line. The average ratio for these specimens is 0.823, though it should be noted that specimen SG2 is higher than the values measured for specimens SG3, SG4 and SG5.

The average ratio for these last three specimens is 0.756. When tested in accordance with ASTM 178 (as discussed above), the null hypothesis that all values come from the same population is disproved at a significance level of 2.5%, suggesting that the anomalous value may be discarded and the average ratio of specimens SG3-5 taken to be a representative average of the ratio of the small granite-filled specimens.

**Table 5.1: Measured lateral-to-vertical deformation ratio and associated  $R^2$  value for specimens SG2-5**

| Specimen | Calculated Lateral-to-Vertical Deformation Ratio | $R^2$ Value of Trend Line |
|----------|--|---------------------------|
| SG2      | 1.023  | 0.996                     |
| SG3      | 0.735  | 0.994                     |
| SG4      | 0.789  | 0.996                     |
| SG5      | 0.744  | 0.999                     |

All specimens displayed the same failure mechanism, involving local failure of the polypropylene bag material leading to a loss of bag fill. This failure mechanism involved the action of “bulges”, as shown in Figure 5.12. As load was applied to the specimens, they compressed vertically and expanded laterally. However, due to irregularities in the geometry of the bags, bulges would typically become apparent wherein one of the bags would expand laterally to a greater extent than the others. Typically, these bulges developed on bags in the middle of the specimen (i.e. in between

two other bags, and not in direct contact with a loading plate), as shown in Figure 5.12. This is likely because the bags in contact with the loading plates are partially restrained from lateral expansion due to friction at the bag-plate interface. Simultaneously, the lateral motion of the granite gravel within the bags severely degraded the bag-to-bag interfaces, leaving them completely disintegrated well before the overall failure of the specimen. Specimens were not disassembled at various loads to determine the load at which this disintegration typically occurs. However, audible crackling of the specimens typically began at loads of around 100-150 kN, with loud, constant crackling by no later than 200 kN, suggesting shifting of gravel and snapping of textile fibres. It is likely that the bag-bag interface disintegrated in this loading range. Once a bulge had protruded sufficiently beyond the bags above and below, the shredded region of the bag became exposed. At this point, stones would begin forcing their way out of this weak shredded region, leading to progressive bag failure, substantial loss of bag fill, and a sudden decrease in capacity.



**Figure 5.12: Granite specimens showing bulging of middle bag leading to exposure of disintegrated bag surface.**

The results of these tests suggest that the location of failure is determined by the individual geometry of the specimen. Prediction of the location and type of failure would be dependent on modeling the complex geometry and behaviour of the individual gravel particles within each specimen, and is beyond the scope of this thesis.

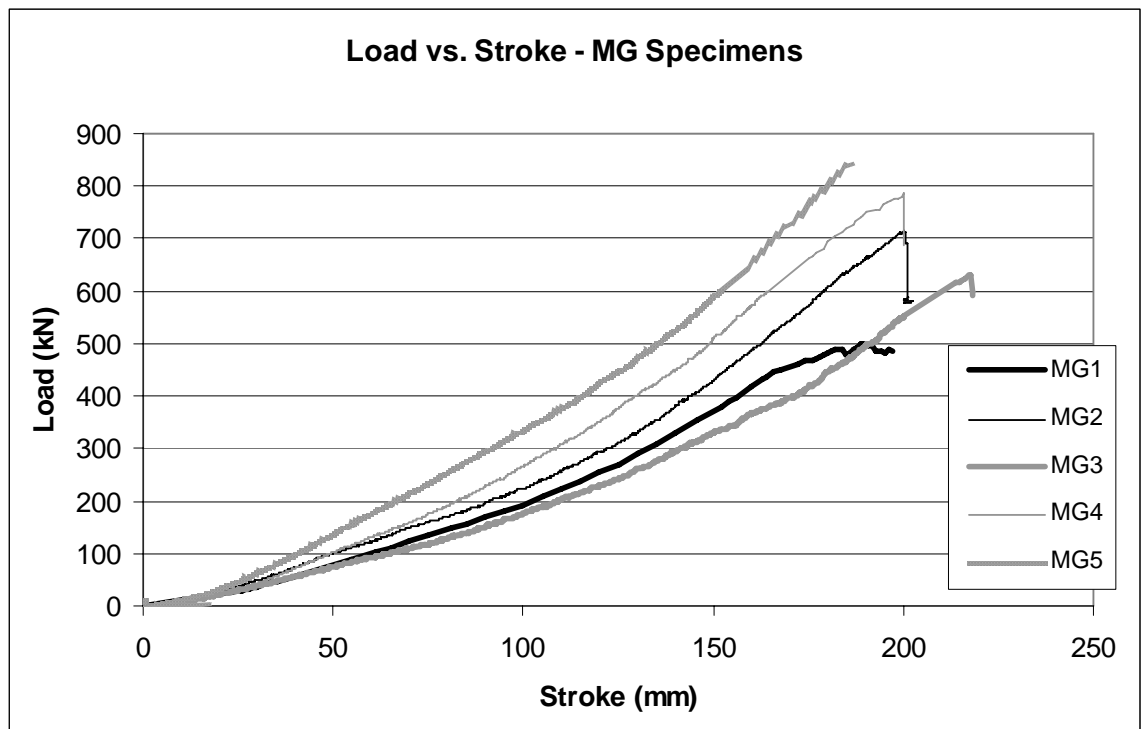
### **5.3.2 Medium Granite-filled 3-Bag Stacks**

Five specimens were tested using medium granite-filled bags. The behaviour of these bags was similar to the small bags in terms of failure mechanisms. As shown in Table 5.2, the ultimate loads for these specimens were higher than those observed for the

small bag specimens, as was expected due to their larger bearing areas. In addition, the medium bags also exhibited steeper load-deflection responses and larger load-to-deflection ratios at ultimate when compared to the small samples, unless the specimens SG6 and SG7 are considered. Since the medium bags were stored for the same period as specimens SG1-5, it is the opinion of the author that a meaningful comparison between small and medium specimens may be made using the values for SG1-5 and MG1-5. The magnitude of these differences is discussed below in Section 5.7. The load-stroke plots for the MG specimens are presented in Figure 5.13. There is some variation in the ultimate load and stiffness of the MG specimens, which is likely due to material heterogeneity and fabrication error, as discussed above in Section 5.3.

**Table 5.2: Summary of test results for SG and MG specimens.**

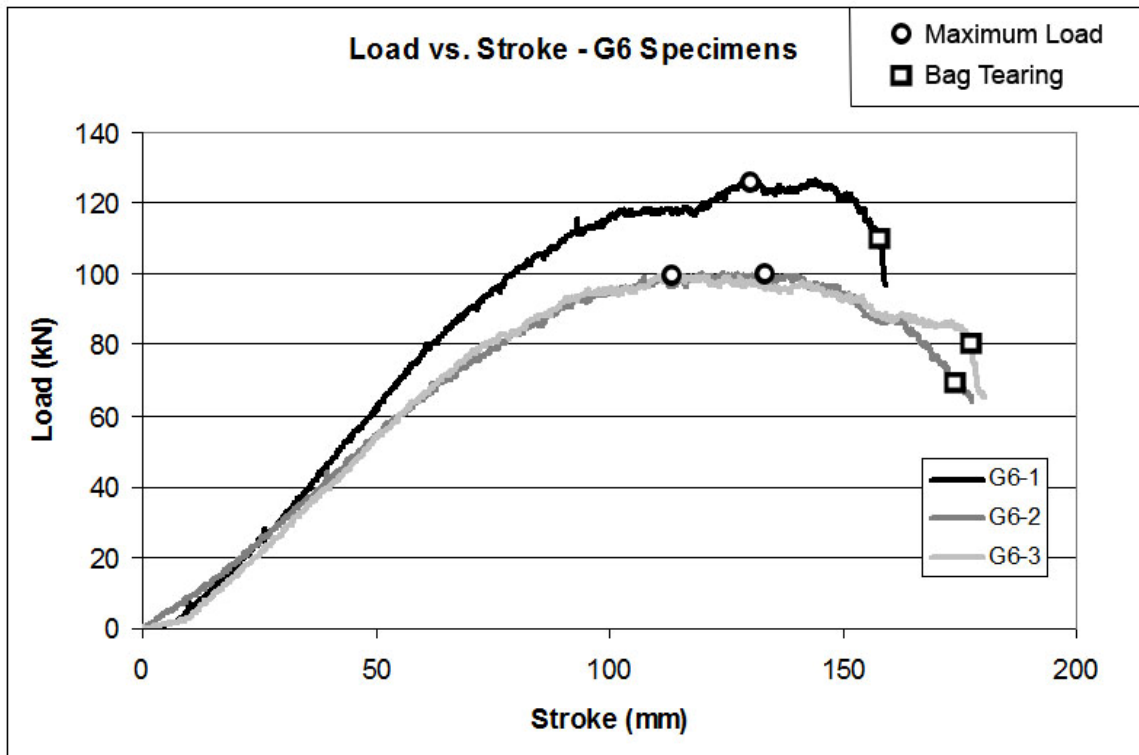
| Test | Ultimate Load (kN) | Earthbag Deformation at Ultimate (mm) | Stress at Ultimate (MPa) | Stiffness at Ultimate (kN/mm) | Load per Metre (kN/m) |
|------|--------------------|---------------------------------------|--------------------------|-------------------------------|-----------------------|
| SG1  | n/a                | n/a                                   | n/a                      | n/a                           | n/a                   |
| SG2  | n/a                | n/a                                   | n/a                      | n/a                           | n/a                   |
| SG3  | 311                | 145                                   | 1.10                     | 2.15                          | 489                   |
| SG4  | 421                | 140                                   | 1.49                     | 3.00                          | 663                   |
| SG5  | 341                | 110                                   | 1.21                     | 3.11                          | 537                   |
| SG6  | 840                | 118                                   | 2.98                     | 7.12                          | 1320                  |
| SG7  | 839                | 105                                   | 2.97                     | 7.98                          | 1320                  |
| MG1  | 501                | 166                                   | 1.39                     | 3.03                          | 669                   |
| MG2  | 715                | 165                                   | 1.98                     | 4.32                          | 954                   |
| MG3  | 630                | 186                                   | 1.74                     | 3.38                          | 841                   |
| MG4  | 785                | 161                                   | 2.17                     | 4.87                          | 1050                  |
| MG5  | 842                | 146                                   | 2.33                     | 5.78                          | 1120                  |



**Figure 5.13: Load versus stroke, all MG specimens.**

### **5.3.3 Small Granite-filled 6-Bag Stacks**

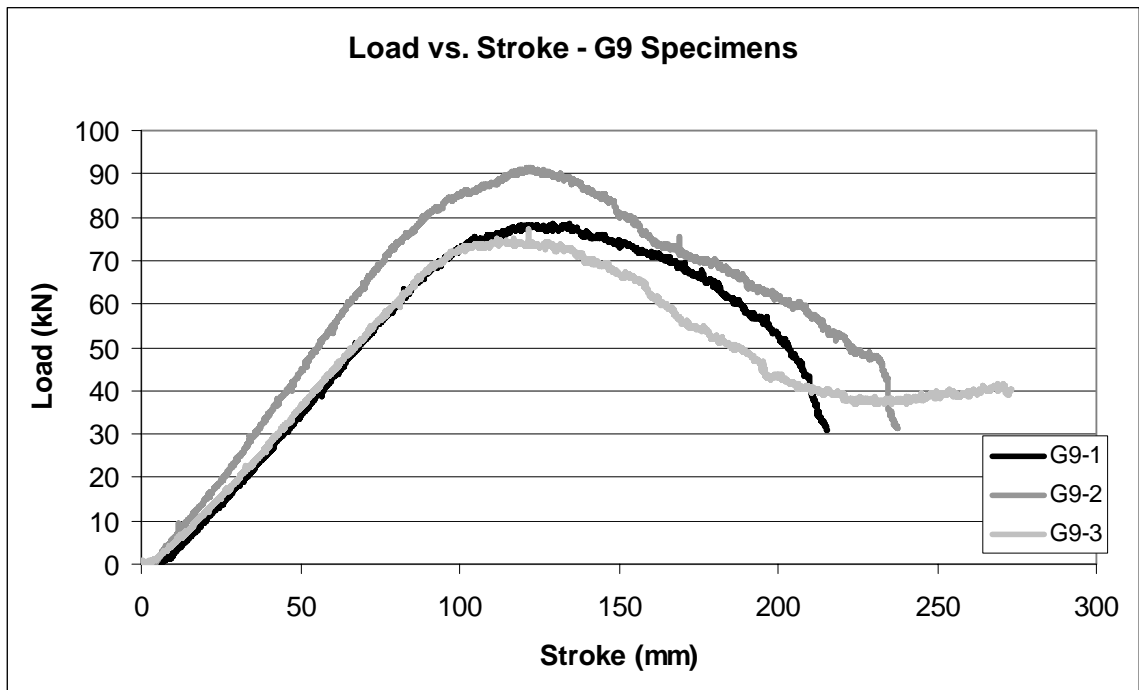
The observed behaviour of the granite-filled 6-bag stacks was similar to the 3-bag stacks in terms of failure mechanisms. The load-deformation response for these specimens, however, was different. The 3-bag stacks deformed in a roughly linear fashion until bag failure and loss of fill caused a sudden loss of strength. In contrast, the 6-bag stacks displayed non-linear load-deformation behaviour, with the maximum load occurring well before specimen failure by bag tearing. After the maximum load was reached, the specimens continued deforming with no visibly observable signs of failure, until bag tearing and loss of fill eventually occurred at lower-than-ultimate loads. The load-stroke plots for the G6 specimens are presented below in Figure 5.14, with maximum load and point of bag tearing indicated for clarification.



**Figure 5.14: Load versus stroke, G6 specimens.**

#### **5.3.4 Small Granite-filled 9-Bag Stacks**

The 9-bag stacks behaved in a similar fashion to the 6-bag stacks, with the maximum observed load occurring well before bag failure and loss of fill. The ultimate strength and stiffness of the 9-bag specimens (G9) was less than the 6-bag stacks (G6). Further discussion of the differences in behaviour of 3-, 6-, and 9-bag stacks can be found below in Section 5.6. The load-stroke plots for the G9 specimens are presented below in Figure 5.15.



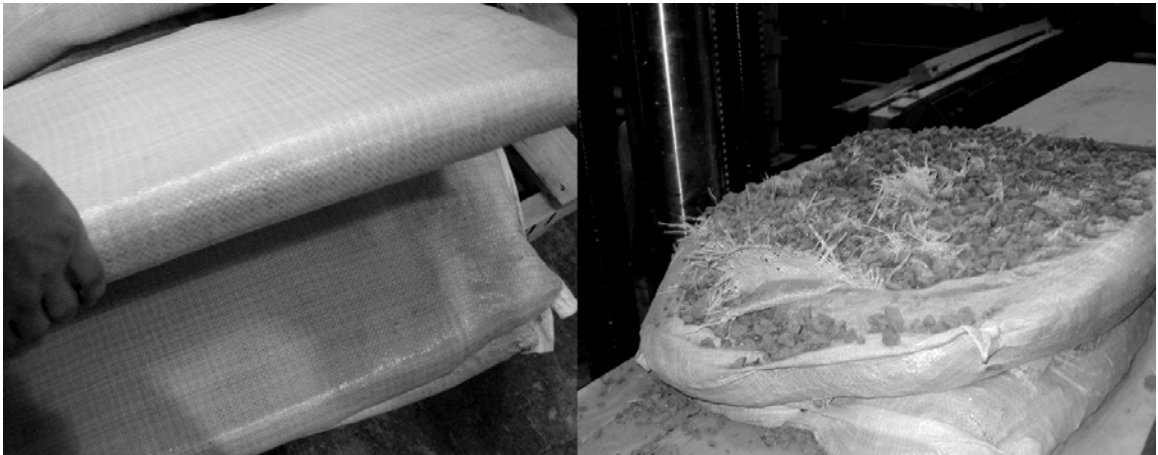
**Figure 5.15: Load versus stroke, G9 specimens.**

#### **5.4 Topsoil-Filled Earthbag Results**

The original intended testing program called for the testing of 5 specimens of each combination of fill type and bag size. The intention was to obtain 5 values for the ultimate strength of each specimen type, from which an average strength value could be determined. However, the first topsoil-filled specimen tests exceeded the capacity of the available testing machinery, and it was thus not possible to obtain 5 ultimate load values. As such, it was decided to run two tests of each soil-filled specimen type to determine the load-deformation characteristics of these specimens between 0 kN and 840 kN.

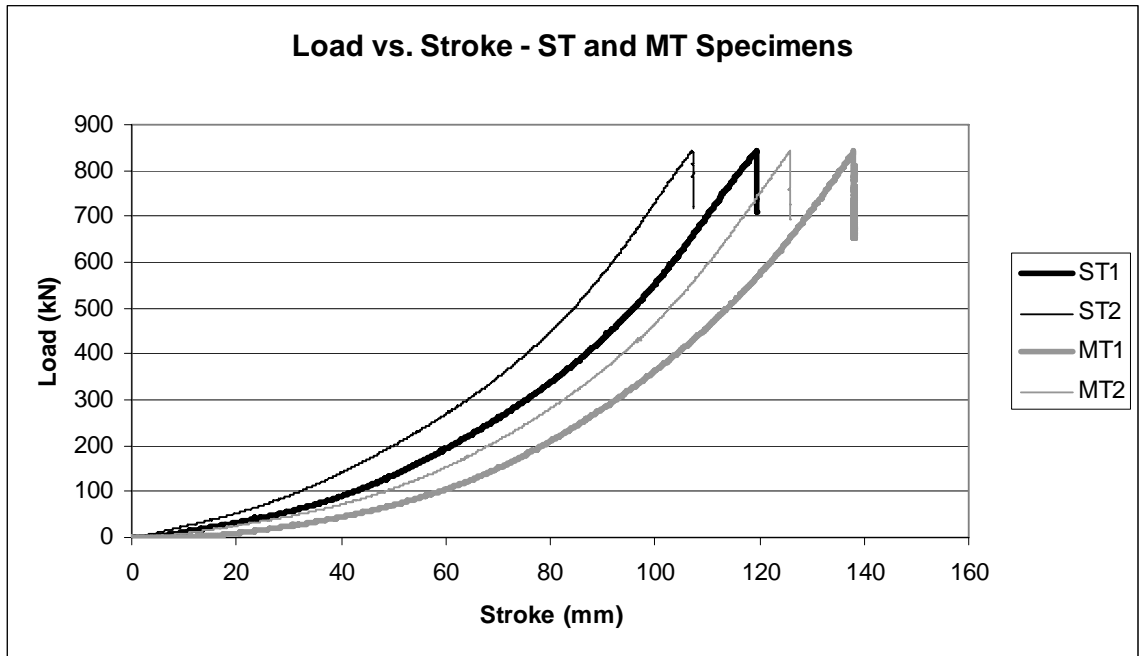
Both small and medium topsoil-filled specimens were tested in accordance with the procedure outlined in Chapter 4. In general, these specimens were substantially

stronger and stiffer than the granite-filled specimens. It is probable that the soil-filled specimens were able to attain higher loads due to the lack of sharp particles, which allowed the bags to deform laterally without developing enough abrasion at the bag-bag interface to tear the polypropylene. This was confirmed by a visual inspection of the topsoil-filled specimens after compressive testing. Figure 5.16 presents a comparison of the state of the bag-bag interface in both topsoil- and granite-filled specimens. It is likely that the higher strength and stiffness of the soil-filled bags is due in part to the confining pressure applied to the soil by the intact polypropylene bags.



**Figure 5.16: Comparison of granite- and sand-filled bag interfaces after testing.**

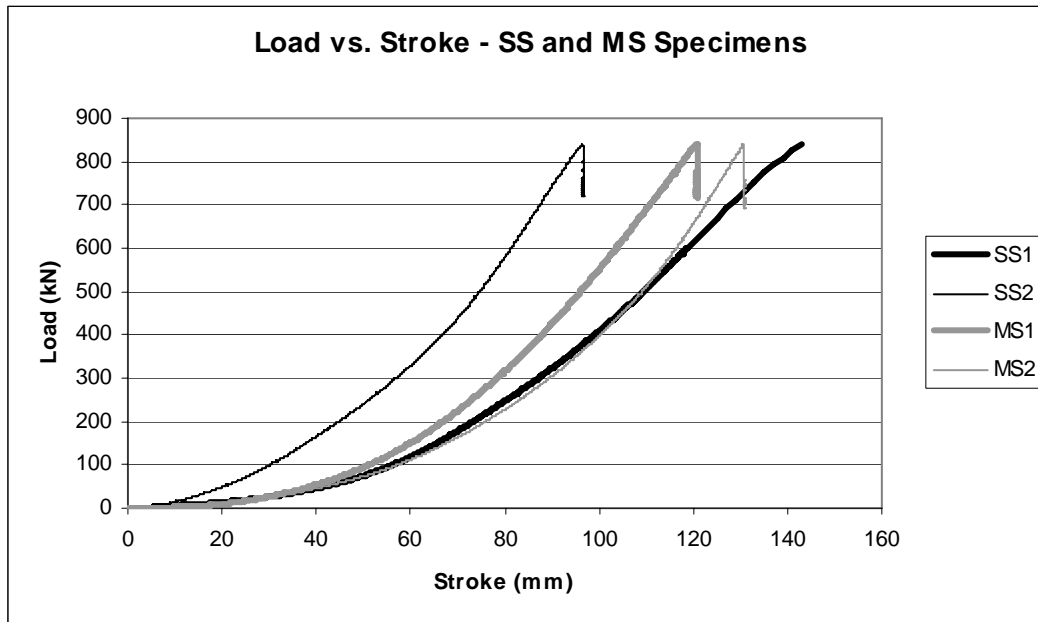
The load-stroke plots for both the small and medium topsoil-filled bags are presented below in Figure 5.17. The variability of stiffness within specimen groups is likely attributable to material heterogeneity, as discussed above, while the variability of stiffness between specimen groups may be attributable to differences in compressive strength, as discussed below in Section 5.6.



**Figure 5.17: Load versus stroke, ST and MT specimens.**

### 5.5 Sandy Soil-Filled Earthbag Results

The results for the sandy soil-filled earthbag specimens were similar in behaviour to the topsoil-filled earthbags in terms of strength and load-deformation characteristics. Given the widely held belief in the earthbag building community that high sand content can lead to suboptimal structural performance, it was anticipated that the sandy soil specimens would have lower strength and/or stiffness than the topsoil-filled specimens. However, as is discussed below in Section 5.5, this was not observed in the specimens tested. The load-stroke plots for both the small and medium sandy soil-filled earthbags are presented below in Figure 5.18.

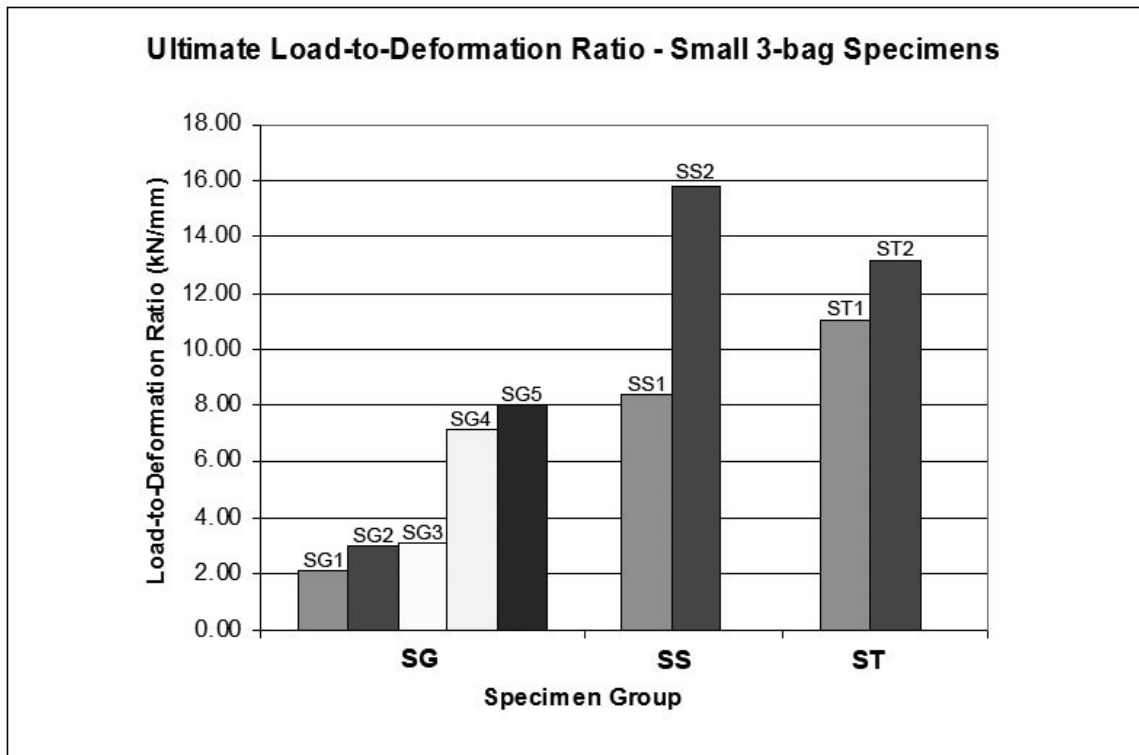


**Figure 5.18: Load versus stroke, SS and MS specimens.**

## 5.6 Effects of Fill Type

Based on the results of the tests presented above, it is clear that there is a significant difference in the material properties and structural performance of earthbags filled with soil and those filled with a coarser granular material such as granite gravel. In general, gravel specimens fail at much lower loads than soil-filled earthbags. This is due to the abrasive action of the gravel, which causes tearing at the interface between bags, leading to loss of fill material and, subsequently, compressive strength. Direct comparisons of the ultimate limit state behaviour of gravel- and soil-filled bags are unfortunately not possible based on the results of these tests, due to the capacity limitations of the available testing equipment.

There were also substantial differences in stiffness between the granite- and soil-filled bags, as measured in terms of the ratio of load to deformation at ultimate. Even including the two anomalously strong granite-filled specimens, all soil-filled specimens were stiffer than any of the granite-filled specimens. Numerically, the small granite-filled specimens had an average stiffness of 2.75 kN/mm (not including specimens SG6 and SG7). The average observed stiffnesses of the small topsoil-filled and sandy soil-filled specimens were both calculated to be 12.1 kN/mm. A graphical comparison of the stiffness of the small granite-, topsoil- and sandy soil-filled specimens is presented in Figure 5.19, with values grouped by specimen type (shading is used only to differentiate between adjacent bars, and has no symbolic meaning).



**Figure 5.19: Stiffness of SG, ST and SS specimens as measured by ratio of ultimate load to deformation at ultimate.**

The difference between topsoil and sandy soil fills is less distinct than the difference between soil and gravel fills. The capacity of the testing machine did not make it possible to observe the ultimate strengths of the soil-filled specimens tested. In terms of stiffness, however, the specimens tested gave no indication of a significant difference between sandy soil and topsoil. The average stiffness of the small topsoil and sandy soil specimens were measured to be identical at 12.1 kN/mm for both fill types. The average observed stiffnesses for the medium topsoil and sandy soil specimens were 9.54 kN/mm and 10.2 kN/mm, respectively. Thus, it appears that the average stiffness of the small soil-filled specimens is higher than that of the medium soil-filled specimens.

Unfortunately, it is not possible to apply a rank-sum test to determine if these samples are likely to come from different populations, since only two specimens of each type were tested. It is possible that a statistically significant difference in stiffness may be observable with larger sample groups.

### **5.7 Effects of Stack Height**

Stack height was explored as a potentially significant parameter affecting the strength of an earthbag structure. It was decided to test the effects of stack height on granite-filled specimens since the results of the 3-bag stack tests clearly indicated that granite-filled specimens fail at lower loads than soil-filled specimens, and indeed were the only specimens which were able to be tested to failure given the loading limitations of the available equipment. This ensured that a comparison of ultimate strength could be made for all stack heights tested.

The 6- and 9-bag stacks failed at much lower loads than the 3-bag stacks. A plot of ultimate load versus stack height is shown in Figure 5.20 with specimens SG6 and SG7 omitted. It indicates that there is an inverse relationship between ultimate strength and stack height, and that this relationship may take the form of an exponential decay. Figure 5.21 shows a similar relationship between stack height and stiffness in terms of kN/mm. The ramifications of this relationship for future earthbag testing efforts are discussed in Chapter 6.

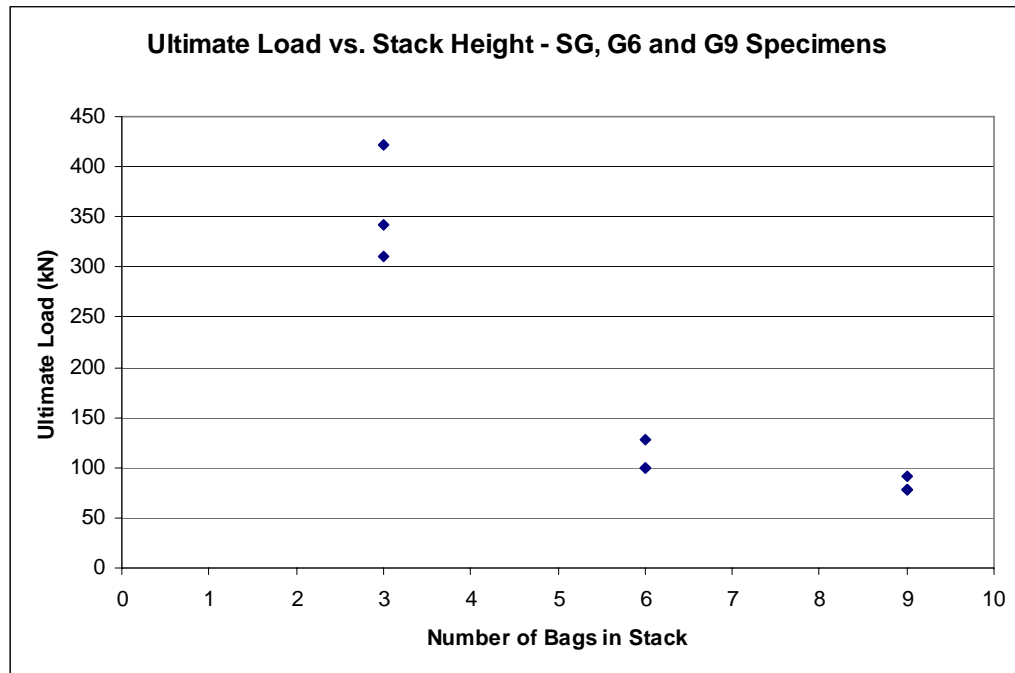


Figure 5.20: Ultimate load versus stack height, SG, G6 and G9 specimens.

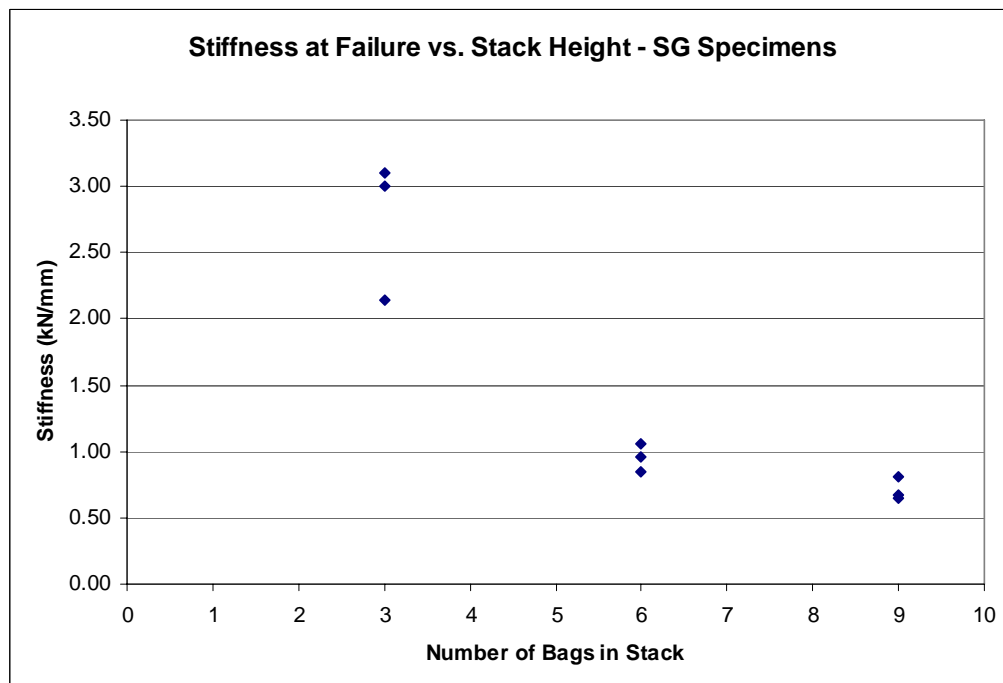


Figure 5.21: Stiffness versus stack height, SG, G6 and G9 specimens.

## 5.8 Effects of Bag Size

Both small and medium bags were tested with each of the fill types in order to determine the effects of bag size on specimen strength and stiffness. For the small granite-filled specimens, the average load at failure was 358 kN (excluding specimens SG6 and SG7). The medium granite-filled specimens had an average load at failure of 695 kN. This yields a ratio of small-to-medium ultimate loads of 0.51. Since the higher strength of the medium bags is likely due to their larger bearing area, it is important to note that the ratio of small-to-medium bag bearing areas is 0.78. Thus, there appears to be an increase in strength relative to bag area for the medium bags, though the significance of this relationship cannot be accurately determined due to small sample size.

The relationship between the measured stiffness of the granite-filled bags and bag area is similar to the relationship between strength and bag area. The small granite-filled specimens had an average stiffness, measured in terms of millimetres of deformation at ultimate load, of 2.75 kN/mm (excluding specimens SG6 and SG7), while the medium specimens had an average stiffness of 4.28. The ratio of small-to-medium specimen stiffness is 0.64.

The relationship between bag size and strength was not possible to determine for the topsoil- and sandy soil-filled specimens, due to the limitations of the testing equipment capacity. However, it is possible to examine the relationship between bag size and specimen stiffness at the machine's maximum load of 840 kN. At this load, the average stiffnesses of both the small topsoil and sandy soil specimens were 12.1 kN/mm.

For the medium topsoil and sandy soil specimens, the average stiffnesses were 10.2 kN/mm and 9.54 kN/mm, respectively. The ratio of small-to-medium specimen stiffness for the topsoil and sandy soil specimens is 1.27 and 1.18, respectively. By comparison, the reciprocal of the small-to-medium bag area ratio of 0.78 is 1.28, which suggests an inverse relationship between bag size and stiffness for soil-filled specimens, though the sample size is too small to determine if this correlation is statistically significant. It is possible that this relationship is due to the larger thickness of the medium-sized specimens. The thinner small-sized specimens may be more thoroughly compacted prior to the beginning of the test, which could result in a smaller measured deformation at the machine's maximum load.

### **5.9 Ancillary Tests - Polypropylene Tensile Test Results**

As discussed in Chapter 5, initial testing of the polypropylene textile used to manufacture the bags used in the earthbag specimen tests was conducted according to the specifications of ISO 13934-1. However, the specimens tested in this manner showed evidence of grip slippage, as well as a tendency to fail at the grips. Both of these factors lead to an underestimation of specimen strength. As such, it was decided to pursue further testing under the specifications of ASTM D 4595. Due to resource limitations, an independent testing laboratory (CTT Group) was commissioned to conduct these tests. The results presented by CTT Group give the ultimate strength of the textile, as well as elongation at ultimate strength, for both the machine direction (longitudinal axis of the earthbags) and the cross machine direction (lateral axis of the earthbags). In addition,

load values were reported at 5% and 10% elongation, relative to elongation at ultimate load. These values are given in Tables 5.3 and 5.4. The full report from CTT Group is presented in Appendix F.

**Table 5.3: Test results for polypropylene textile, machine direction.**

| Specimen                  | Breaking Strength (kN/m) | Elongation at Break (%) | Load at 5% Elongation | Load at 10% Elongation |
|---------------------------|--------------------------|-------------------------|-----------------------|------------------------|
| M1                        | 6.8                      | 27.3                    | 2.7                   | 4.3                    |
| M2                        | 6.9                      | 29.8                    | 2.4                   | 4.1                    |
| M3                        | 6.8                      | 28.5                    | 2.5                   | 4.2                    |
| M4                        | 6.8                      | 29.7                    | 2.1                   | 3.8                    |
| M5                        | 6.3                      | 29                      | 2.1                   | 3.7                    |
| M6                        | 6.7                      | 29.6                    | 1.7                   | 3.5                    |
| <b>Mean</b>               | 6.7                      | 29.0                    | 2.3                   | 3.9                    |
| <b>Standard Deviation</b> | 0.2                      | 1.0                     | 0.4                   | 0.3                    |

**Table 5.4: Test results for polypropylene textile, cross-machine direction.**

| Specimen                  | Breaking Strength (kN/m) |
|---------------------------|--------------------------|
| C1                        | 6.6                      |
| C2                        | 6.8                      |
| C3                        | 7.0                      |
| C4                        | 7.0                      |
| C5                        | 6.9                      |
| C6                        | 6.8                      |
| <b>Mean</b>               | 6.9                      |
| <b>Standard Deviation</b> | 0.2                      |

These results indicate similar average strength values for the machine direction and the cross-machine direction. A rank-sum test applied to these data indicates that the

difference between ultimate load for machine and cross-machine directions is insignificant at the 2% significance level.

Since bag tearing, leading to loss of fill, was the governing failure mode for all tests which reached failure, strength of the bag textile is an important parameter governing the overall performance of earthbag housing. In addition to this, the stiffness of the bag textile likely has an effect on the stiffness of the bag, as a stiffer bag material would provide more confining stress at smaller deformations. Thus, as discussed in Chapter 6, it will be useful for future earthbag studies to examine bag tensile strength as a parameter affecting earthbag housing performance.

## **Chapter 6**

### **Discussion**

This chapter presents a discussion of the results presented in Chapter 5. These results are compared with the results of the earthbag testing conducted by Dunbar and Wipplinger (2006). The strength of earthbag housing is then compared with strength values for conventional housing systems, as well as straw bale housing. Finally, the information presented in Chapter 2 on alternative construction techniques is synthesized with the Sri Lankan case study information presented in Chapter 3 and the results of Chapter 5 to identify the suitability of a variety of alternative building materials in the context of southern Sri Lanka.

#### **6.1 Earthbag Testing Results - Comparison with other earthbag studies**

The tests conducted by Dunbar & Wipplinger (2006) at West Point Military Academy reported observed ultimate stresses for sand-, rubble- and soil-filled earthbags of 0.30 MPa, 0.40 MPa, and 2.14 MPa, respectively. By comparison, the stresses calculated from the results presented in Chapter 5 range from 1.10 MPa to 2.98 MPa for crushed granite filled specimens, and 2.33 MPa to 2.98 MPa for both sandy soil and topsoil filled specimens, for the 3-bag configuration most similar to the West Point tests. It should be noted that the strength values for soil-filled bags from both this thesis and the West Point tests are not indicative of specimen failure, but rather the limitations of available testing equipment. As such, it is possible that actual ultimate strengths may be

observed in a significantly higher range. A summary of all ultimate loads and stresses can be found in Appendix E.

For the taller specimens, stresses ranged from 0.35 MPa to 0.45 MPa for the 6-bag specimens, and 0.27 MPa to 0.32 MPa for the 9-bag specimens. These values suggest that there is some agreement between the soil-filled specimen results, at least in terms of the general range of strengths observed for soil-filled earthbags ( $>2$  MPa). However, the 3-bag granite-filled specimens were substantially stronger than the values reported for sand- and rubble-filled specimens at West Point. This may be due to the characteristics of the sand and rubble used in the aforementioned tests. Unfortunately, the data published online does not give specific details of the fill materials in terms of particle size distribution, or the constituent materials present in the rubble. Additionally, comparisons are complicated by the fact that the West Point study opted to close the earthbags by cinching and tying the open end shut, which may result in different behaviour than bags which have been folded and pinned in order to approximate the expected bag geometry of earthbag walls.

## **6.2 Earthbag Housing**

The results of the earthbag testing program presented in this thesis, while preliminary, may be used to make some initial comparisons with existing construction technologies in terms of both wall strength and constructability.

When determining the suitability of a building material for use in housing or other similar structures, compressive strength is of fundamental importance. The compressive

strength of an alternative building technology must compare favourably with the strengths produced by conventional housing materials and methods if it is to be practically useful. However, many alternative building technologies have significantly different form factors than conventional materials; stick-frame houses using 38 mm x 140 mm (2" x 6" nominal) studs have much thinner walls than straw bale homes, for example. As such, it is useful to normalize wall strength in terms of load-bearing capacity per metre of wall length, which allows for a more meaningful comparison of strength than does the conventional parameter of ultimate stress.

Riley & Palleroni (1999) cite a typical strength range of 12 kN/m to 18 kN/m for typical residential construction using 38 mm x 140 mm stud framing. Straw bale housing has been shown to compare favourably with conventional stud framing, with published strength values ranging from 20 kN/m to 80 kN/m for plastered straw bale specimen tests (Vardy & MacDougall, 2006), and 30 kN/m for full-scale (2.44 m x 2.44 m) wall tests (Vardy et al., 2006). By comparison, the lowest strength values for the earthbag specimens tested in this thesis, those of the small 9-bag granite-filled specimens, range from 122 kN/m to 144 kN/m. The values for soil-filled specimens are an order of magnitude higher, ranging from 1123 kN/m to 1327 kN/m. A full summary of test results is presented in Appendix E. This clearly demonstrates the adequacy of earthbag technology for use in housing applications from a strength perspective. Even the weakest specimens observed outperformed the published strength values of conventional housing by a factor of nearly 10. This confirms the notion that excessive deflection is likely to

govern the design of earthbag structures, highlighting the need for an examination of the stiffness of plastered earthbag assemblies.

Beyond the quantitative results of this thesis, the lessons learned in manipulating the specimens confirm that earthbag construction is a low-technology building technique which can be easily learned by those not trained in the construction trades. The small bags tested in this thesis (which match the measurements of the de facto standard bag size used in earthbag construction) were easily moved by two people, and it was possible to move them with a single person when extra hands were not available. The medium bags were more unwieldy, requiring a minimum of two people for safe movement and stacking. This, combined with the high strength values observed for all small specimens, suggests that small (457 mm x 762 mm) bags are the optimal size for earthbag construction, providing a good balance between strength and ease of manipulation. However, medium bags may be useful for foundations and lower tiers, where less lifting is required, and compressive loads may be highest. Additionally, the wider width of medium bags relative to small bags may act to buttress earthbag walls against out-of-plane lateral forces.

With regard to embodied energy, the question of whether earthbag housing is preferable to conventional materials such as concrete or structural timber depends on several factors such as the form and length of transportation required for all materials, as well as the size and expected life span of the structure in question. In the absence of such data, it is difficult to make a direct comparison between materials, though an examination of approximate embodied energy values for the constituent materials is still possible.

Table 6.1 presents a summary of embodied energy values for several common construction materials, taken from Hammond & Jones (2006). The value for rammed earth is presented, as there is currently no published value for earthbags. This is likely to be an overestimate of the embodied energy of the soil fraction of earthbag housing, as it is not necessary to construct formwork or use mechanized compaction devices for earthbag housing, as is required of rammed earth. It should be noted that the embodied energy of polypropylene is much higher than all other common building materials presented in Table 6.1, but also that polypropylene makes up a small fraction of the total mass of an earthbag wall.

**Table 6.1: Embodied energy values for common construction materials.**

| <b>Material</b>                           | <b>Embodied Energy<br/>(MJ/kg)</b> |
|---|------------------------------------|
| Concrete                                  | 0.99                               |
| Brick                                     | 3.0                                |
| Sawn Softwood                             | 7.4                                |
| Gypsum (for use in<br>drywall or plaster) | 1.8                                |
| Rammed Earth                              | 0.45                               |
| Polypropylene<br>Textile                  | 99.2                               |

### **6.3 Alternative Construction Techniques in a Development Context**

In light of the examination of existing knowledge on alternative building technologies explored in Chapter 2, as well as the results of the earthbag study presented

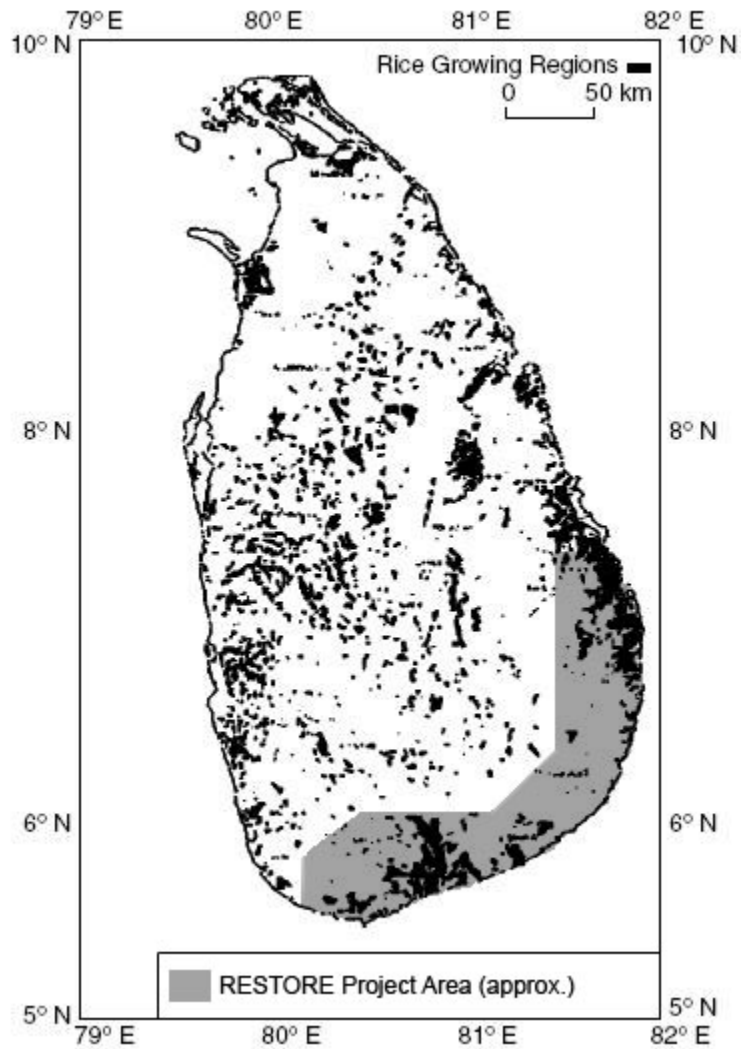
in Chapter 5, it is clear that there is significant potential for the use of alternative building technologies in the context of developing countries. Specifically, the observational research presented in Chapter 3 suggests that there is the potential for these technologies to play a role in the reconstruction of housing along Sri Lanka's southern coast, still badly damaged from the Indian Ocean tsunami of 2004.

In order to determine which alternative construction materials would be suitable for use in a specific context, several criteria need to be considered. First, which alternative construction techniques employ materials which are native to the region? Second, which techniques are capable of producing houses which are suitable for the local environment in terms of climate? Third, what is the availability of skilled trades required, if any, for the use of a specific technique? Finally, what are the preferences of the local people in terms of architectural style? These questions are addressed here in the context of southern Sri Lanka, with respect to straw bale, earthen and bamboo housing.

Addressing the question of material availability in a developing country from the perspective of an engineer in a developed country can be a challenge due to a lack of local experience. Site visits and interviews with local homeowners, farmers and construction industry workers are arguably the best technique for assessing material availability. Where this is impossible or impractical, geographic and statistical resources may be used to gain a broad sense of material availability in a specific area. When considering straw bale housing, the availability of straw may be inferred by the production of wheat and/or rice in a region or country, as the straw produced as a by-product of these two crops is favoured by the straw bale construction industry (Corum,

2005). The United Nations Food and Agriculture Organization (UN FAO) maintains FAOSTAT, a statistical database which provides national production statistics for all countries and major crops. This database shows that, for the years 1996 to 2006, wheat production in Sri Lanka is nonexistent, but rice production ranged from 2.1 million tonnes in 1998 to 3.3 million tonnes in 2006 (UN FAO, 2008). This suggests rice straw may be available for use in building construction.

More detailed regional data is available in the form of resource maps. Figure 6.1 shows the regional distribution of rice production in Sri Lanka, further suggesting that rice straw may be locally available along the southern and eastern coasts. It should be noted, however, that this resource map was produced prior to the 2004 tsunami, and thus may not accurately reflect the current state of rice production in the coastal regions of Sri Lanka. Detailed production statistics and maps are not commonly available in real-time. This highlights the importance of site visits and interviews when accurate, up-to-date information is required.



**Figure 6.1: Rice producing regions of Sri Lanka (dark shading). Light shading denotes extent of RESTORE Project area (adapted from Zubair, 2002).**

Several species of bamboo are cultivated in Sri Lanka, mainly for use in the handicraft industry. The introduced species *Bambusa vulgaris* and *Dendrocalamus giganteus* are used by the construction industry, and are mainly cultivated in the coastal wet zones of the country, which includes the southern coastal region. Typical uses in the

construction industry include scaffolding, shoring poles and ladders, though bamboo walls and framing do exist (Kariyawasam, 1998). The overall size of the structural bamboo market is small, however, with some accounts putting the size of the national structural bamboo market at less than \$25,000 CAD per year (UN FAO, 2002). The size of this market suggests that bamboo does not currently have the potential to meet housing needs in Sri Lanka, except on a small scale where there exists local availability of and experience with structural bamboo, specifically *Bambusa vulgaris* and *Dendrocalamus giganteus*.

Knowledge of soil type distribution is useful in determining the viability of earthen construction techniques such as earthbag, adobe or rammed earth housing. Soil maps of Sri Lanka generally describe the soils of the southern coast as belonging to the reddish brown earth or red-yellow podzolic soil groups (Panabokke, 1975; Sri Lanka Land Use Division, 1988). While particle size distribution may vary within a general soil type classification from one region to another, both reddish brown earth and red-yellow podzolic soils have been shown to be suitable for earthen housing purposes (Minke, 2006; Mbumia et al., 2000). This suggests that material availability would not be a limiting factor in the suitability of earthen housing for southern Sri Lanka.

Beyond material availability, climactic conditions must also be considered to ensure optimal selection of building materials. Sri Lanka is a tropical country, with national average monthly rainfall values ranging from 60 mm to 300 mm, with a yearly average value of approximately 1900 mm (Suppiah, 1997). It should be noted that these average values were calculated from 29 stations distributed throughout the country. The

southern coast of Sri Lanka occupies the country's "wet zone" (Kariyawasam, 1998), and as such, receives a higher than average amount of rainfall. These conditions suggest moisture issues may be a key concern in determining the suitability of any building technology.

The performance of straw bale housing in areas with high rainfall and humidity is a concern, as high wall moisture levels can promote mould and insect growth. However, as discussed in Chapter 2, these issues can be minimized through appropriate design choices, including ample roof overhangs and footings, as well as the selection of rice straw for bales, as its high silica ash content increases rot resistance. With respect to temperature, Sri Lanka's warm, tropical climate suggests the excellent insulation performance of straw bale housing would not be as important as it would in a temperate climate.

Bamboo is also limited by moisture-related concerns. As discussed in Chapter 2, its organic nature makes it susceptible to moisture-induced decay, and its cellular composition makes simple curing techniques difficult. With uncured bamboo structures estimated to last only 3 to 5 years in tropical conditions (DeBoer & Bareis, 2000), its suitability in southern Sri Lanka is likely to be limited to short-term structures.

Due to the inorganic nature of soil, earthen housing is not susceptible to the same moisture-driven rot issues as bamboo or straw bale houses. However, long-term durability can be an issue, as high rainfall can lead to erosion of exterior plaster finishes. As with straw bale housing, these issues can be mitigated through appropriate design choices such as large roof overhangs and footings. In terms of temperature, earthen

housing is particularly attractive due to its large thermal mass, which can act to moderate internal temperature fluctuations by absorbing excess heat during the day and releasing it at night.

With regard to skilled trade availability, both straw bale housing and earthen housing are systems which require little expertise to construct. They do, however, require a large labour input and thus would be suitable in areas where there is plentiful labour (in the form of construction industry personnel or community participation). Conversely, structural design in bamboo is more technically detailed than straw bale or earthen housing, and as such would require the availability of construction workers with experience in bamboo construction. This suggests that straw bale and earthen houses would be easier to construct than bamboo houses, from a construction logistics perspective.

The final question posed above, that of architectural preference, was discussed in the context of southern Sri Lanka in Chapter 3. Based on interviews with villagers, academics and NGO employees in the area, it was determined that there exists a strong architectural preference for concrete and masonry structures, for both aesthetic and social reasons. Of the three general types of alternative technology discussed here, bamboo is least similar to concrete and masonry housing due to its thin walls and post-and-beam appearance, which differ from the thick, monolithic appearance of concrete and masonry walls. Straw bale and earthen housing are not visually identical to concrete and masonry housing, but if cement-based plasters are used for exterior finishing, they can be made to look similar in terms of wall thickness and finish. It may also be possible to more closely

emulate the appearance of concrete and masonry housing through the use of thin concrete siding panels attached directly to earthen or straw bale walls, though this has not yet been explored in the literature of alternative building materials.

The above discussion of the relative merits of straw bale, earthen and bamboo housing in the context of material availability, climactic suitability, trades availability and architectural preference indicates that earthen housing is the most suitable choice for housing construction in the southern coastal region of Sri Lanka. Specifically, the widespread availability of the required materials and the rot resistance of earthen housing indicate it is a superior choice over straw bale and bamboo housing, though the availability of rice straw does suggest straw bale housing may also be a feasible choice, assuming careful design choices are made regarding moisture protection. Bamboo does not appear to be an appropriate choice on the basis of material and skilled trade availability, as well as moisture-related degradation concerns.

The specific method of earthen construction selected may depend on the specific characteristics of the local area being investigated. If the soil has the ideal composition for soil bricks, adobe housing may be the simplest and least environmentally damaging method available, due to the fact that it does not rely on any heavily processed materials such as polypropylene bags or plywood/metal formwork. However, if the soil composition is not ideal for the formation of bricks, earthbag housing may be an appropriate technology. Polypropylene bags, similar to the ones tested in this thesis, are widely used in Sri Lanka for the bulk transport of rice, and thus it is likely that bags will be available for housing purposes. Rammed earth may be feasible as well, though the

large material demands of rammed earth formwork and the heavy labour demands of compaction may make it inferior to earthbag housing in terms of construction logistics.

In light of all available contextual data, as well as the results of the earthbag testing program presented in Chapter 5, earthbag housing appears to be an excellent candidate for use in housing construction in southern Sri Lanka.

## **Chapter 7**

### **Conclusions and Future Work**

Alternative housing techniques show significant promise for meeting the housing needs of society in both developing and developed countries. As discussed in Chapter 1, this thesis addressed three objectives: first, to gain insight into the structural behaviour and constructability of earthbag housing; second, to develop the practice of earthbag testing and third, to assess the suitability of alternative construction materials for developing countries in general, and Sri Lanka in particular.

#### **7.1 Conclusions – Earthbag Housing**

With regard to the first objective, the results and discussion of the earthbag testing program presented in Chapters 5 and 6 show that the strength of unplastered earthbag specimens matches or exceeds the strengths of conventional construction techniques such as stud framing, and alternative construction techniques such as straw bale housing under vertical compressive loading. The weakest specimens tested (G9, the small, granite gravel-filled 9-bag stacks) obtained maximum compressive strengths ranging from 120 kN/m to 140 kN/m, almost 10 times as great as those typically achieved by conventional stud-frame housing in terms of load per metre of wall length. However, these tests do indicate that substantial deformation of unplastered earthbags can be expected, which should be considered when designing and building earthbag houses. The lowest load-deformation response was observed for the G9 specimen group, at 0.7 kN/mm. The

strongest and stiffest results were observed for the 3-bag soil-filled specimen, with load-deformation responses ranging from 8 kN/mm to 15 kN/mm, and compressive strength two orders of magnitude higher than conventional stud-frame housing, ranging from 1100 kN/m to 1300 kN/m.

It should be noted that the above conclusions regarding earthbag housing are based on the *unplastered* tests conducted in this thesis. It is possible that plastering of specimens will lead to increased stiffness, though it is unlikely that plastered specimens will be able to achieve the loads presented above without first experiencing plaster failure. This suggests that the allowable service loads for earthbag housing may be governed by the integrity of the plaster skins. From an ultimate limit states perspective, however, failure of the plaster skins is not likely to impact the ultimate strength of the earthbags themselves.

While this thesis does provide evidence that earthbag housing is a structurally sound technology in the context of vertical compressive loads, further knowledge of plastered behaviour, behaviour under in-plane and out-of-plane shear loading, as well as behaviour under uplift forces, is required in order to develop comprehensive, empirically based design recommendations for earthbag housing.

With regard to constructability and material availability, earthbag housing is a very attractive construction technique. Soil, of one form or another, is available in virtually all inhabited regions of the world, and polypropylene bags are already manufactured for a variety of purposes in many developing and developed countries. The level of expertise required to assemble an earthbag house is attainable by virtually

anyone, regardless of previous construction experience. The trade-off for this ease of construction is the high amount of labour input required to construct earthbag structures. Thus, earthbag housing is best suited to regions where labour availability is high, and/or where community participation in housing construction can be achieved.

The above conclusions may be summarized as follows:

1. Gravel-filled earthbag specimens fail at lower loads than soil-filled specimens due to abrasion at the bag-bag interface, leading to loss of fill.
2. Small granite gravel-filled specimens, measuring 457 mm x 762 mm and stacked 9 bags high, were the weakest specimens tested in this study. They yielded a strength per metre of wall length of 120 kN/m to 140 kN/m. The load-deformation response for these specimens was 0.7 kN/mm.
3. Soil-filled earthbag specimens were stronger and stiffer than gravel-filled specimens fabricated with bag of the same size and assembled with an identical stack height. The observed compressive strength for small soil-filled specimens, measuring 457 mm x 762 mm, ranged from 1100 kN/m to 1300 kN/m, and the load-deformation response for these specimens ranged from 8 kN/mm to 15 kN/mm. Strength and stiffness values for medium soil-filled specimens measuring 508 mm x 914 mm were in the same range as the values for the small specimens.
4. There was little difference in stiffness between specimens filled with topsoil and those filled with a 4:1 ratio of topsoil to masonry sand, though

small sample size prevents a meaningful statistical analysis of the variance between the two fill materials.

## **7.2 Conclusions – Earthbag Testing**

With regard to the second objective, the tests conducted in this thesis suggest that existing standards for non-earthbag materials are useful as a general guideline for earthbag testing, but do not provide information on earthbag-specific specimen construction details, and may not produce results which are characteristic of the full-scale earthbag housing system. For unplastered specimens, it was found that a folded, pinned closure was sufficient to prevent premature failure due to fill loss through the bag opening. It was also found that taller earthbag stacks led to lower specimen strength and stiffness. This suggests that three-unit specimens, as specified in ASTM E 447, may overestimate the strength and stiffness of unplastered earthbag stacks. It can be concluded that stack height is a key parameter to consider for future earthbag testing programs. Furthermore, it was determined that the hemlock loading plates used in this thesis were adequate for testing within the range of the testing machine (0 kN to 840 kN), but that the integrity of the wood became a concern at the top end of this loading range, where compression of the plates was observed. It was possible to correct for the load-deformation response of the hemlock plates, but this suggests that steel loading plates may be needed to test soil specimens to failure, and also that steel plates may be desirable from a durability perspective as well.

These conclusions can be summarized as follows.

1. Stack height affects the strength and stiffness of earthbag specimens, with taller stacks (i.e. 6 or 9 bags) exhibiting lower strength and stiffness values, as well as different load-deformation behaviour than shorter stacks (i.e. 3 bags).
2. The testing procedures outlined in ASTM E 447 are inadequate for testing earthbag specimens due to their reliance on 3-unit stacks which may overestimate compressive strength.
3. Soil-filled bags measuring 457 x 762 mm require loads in excess of 840 kN to reach bag failure (defined as a loss of fill leading to reduced compressive load-bearing capacity). This is also true for soil-filled bags measuring 508 mm x 914 mm.
4. Steel load-distribution plates are required for testing at high loads (i.e. >800kN), and are also likely a suitable choice for testing at lower loads where many load-unload cycles make wood an unsuitable choice. Exact plate dimensions will vary based on specimen geometry and loading range.

## **7.3 Future Work**

### **7.3.1 Future Testing - Unplastered Prism Specimens**

As discussed in Chapter 2, the practice of earthbag construction is a relatively new idea. Correspondingly, the practice of earthbag testing in a laboratory setting has yet to be fully explored or standardized. The tests conducted in this thesis provide some

insight into the mechanical behaviour of unplastered earthbag specimens, but also into potential areas for improvement of testing methodologies. This section will also discuss the author's recommendations for future earthbag tests, based partly on the lessons learned from the tests presented in this thesis, with an eye towards a more complete understanding of the mechanics of the earthbag housing system.

The first task encountered in an earthbag testing program will necessarily be that of specimen preparation. Bag filling and sealing is a relatively straightforward task, and the methods used in this thesis were adequate in terms of ease and efficiency. For bag filling, the convenience of a folding metal bag stand allows bags to be filled quickly and with little spillage. However, it should be noted that, if a "C"-shaped bag stand is used (such as the one pictured in Figure 4.2), it is important that the free ends of the steel section are ground and/or filed until smooth, as any sharp edges have the potential to tear the bags as they are filled. This can be avoided by using fully rectangular bag stands such as those recommended by Hunter & Kiffmeyer (2004), though C-shaped stands allow for easier bag removal, as the filled bags can be pulled out the side of the stand. In areas where metal or welding resources may not be available, the stands could be fabricated out of wood with little effect on performance.

In full-scale earthbag construction, bags directly abut each other along the seam and folded edges, forcing failure to occur along the long edges. Thus, if the sealed edge of a bag fails, it can be assumed that the observed specimen strength will be lower than what would be observed in a full-scale wall. Effective bag sealing is important to ensure that failure of the sealed end does not govern overall specimen failure. The method of

bag sealing used for these tests, detailed in Chapter 4, appears to be sufficient to meet this goal, as 28 tests were run without a single incidence of failure at the pinned bag closure.

In terms of bag filling, field construction guidelines were followed in order to replicate as closely as possible the behaviour of bags used in earthbag housing. The resultant bags had generally similar masses, but with some variation from bag to bag. For the small, granite-filled gravel specimens (the bag configuration with the largest sample group size of 66 bags) the average mass of the filled bags was 25.01 kg, with a standard deviation of 2.13 kg. The minimum and maximum bag masses measured were 21.24 kg and 29.71 kg, respectively. Since bag mass was not studied as a parameter affecting specimen behaviour in these tests, it is not yet possible to determine the effect of bag fullness on earthbag strength or stiffness. It would be informative for future earthbag tests to study specimens filled to several different masses, while keeping bag size and fill type constant, to examine the effect of bag fullness on structural performance. This may help control for some of the variability observed in the test results presented here.

The hemlock load distribution plates used in this test were convenient from the perspective of weight, in that they allowed for test setup without the use of mechanical lifting assistance (i.e. cranes). The trade-off for this benefit, however, is that the hemlock plates displayed a more significant load-deformation response than could have been expected from a thick (i.e. 40 mm) steel plate. While it was possible to correct for the compression of the hemlock plates, and the plate surfaces in contact with the earthbags displayed very little observable bending (which would result in less efficient load

distribution), it may be beneficial for future earthbag testing programs to invest in large steel plates to use for load distribution purposes above and below the earthbag specimen. Large steel bearing plates would be particularly important for comprehensive testing programs with many individual tests, where the durability of wood plates may become a concern after repeated loading-unloading cycles, as well as for testing soil-filled and/or plastered specimens to failure, which would occur at loads much higher than are possible to achieve with the wood loading plate configuration used here.

The results of the tests presented in Chapter 5 also clearly highlight the effect of stack height on earthbag specimen strength and stiffness. The data suggest that earthbag strength and stiffness decay exponentially as stack height increases. An inverse relationship between stack height and specimen strength and stiffness (in terms of kN/mm) makes intuitive sense, since an equivalent deflection will compress a short specimen more as a percentage of its total height than the same deflection applied to a taller specimen. The implications of this relationship for future earthbag testing concern the determination of an appropriate stack height. If testing is done with the intent of simulating the behaviour of full-scale walls, it is clear that the 3-bag stack height used in this thesis, as well as in the only other laboratory-based compression testing of earthbag specimens (Dunbar & Wipplinger, 2006), may overestimate the strength of a full-scale assembly. It would be useful for future testing efforts to compare the strength and stiffness of a full-scale wall to the strength and stiffness of a series of earthbag stacks to determine the height at which the small-scale specimens accurately represent the behaviour of the full-scale wall. It is possible that this stack height may vary with fill

type, as more densely packed materials may not be as susceptible to losses in stiffness as stack height increases.

The results presented in Chapter 5 showed little difference in behaviour between the topsoil- and sandy soil-filled specimens. It is likely, however, that differences in strength and stiffness will appear with specimens filled with soils with a greater differential in terms of clay and sand fractions. Further testing on soils with a wider range of particle distributions may help derive a numerical relationship between soil particle size distribution and earthbag strength and stiffness. It is anecdotally believed (Hunter & Kiffmeyer, 2004; Minke, 2006) that this relationship will take the form of a curve, with some optimal clay fraction above which the volumetric stability of the soil becomes a concern, and below which the lack of interparticle cohesion results in weaker earthbags. What is most important, from an engineering perspective, is to understand the shape of this curve. Is there a smooth variation in strength between optimal and sub-optimal soils as the clay fraction is altered, or is there a broad range of acceptable clay fractions, with significantly different performance above and below some threshold value? This knowledge would provide excellent guidelines for the future development of a model building code for earthbag houses.

Additionally, different initial void ratios, in the form of varying degrees of compaction, will likely affect specimen stiffness. It would be useful for future tests to examine the strength and stiffness of earthbag specimens with different amounts and/or methods of compaction.

The results from specimens SG6 and SG7 also suggest that specimen age may affect strength and stiffness. It would be useful for future tests to compare the performance of specimens prepared shortly before testing to the performance of specimens fabricated and stacked in advance (i.e. 1 month or more) of testing. The effects of creep may be significant, which would have implications for the long-term strength and stiffness of earthbag housing.

Chapter 5 also presents the results of ancillary tensile tests on the polypropylene bag textile. Since no other earthbag tests have yet been published which include bag strength as a reported value, it is not yet possible to discuss the effects of bag strength and stiffness on earthbag housing performance. However, as discussed in Chapter 5, it is likely that stronger, stiffer bags will result in stronger, stiffer earthbag housing assemblies. In order to control for this, future tests should include ancillary testing on bag strength. Furthermore, it would be useful to test specimens using bags of varying known strengths in order to determine the magnitude of any potential increases in strength and/or stiffness with bag strength.

The mechanical behaviour of polypropylene is also dependent upon the strain rate at which it is being investigated. Generally, higher strain rates result in higher elastic moduli (Drozdo & Christiansen, 2003). As such, it would be useful for future tests to conduct a more rigorous analysis of the behaviour of polypropylene earthbags under a variety of strain rates. Before this is possible, however, it will be necessary to determine the relationship between applied load, earthbag stress and strain in the polypropylene textile. Given the irregular geometries of earthbag specimens, this is not a

straightforward task. One possible approach would be to conduct an index test using soil-filled earthbags fabricated such that they have an approximately cylindrical cross-section, wherein they are subject to longitudinal compressive loading. Under this loading, the strains in the polypropylene may be measured either directly using strain-measurement equipment, or graphically using an image-based technique such as particle image velocimetry.

### **7.3.2 Future Testing – Effects of Plaster, Confinement, Reinforcement and Beyond**

The results presented in this thesis for the granite gravel-filled specimens demonstrate that such specimens are capable of sustaining loads equal or greater to the capacity of conventional housing systems and other alternative construction technologies, as will be discussed further below in Section 6.2. However, it is likely that unplastered, unconfined prism tests underestimate the strength and stiffness of these bags in a housing application. Since gravel-filled bags are being considered for use in foundations, where they would be laid in a trench dug into the native soil of a given site, it is likely that there will be significant confining pressure acting to restrain the lateral expansion of the earthbags. It is reasonable to assume that the bags would display significantly higher strength and stiffness if restrained in such a manner. Tests of laterally confined gravel-filled earthbag foundations would provide insight into the mechanical behaviour of the earthbag foundation system, in particular the strength per metre length and load-deformation characteristics, in a much more detailed fashion.

In addition to confinement, it would also be informative to test earthbag prism specimens in a similar manner to the tests discussed in Chapters 4 and 5, but with the addition of plaster skins on the long faces (i.e. the faces that would be exposed in a full-scale wall). Specimens tested in such a manner will likely provide strength and stiffness data more representative of full-scale wall behaviour. Additionally, the results of plastered earthbag prism tests may be compared with the results of the unplastered tests presented in this thesis in order to determine the relative contributions of the earthbags and the plaster, and the degree to which composite behaviour is achieved in plastered earthbags. This information could eventually be used to develop empirical relationships for earthbag housing systems.

The effect of reinforcement should also be tested for various specimen configurations. The results of the tests presented in Chapter 5 suggest that tearing of the polypropylene bags by sharp particles leads to loss of confinement and eventual specimen failure. It is, thus, possible that the current practice of providing shear reinforcement in the form of barbed wire laid between courses of earthbags may have a detrimental effect on overall wall strength. Several types of tests may help address this issue. First, compression tests similar to those presented in Chapter 5 may be run to compare the compressive behaviour of specimens with and without barbed wire reinforcement between each bag. Second, direct shearing of earthbag specimens with and without reinforcement should be measured to determine the extent to which barbed wire reinforcement actually strengthens an earthbag structure against shear. Direct shear tests of sand-filled polypropylene bags without reinforcement have already been conducted

(Krahn et al., 2007), and though the intended application of these tests was for temporary sandbag dykes, the data presented may be of use for comparing the reinforced and unreinforced shear strength of polypropylene bag-to-bag interfaces. Finally, mixed mode tests, wherein specimens are subject to both vertical compression and lateral shear, may be useful in analyzing the behaviour of reinforced earthbag walls under loading conditions similar to what would be seen in an actual earthbag structure.

Long-term tests of earthbag walls under constant and/or cyclical loading (to simulate dead and live loads) would also be useful in order to gauge the effects of sustained loads on the earthbag system, and the integrity of the polypropylene bags in particular. It would be most useful to conduct these tests on full-scale test structures in order to fully characterize the long-term behaviour of earthbag structures, though tests on individual walls may also provide useful information with fewer resource and space demands.

Beyond the structural performance of earthbag wall systems, further tests are also needed in order to gauge the behaviour of these systems under a variety of other service conditions. Minke (2006) presents a detailed analysis of the behaviour of several earthen wall construction techniques with respect to moisture, insulation value and abrasion, though the earthbag system, as defined in this thesis, is not directly addressed. Furthermore, fire resistance and seismic performance must be accurately characterized if earthbag housing is to be accepted under existing national and regional building codes.

#### **7.4 Conclusions – Alternative Construction Techniques in Developing Countries**

With regards to the third objective, it is clear that there exists an opportunity for the implementation of alternative construction techniques in developing countries, and specifically in southern Sri Lanka. The wide availability of alternative construction materials, coupled with the generally inexpensive and low-technology nature of their related construction techniques, makes them well suited to use in developing countries. Furthermore, the large (and increasing) number of well-developed alternative construction techniques means the potential range of situations in which these techniques are possible and appropriate is also large and increasing. In the specific case of southern Sri Lanka, local architectural preferences and material availability suggest that earthbag housing is very well suited for use in this region. Straw bale housing may also be suitable, though significant attention should be paid to moisture-related concerns, given southern Sri Lanka's wet climate. Rammed earth structures may be possible, though aesthetic and constructability concerns suggest it is not the best choice for the region. Bamboo structures may also be possible, but limited material availability may limit its applicability on a large scale. Also, bamboo's current role in the Sri Lankan construction industry, as scaffolding and temporary reinforcement, may lead to a negative perception of its capabilities as a permanent structural solution, hindering project buy-in.

For the general case of housing construction in developing countries, it should be emphasized that the above conclusions do not mean that every alternative construction technique is superior to conventional construction in all cases. As discussed in Chapter 3, there are several technical and non-technical factors which must be considered before a

construction technique is chosen, if long-term success of a given construction project is to be ensured.

In order to ensure that the underlying goal of alternative construction techniques, the reduction of material and energy consumption, is achieved, material availability must be assessed at the local or regional level, and long-distance transport of materials avoided wherever possible. Additionally, social preferences for housing design and aesthetics must be considered in order to minimize the likelihood of housing abandonment. Finally, community involvement in construction projects should be maximized from as early in the project timeline as possible. This will improve project buy-in, increase the likelihood of long-term structural occupancy and maintenance, and ensure acceptable building design and aesthetics. Indeed, community involvement may help address problems beyond housing need. By encouraging participatory action in the application of alternative construction techniques, there is potential for capacity building and livelihood generation which may help develop local economies which are based on more responsible, efficient use of natural resources and energy.

## References

- Anderson, M. B. (2000). "Aid: A mixed blessing". *Development in Practice*. Vol. 10, Nos. 3 & 4, pp. 495-500.
- Arce, O. A. (1993). "Fundamentals of the Design of Bamboo Structures". PhD Dissertation, Eindhoven Technical University.
- ASTM (American Society for Testing and Materials) (2004). "C 144 – Standard Specification for Aggregate for Masonry Mortar". American Society for Testing and Materials, Pennsylvania, USA.
- ASTM (American Society for Testing and Materials) (1985). "D 421 - Standard Practice for Dry Preparation of Soil Samples for Particle-Size Analysis and Determination of Soil Constants". American Society for Testing and Materials, Pennsylvania, USA.
- ASTM (American Society for Testing and Materials) (1985). "D 422 – Standard Test Method for Particle-Size Analysis of Soils". American Society for Testing and Materials, Pennsylvania.
- ASTM (American Society for Testing and Materials) (2005). "D 4595 – Standard Test Method for Tensile Properties of Geotextiles by the Wide-Width Strip Method". American Society for Testing and Materials, Pennsylvania, USA.
- ASTM (American Society for Testing and Materials) (1989). "E 178 – Standard Practice for Dealing With Outlying Observations". American Society for Testing and Materials, Pennsylvania, USA.

- ASTM (American Society for Testing and Materials) (1984). “E 447 – Standard Test Methods for Compressive Strength of Masonry Prisms”. American Society for Testing and Materials, Pennsylvania, USA.
- Bou-Ali, G. (1993). “Straw Bales and Straw Bale Wall Systems”. *M.Sc. Thesis, submitted to Dept. Of Civil Engineering, University of Arizona.*
- Brooks, D. B. (2002). “Water: Local-Level Management”. *International Development Research Centre*. Ottawa, Ontario, Canada.
- Brown, J. (2004). “Bamboo House Passes Seismic Test”. *Civil Engineering Magazine*, Vol. 74, No. 11.
- Callen, T. (2007). “Emerging Markets Main Engine of Growth”. *IMF Survey Magazine*. Available online:  
<http://www.imf.org/external/pubs/ft/survey/so/2007/NUM1017A.htm>. Last accessed: August 14, 2008.
- Canadian Commission on Building and Fire Codes (2005). “National Building Code of Canada”. *National Research Council of Canada*, Ottawa, Ontario, Canada.
- Canadian Wood Council (2001). “Wood Design Manual”. *Canadian Wood Council*, Ottawa, Ontario, Canada.
- Chung, K.F.; Yu, W.K. (2002). “Mechanical properties of structural bamboo for bamboo scaffolding”. *Engineering structures*, Vol. 24, pp. 429-442.
- CISC (Canadian Institute of Steel Construction) (2004). “Handbook of Steel Construction, Eighth Edition”. Canadian Institute of Steel Construction, Willowdale, Ontario, Canada.

- CMHC (Canada Mortgage and Housing Corporation) (2002). “Wood Usage in Straw Bale Houses”. *Research Highlights*, Technical series 02-116.
- CMHC (Canada Mortgage and Housing Corporation) (2000a). “Straw Bale House Moisture Research”. *Research Highlights*, Technical series 00-103.
- CMHC (Canada Mortgage and Housing Corporation) (2000b). “Moisture Properties of Plaster and Stucco for Straw Bale Buildings”. *Research Highlights*, Technical series 00-132.
- Colorado School of Mines (2005). “Humanitarian Engineering at CSM”.  
<http://humanitarian.mines.edu> . Last accessed: May 9, 2008.
- Corum, N. (2005). “Building a Straw Bale House: The Red Feather Construction Handbook”. *Princeton Architectural Press*, New York, New York, USA.
- Daiglis, T. D. (1999). “Bamboo composite materials for low-cost housing”. PhD Dissertation, Queen’s University.
- Das, B. M. (2005). “Fundamentals of Geotechnical Engineering, Second Edition”. *Thomson Canada Limited*, Toronto, Ontario, Canada.
- DeBoer, D.; Bareis, K. (2000). “Bamboo”. In Elizabeth, Lynne; Adams, Cassandra (Eds.) “Alternative Construction: Contemporary Natural Building Methods”. *John Wiley & Sons*, New York, New York, USA.
- Devore, J.; Peck, R. (1993). “Statistics: The Exploration and Analysis of Data, Second Edition”. *Duxbury Press*, Belmont, California, USA.

- Drozdov, A.D.; Christiansen, J. De C. (2003). "The effect of strain rate on the viscoplastic behavior of isotactic polypropylene at finite strains". *Polymer*, Vol. 44, No. 4, pp. 1211-1228.
- Dunbar, R.; Wipplinger, L. (2006). "Prism Testing of Polypropylene Earthbags". Unpublished report, West Point Military Academy.  
<http://www.earthbagbuilding.com/Testing/prismtest.htm>. Last accessed: July 1, 2008.
- Forest Products Laboratory (1999). "Wood Handbook – Wood as an engineering material. Gen. Tech. Rep. FPL-GTR -113". *US Department of Agriculture Service*, Madison, Wisconsin, USA.
- Franceschini, F.; Rossetto, S. (1995). "QFD: The Problem of Comparing Technical/Engineering Design Requirements". *Research in Engineering Design*. Vol. 7, pp. 270-278.
- Ghavami, K. (2005). "Bamboo as reinforcement in structural concrete elements". *Cement and Concrete Composites*, Vol. 27, pp. 637-649.
- Gordon, R.B.; Bertram, M.; Graedel, T.E. (2006). "Metal stocks and sustainability". *Proceedings of the National Academy of Sciences*, Vol. 103, pp. 1209-1214.
- Grandsaert, M.F.; Ruppert, J. (1999). "A Compression Test of Plastered Straw Bale Walls". *Unpublished research summary*, University of Colorado at Boulder. Available online: <http://www.cc-w.co.uk/Documents/Grandsaert.pdf>. Last accessed: May 16, 2008.
- Greenwood, D.J.; Whyte, W.F.; Harkavy, I. (1993). "Participatory action research as a process and as a goal". *Human Relations*. Vol. 46, No. 2, pp. 175-192.

- Grossman, G.M.; Krueger, A.B. (1995). "Economic growth and the environment". *The Quarterly Journal of Economics*, Vol. 110, No. 2, pp. 353-377.
- Gutierrez, J.A. (2000). "Structural Adequacy of Traditional Bamboo Houses in Latin America". *International Network for Bamboo and Rattan*, Technical Report No. 19. Beijing, China.
- Hagey, R.S. (1997). "The Use and Abuse of Participatory Action Research". *Chronic Diseases in Canada*, Vol. 18, No. 1.
- Hammond, G.; Jones, C. (2006) "Inventory of Carbon and Energy, Version 1.5 Beta". Available online: <http://people.bath.ac.uk/cj219/>. Last accessed: September 7, 2008.
- Hillman, A.L. (2000). "Development failure, or the persistence of poverty in poor countries (an overview)". *Seminar outline prepared for the Department of Economics, Bar-Ilan University, Israel*.
- Hunter, K.; Kiffmeyer, D. (2004). "Earthbag Building". *New Society Publishers*, Gabriola Island, British Columbia, Canada.
- IPCC (Intergovernmental Panel on Climate Change) (2007). "Climate Change 2007: Synthesis Report". *An Assessment of the Intergovernmental Panel on Climate Change*, Geneva, Switzerland.
- ISO (International Standards Organization ) (2004). "22156: Bamboo – Structural Design". *International Standards Organization*, Geneva, Switzerland.
- ISO (International Standards Organization) (1999). "13934-1: Determination of maximum force and elongation at maximum force using the strip method." *International Standards Organization*, Geneva, Switzerland.

- Jayanetti, L. (2004). "Seismic testing of a bamboo based building system". *Report published by Timber Research and Development Association, Buckinghamshire, United Kingdom*. Available online:  
[http://www.inbar.int/Econo\\_devep/proceeding/Pa-Lionel-Seismic%20Testing%20of%20a%20Bamboo-based%20Building%20System.pdf](http://www.inbar.int/Econo_devep/proceeding/Pa-Lionel-Seismic%20Testing%20of%20a%20Bamboo-based%20Building%20System.pdf). Last accessed: October 24, 2007.
- Kariyawasam, D. (1998). "Bamboo Resources and Utilization in Sri Lanka". *Bamboo Conservation, Diversity, Ecogeography, Germplasm, Resource Utilization and Taxonomy*, Chapter 31. International Plant Genetic Resources Institute, Rome, Italy.
- King, B. (2006). "Design of Straw Bale Buildings". *Green Building Press*, San Rafael, CA.
- King, B. (2000). "Structural Properties of Alternative Building Materials". In Elizabeth, Lynne; Adams, Cassandra (Eds.) "Alternative Construction: Contemporary Natural Building Methods". *John Wiley & Sons*, New York, New York, USA.
- Koehn, E.; Kothari, R.K.; Pan, C.S. (1995). "Safety in Developing Countries: Professional and Bureaucratic Problems". *Journal of Construction Engineering and Management*, September 1995, pp. 261-265.
- Koerner, R.M. (1997). "Designing with Geosynthetics – Fourth Edition". *Prentice Hall*, New Jersey, USA.
- Krahn, T.; Blatz, J.; Alfaro, M.; Bathurst, R.J. (2007). "Large-scale interface shear testing of sandbag dyke materials". *Geosynthetics International*, Vol. 14, No. 2, pp. 119-126.

- Lee, S.H.; Wang, S. (2006). "Biodegradable polymers/bamboo fiber biocomposite with bio-based coupling agent". *Composites Part A: Applied Science and Manufacturing*, Vol. 37, No.1, pp. 80-91.
- Ley, T.; Widgery, M. (1997). "Devon Earth Building Association: cob and the Building Regulations". *Structural Survey*, Vol. 15, No. 1, pp. 42-49.
- Li, S.H.; Zeng, Q.Y.; Xiao, Y.L.; Fu, S.Y.; Zhou, B.L. (1995). "Biomimicry of bamboo bast fiber with engineering composite materials". *Materials Science and Engineering*, Vol. C-3, pp. 125-130.
- Liese, W. (1987). "Research on Bamboo". *Wood Science and Technology*, Vol. 21, pp. 189-209.
- Lindquist, J. (2000). "Modern spaces, wild places and international hinterlands: the cultural economy of decoupling and misrecognition". *Anthropology Today*, Vol. 16, No. 3, pp. 15-17.
- Mannari, V. M.; Massingill, J.L. (2006). "Two-component high-solid polyurethane coating systems based on soy polyols". *Journal of Coatings Technology and Research*, Vol. 3, No. 2, pp. 151-157.
- Mbumia, L.; de Wilmars, A.M.; Tirlocq, J. (2000). "Performance characteristics of lateritic soil bricks fired at low temperatures: a case study of Cameroon". *Construction and Building Materials*, Vol. 14, pp. 121-131.
- Messick, D.M.; Mackie, D.M. (1989). "Intergroup Relations". *Annual Review of Psychology*. Vol. 40, pp. 45-82.

- Miller, J.D. (2008). “Humanitarian Engineering: Addressing the global influence of applied technology in engineering education”. *Master’s Thesis*. Queen’s University.
- Minke, G. (2006). “Building With Earth”. *Birkhäuser – Publishers for Architecture*. Basel, Switzerland.
- Minke, G. (2001). “Construction manual for earthquake-resistant houses built of earth”. *Building Advisory Service and Information Network*, Eschborn, Germany. Available online: <http://www.basin.info/publications/books/ManualMinke.pdf>. Last accessed: September 27, 2007.
- Mohanty, A.K.; Misra, M.; Drzal, L.T. (2002). “Sustainable bio-composites from renewable resources: opportunities and challenges in the green materials world”. *Journal of Polymers and the Environment*, Vol. 10, Nos. 1 and 2, pp. 19-26.
- Moquin, M. (2000). “Adobe”. In Elizabeth, Lynne; Adams, Cassandra (Eds.) “Alternative Construction: Contemporary Natural Building Methods”. *John Wiley & Sons*, New York, New York, USA.
- OK OK OK Productions (2008). “Earthbag Case Studies – The Sand Castle”. Available online: <http://www.okokok.org/cs-sand-07.php>. Last accessed: August 15, 2008.
- Panabokke, C.R. (1975). “Sri Lanka – Showing Approximate Distribution of Great Soil Groups”. *European Digital Archive of Soil Maps*.  
[http://eusoils.jrc.it/ESDB\\_Archive/EuDASM/Asia/lists/clk.htm](http://eusoils.jrc.it/ESDB_Archive/EuDASM/Asia/lists/clk.htm). Last accessed: August 5, 2008.
- Price Waterhouse Cooper (2008). “Engineering & Construction Industry Sector”. Available online:

- <http://www.pwc.com/extweb/industry.nsf/docid/707e1d1bdd3b2e0785256df800185c8>  
c. Last accessed: September 4, 2008.
- Rammed Earth Constructions (2007). "Rammed Earth". *Promotional flyer*. Available online: <http://www.rammedearthconstructions.com.au/rammedearthhb.pdf>. Last accessed: August 22, 2007.
- Rank, E. (2006). "Habitat for Humanity Scours L.A. Region to Find Properties & Build Affordable Housing". *Interview with "The Planning Report"*.  
[http://www.planningreport.com/tpr/?module=displaystory&story\\_id=1234&format=html](http://www.planningreport.com/tpr/?module=displaystory&story_id=1234&format=html), Last accessed: August 10, 2007.
- Riley, D.; Palleroni, S. (1999). "Community-built Housing Solution: A Model Strawbale Home Design". Unpublished report. Available online:  
<http://www.nibs.org/BETEC/Pres/riley.pdf>. Last accessed: July 31, 2008.
- Roodman, D.M.; Lenssen, N. (1994). "Our Buildings, Ourselves". *World Watch*, Vol. 7, No. 6, pp. 21-29.
- Saxena, M.; Gowry, V. S. (2003). "Studies on bamboo polymer composites with polyester amide polyol as interfacial agent". *Polymer Composites*, Vol. 24, No. 3.
- Selinger, E. (2007). "Technology Transfer: What Can Philosophers Contribute?". *Philosophy and Public Policy Quarterly*. Vol. 27, Nos. 1 & 2, pp. 12-17.
- "Sri Lanka". (2008) *CIA World Factbook*. <https://www.cia.gov/library/publications/the-world-factbook/geos/ce.html>. Last accessed: July 16, 2008.

- Sri Lanka Land Use Division (1988). "Soil Map of Sri Lanka". *European Digital Archive of Soil Maps*. [http://eusoils.jrc.it/ESDB\\_Archive/EuDASM/Asia/lists/clk.htm](http://eusoils.jrc.it/ESDB_Archive/EuDASM/Asia/lists/clk.htm). Last accessed: August 5, 2008.
- Suppiah, R. (1997). "Extremes of the Southern Oscillation Phenomenon and the Rainfall of Sri Lanka". *International Journal of Climatology*, Vol. 17, pp. 87-101.
- Terzaghi, C. (1923). "Principles of Soil Mechanics: V-Physical Differences Between Sand and Clay." *A History of Progress. Selected US Papers in Geotechnical Engineering, Volume 1*. American Society of Civil Engineers.
- Theis, B. (2003). "Straw Bale Fire Safety: A Review of Testing and Experience to Date". *Ecological Building Network (EBNet)*. <http://www.ecobuildingnetwork.org>. Last accessed: August 14, 2007
- Tolles, E.L.; Kimbro, E.E.; Webster, F.A.; Ginell, W.S. (2000). "Seismic Stabilization of Historic Adobe Structures: Final Report of the Getty Seismic Adobe Project". *The Getty Conservation Institute*, Los Angeles, California, USA.
- UN FAO (United Nations Food and Agriculture Organization) (2002). "Non-wood Forest Products in 15 Countries of Tropical Asia – An Overview". *FAO Corporate Document Repository*. <http://www.fao.org/docrep/005/ab598e/ab598e00.htm>. Last accessed: August 4, 2008.
- UN FAO (United Nations Food and Agriculture Organization) (2008). [Production statistics for wheat and rice in Sri Lanka]. <http://faostat.fao.org/site/567/default.aspx>. Last accessed: August 4, 2008.

USGS – United States Geological Survey (2007). “Seismic Maps Factsheet”.

<http://quake.usgs.gov/prepare/factsheets/SeisMaps/> Last accessed: August 16, 2007.

Vardy, S.; MacDougall, C. (2006). “Compressive Testing and Analysis of Plastered Straw Bales”. *Journal of Green Building*, Vol. 1, No. 1.

Vardy, S.; MacDougall, C.; Magwood, C.; Spick, A. (2006). “The Design and Construction of the 4C’s Building”. *Journal of Green Building*, Vol. 1, No. 2, pp. 49-62.

Velez, S. (2008). “Pont de bambou”. *L’internaute*. Available online:

<http://www.linternaute.com/savoir/magazine/photo/l-alter-architecture/sur-un-pont-de-bambou.shtml>. Last accessed: August 15, 2008.

Zubair, L. (2002). “El Nino – Southern Oscillation Influences on Rice Production in Sri Lanka”. *International Journal of Climatology*, Vol. 22, pp. 249-260.

## **Appendix A**

### **RESTORE Project Activity Summary – New Technology**

#### *Activity 1: Water Harvesting Units (household scale for drinking water)*

- Who: Faculty of Engineering, Faculty of Agriculture Ruhuna University, Eastern University, Southeastern University
- Where: All selected villages, if in arid zone
- When/How Long:
  - Workshops (2 types, awareness and capacity building): after selecting beneficiary villages (Q4 – Jan 2007)
  - Construction: after conducting workshops (Q1-Q2 2007)
- How:
  - Find experienced masons through NGOs to lead workshops
  - Will construct model structure, further units can be constructed with aid of other agencies (Rainwater Harvesting Forum)
- Constraints/Other Issues:
  - Aboveground tanks recommended to avoid root damage
  - Selection criteria: need to determine greatest need, since resources not available to supply for entire village
  - find other available funds to supply greater percentage of village
- Outputs:
  - water harvesting units installed (6 per village)
  - Safe drinking water
  - Improved water quality
  - Increased awareness of water harvesting techniques

#### *Activity 2: Biosand Filters/UV Treatment/Wastewater Treatment*

- Who: Faculty of Agriculture, Ruhuna (Professor Weerasinghe), Queen's University (S. Imran Ali), Eastern University, Southeastern University

- Where: All selected villages
- When/How Long:
  - Water testing will be conducted according to the provisions of 4.1 (check date?)
  - Construction: after testing results obtained
- How: If need is established, Dept. of Agriculture will procure required hardware
- Constraints/Other Issues: More research required to use plants for wastewater treatment (i.e. which plants are effective? – S. Imran Ali), biosand filters (behaviour characteristics)
- Outputs:
  - better water quality
  - improved sanitation

*Activity 3: Biogas Demonstration Units*

- Who: Faculty of Agriculture, Ruhuna University (Professor Weerasinghe), Eastern University, Southeastern University
- Where: All selected villages
- When/How Long:
  - Workshops (awareness and capacity building): after selecting beneficiary villages
  - Model construction: after conducting workshops
- How:
  - Manure, garbage, industrial waste as fuel source
  - NGOs (Practical Action) to provide expertise

- Constraints/Other Issues:
  - Workshops must include info on maintenance, community units must have designated maintenance supervisor
  - Info on garbage sorting can facilitate collection of materials
- Outputs:
  - Clean energy for lighting and cooking
  - Cleaner environment
  - Organic fertilizer for crops
  - New enterprises
  - 4 units per village

*Activity 4: Local and Alternative Building Materials*

- Who: Faculty of Engineering & Faculty of Agriculture, Ruhuna University (Professor Veerasinghe), Queen's University (Bryce Daigle), Eastern University, Southeastern University
- Where: All selected villages where housing is needed
- When/How Long:
  - Participatory Rural Appraisal data collection/analysis: (Q4/Q1 2007)
  - Construction: (Q1/Q2 2007)
- How:
  - Obtain PRA data on housing needs (sq. ft, # bedrooms etc.), also materials available in each village (recycled as well as alternatives – bamboo, soil brick, etc.)
  - Design housing based on above data
- Constraints/Other Issues:

- Expertise from Canada can be used in design/research phase as well as for capacity building
- Research/design work to be done in Sri Lankan context (Ruhuna University)
- Unknown housing need
- Issues of social imbalance may necessitate the construction of community structures instead of individual housing units
- Outputs:
  - Reuse of materials
  - Increased knowledge of design information for low cost, appropriate building materials
  - Reduction of plastics waste
  - Potential solution for materials scarcity

## **Appendix B**

### **Field Notes – Sri Lanka, September 2006**

The following notes were transcribed directly from the author's handwritten notes taken during the site visit to southern Sri Lanka in September, 2006. These notes include observations on all discussions and presentations that led directly to the discussion of the RESTORE Project in Chapter 3. Field notes not directly relating to this thesis have been omitted.

#### *Meeting – Colombo, September 10, 2006*

Attendance: Bryce Daigle (Queen's), S. Imran Ali (Queen's), Dr. Jana Janakiram (Guelph)

Guiding principles for project:

1. Do no harm. Ensure benefits bestowed on some don't harm others (also avoid consolidating power, i.e. gender)
  2. Don't displace local expertise. Use participatory feedback to shape project content.
- Budget info: \$195,000 contribution from universities (\$40,000 each from Queen's, Waterloo, Manitoba, \$75,000 from Guelph). \$1.75 million contribution from Canadian International Development Agency (CIDA)
  - When collecting participatory research, make a conscious effort to collect data from female demographic. May need to find a woman involved in project to solicit data, as

village women in southern Sri Lanka tend to be hesitant to communicate directly with men.

- Peace and conflict issues – consider at a household and community scale more so than a national one

*Meeting – Sri Lankan Centre for Development Facilitation - Colombo, Sept. 11, 2006*

Attendance: Bryce Daigle (Queen's), S. Imran Ali (Queen's), Dr. Jana Janakiram (Guelph), Dr. Brent Doberstein (Waterloo), Dr. Abeydeera (SLCDF).

- SLCDF (founded 1994) acts as networking hub for NGOs, aids collaboration at the “district” level (roughly analogous to provinces in Canada)
- 16 districts total, excluding northern regions (not covered due to conflict issues)
- Also operate as an intermediate funding mechanism, providing funds to NGOs who then distribute cash as low-interest loans to poverty groups
- Also provide training at nominal rates (have both in-house and external trainers)
- Deal with many (~3300) community-based organizations (CBOs). 15 or 16 CBOs can consort as a district-level NGO.
- Budgets explained to community line by line.
- SLCDF does no project implementation, only capacity building and networking
- NGOs must be registered with government to qualify for SLCDF

- SLCDF also has links with National NGO Action Front, which conducts policy advocacy at the national government level
- District consortia of NGOs registered as NGOs themselves, lets them qualify as “mid-size” NGOs to achieve CIDA recognition
- RESTORE Project deals with four districts: Batticaloa (east), Ampara (southeast), Hambantota (south), and Matara (south), of which Batticaloa and Ampara are currently significantly affected by conflict.
- Using remote sensing (satellite imagery, etc. to determine “before and after” conditions at pilot sites can inform rebuilding strategies for critical infrastructure
- Potential for the development of learning materials to be distributed to villages re: infrastructure development/construction techniques, to increase local awareness of critical issues, alternative tech, etc.
- Presentation: Dr. Brent Doberstein – Tsunami Vulnerability
  - Key vulnerability indicators: wealth (lower = higher vulnerability), ethnic groups (such as “sea gypsies”, a population of illegal Burmese immigrants), religion (Islamic population restricted from alcohol trade, affects wealth)
  - Building codes existed but were poorly enforced
  - Rebuilding has been mostly in the same style as pre-tsunami housing, reproducing similar structural vulnerabilities

- Actual statistics on damage are questionable – ex: Thai government inflated figures to qualify for more aid

*Meeting – CIDA Project Support Unit - Colombo, Sept. 11, 2006*

Attendance: Bryce Daigle, S. Imran Ali, Dr. Jana Janakiram, Dr. Brent

Doberstein, CIDA Project Support Unit coordinator

- CIDA Project Support Unit (PSU) serves as watchdog against conflict sensitivity issues
- Supports around 31 CIDA-funded projects (was around 7-8 before tsunami)
- Tremendous dissatisfaction among youth due to lack of opportunities. Stagnant higher education curricula still focused on civil service, but no jobs available in this sector due to strong job security, low turnover
- Dissatisfaction increases susceptibility to recruitment from Tamil and Sinhalese ultranationalists, militias
- JVP: ultranationalist Sinhala group based in the south, vehemently anti-Tamil. In talks with government, high enrolment of disaffected youth.
- Prevailing view among groups like JVP- “if anybody talks about peace, you are no longer a nationalist, you are a terrorist.”
- Teachers unions pose a potential obstacle to curriculum reform – fears about being made obsolete, resistance to change.

*RESTORE Project Meeting, Day 1 – Matara, Sept. 13, 2006*

Attendance: all project partners (2-3 delegates each) from Eastern University, Southeastern University, University of Ruhuna, as well as Bryce Daigle, S. Imran Ali, Dr. Jana Janakiram, Dr. Brent Doberstein,

- Participatory Rural Appraisals (PRAs) – ensure capability for participation is built into design process (all stakeholders should participate). Communication framework is critical for multi-partner projects with PRA component
- When seeking participatory feedback, ensure all affected groups are represented (ex: women, elderly, youth), not just more vocal authority figures (typically adult males)
- Project adjustments due to conflict as of Sept. 2006 – eastern district most affected: 3 of 13 villages very problematic in terms of conflict, but also most affected, in need of reconstruction aid. Risk in southeastern district can be mitigated with proper village selection. Risk in southern district is minimal [note: this changed shortly after the end of the project meeting, with a sudden increase in violence in the southern district.]
- Conflict mitigation strategy: structure PRA framework so surveying and monitoring is taken care of by CBOs at the village level. This eliminates unnecessary travel, and also allows for organic spread of project ideas and techniques from community to community. Heavily dependent on strong CBO/NGO communication network (see SLCDF notes above).
- In order to optimize village selection, need to produce set of selection criteria

- Village Selection Criteria (determined by group brainstorming)
  - Political importance (lower importance = easier to operate)
  - Tsunami affected (more damage = greater need)
  - Poverty level
  - Existing industries/livelihoods
  - Environmental damage (more damage = higher need)
  - Gender balance/women-headed households
  - Community size (350 max)
  - Accessibility (roads, etc.)
  - Technology gap
  - Availability of CBOs
  - Level of indigenous knowledge
  - Level of organization at village level
  - Existence of enabling environment (government level)
  - Current level of recovery

- Above criteria were ranked by each participant using a scale of 1 (unimportant) to 5 (most important). The total score for each criterion was then divided by the number of respondents to obtain an average score. The top 11 criteria are as follows:

1. Tsunami affected area
2. Poverty level
3. Manageable community size
4. Non-conflict area
5. High # of industries/livelihoods affected
6. Environmentally affected
7. Village accessibility
8. Politically/strategically unimportant
9. Villager commitment/buy-in
10. High vulnerability (social, economical, environmental)
11. Availability of CBOs

*RESTORE Project Meeting, Day 2 – Matara, Sept. 14, 2006*

- Today's itinerary: production of action plans (who, what, where, when, how) for each project activity. [note: see Appendix A for housing-related action plan]

- Financial concerns: in countries where significant depreciation is possible, efforts should be made to keep project funds in a foreign currency account in the country hosting the project. This mitigates losses due to depreciation, as well as access limitations due to holding funds outside the project host country. For RESTORE Project, open a \$CDN account with a Sri Lankan bank.
- Key concepts for activity plans: capacity building, subsidiarity, enabling environment.
  - o Capacity building: training and material supplying with the intent of teaching villagers to solve their own problems/establish expertise and livelihoods which are sustainable beyond the project intervention
  - o Subsidiarity: a concept which says that projects should aim to achieve results at the lowest possible level (i.e. benefits should extend beyond the NGO/CBO/village leaders)
  - o Enabling environment: willingness of village leaders, villagers and government officials to see project through to completion
- Notes on production of action plan: strong tendency among all participants to schedule all activities for “as soon as the PRA is completed”. However, this results in a flood of scheduled tasks immediately after PRA is completed. A conscious effort must be made to attach realistic start dates to all activities in light of workflow rate of partners involved, expected duration of each activity, and project critical path.

*RESTORE Project Meeting, Day 3 – Matara, Sept. 15, 2006*

- Participatory Rural Appraisal discussion
  - Village pre-selection will be conducted using district census data. 5 villages per district will be selected for baseline survey (to be conducted by project partners, not participatory).
  - NGO input will also be sought on potential villages
  - Remote sensing will be used to pre-select villages based on observed environmental damage
  - PRA questionnaires will be prepared by interested project partners and distributed to project team for comment
  - Note: the benefits of conducting a PRA (i.e. increased knowledge of community resources and demographics) must be incentive enough for villages to complete the PRA. Implying or promising that PRA completion will lead to aid obscures the true amount of cooperation present at the village level. Similarly, trust and cross-checking of PRA data is very important, as benefits of project can act as an incentive to provide false data, including exaggerated damage figures.

*Housing Project Visit – Kalutara, Sept. 16, 2006*

- Kalutara: small town, 2.5 km inland from southern coast. Site of government-sponsored relocation project.
- Housing: \$2700 per unit, kitchen, two bedrooms. Detached bathroom. Masonry construction, terra cotta tile roofs.
- Location chosen to minimize risk of future tsunami damage. Downside: relocated villagers still dependent on coastal areas for livelihoods, now need to walk to coast every day.

## Appendix C

### Grain Size Distribution Data

**Table C.1: Specifications given in ASTM C 144 for the allowable particle size distribution of masonry sand.**

|           |               | Percent Passing |             |                   |             |
|-----------|---------------|-----------------|-------------|-------------------|-------------|
|           |               | Natural Sand    |             | Manufactured Sand |             |
| Sieve No. | Diameter (mm) | Lower Bound     | Upper Bound | Lower Bound       | Upper Bound |
| 4         | 4.75          | 100             | 100         | 100               | 100         |
| 8         | 2.36          | 95              | 100         | 95                | 100         |
| 16        | 1             | 70              | 100         | 70                | 100         |
| 30        | 0.6           | 40              | 75          | 40                | 75          |
| 50        | 0.3           | 10              | 35          | 20                | 40          |
| 100       | 0.15          | 2               | 15          | 10                | 25          |
| 200       | 0.075         | 0               | 5           | 0                 | 10          |

**Table C.2: Results of particle size distribution analysis of sandy soil and topsoil.**

| Sandy Soil          |                 | Topsoil             |                 |
|---------------------|-----------------|---------------------|-----------------|
| Grain Diameter (mm) | Percent Passing | Grain Diameter (mm) | Percent Passing |
| 19.050              | 100             | 19.050              | 100.00          |
| 9.525               | 99.54           | 9.525               | 99.49           |
| 4.750               | 97.47           | 4.750               | 96.52           |
| 2.000               | 94.62           | 2.000               | 92.14           |
| 0.850               | 90.2            | 0.850               | 89.28           |
| 0.500               | 79.4            | 0.500               | 82.56           |
| 0.250               | 56.24           | 0.250               | 66.44           |
| 0.106               | 31.97           | 0.106               | 43.46           |
| 0.075               | 26.97           | 0.075               | 37.29           |
| 0.0357              | 13.9            | 0.0337              | 22.57           |
| 0.0227              | 10.62           | 0.0218              | 15.80           |
| 0.0133              | 7.92            | 0.0127              | 11.85           |
| 0.00939             | 6.95            | 0.00909             | 9.03            |
| 0.00667             | 4.82            | 0.00647             | 6.21            |
| 0.00329             | 2.12            | 0.00321             | 2.63            |
| 0.00137             | 1.35            | 0.00134             | 0.38            |

## Appendix D

### Bearing Plate Deflection Versus Load Response

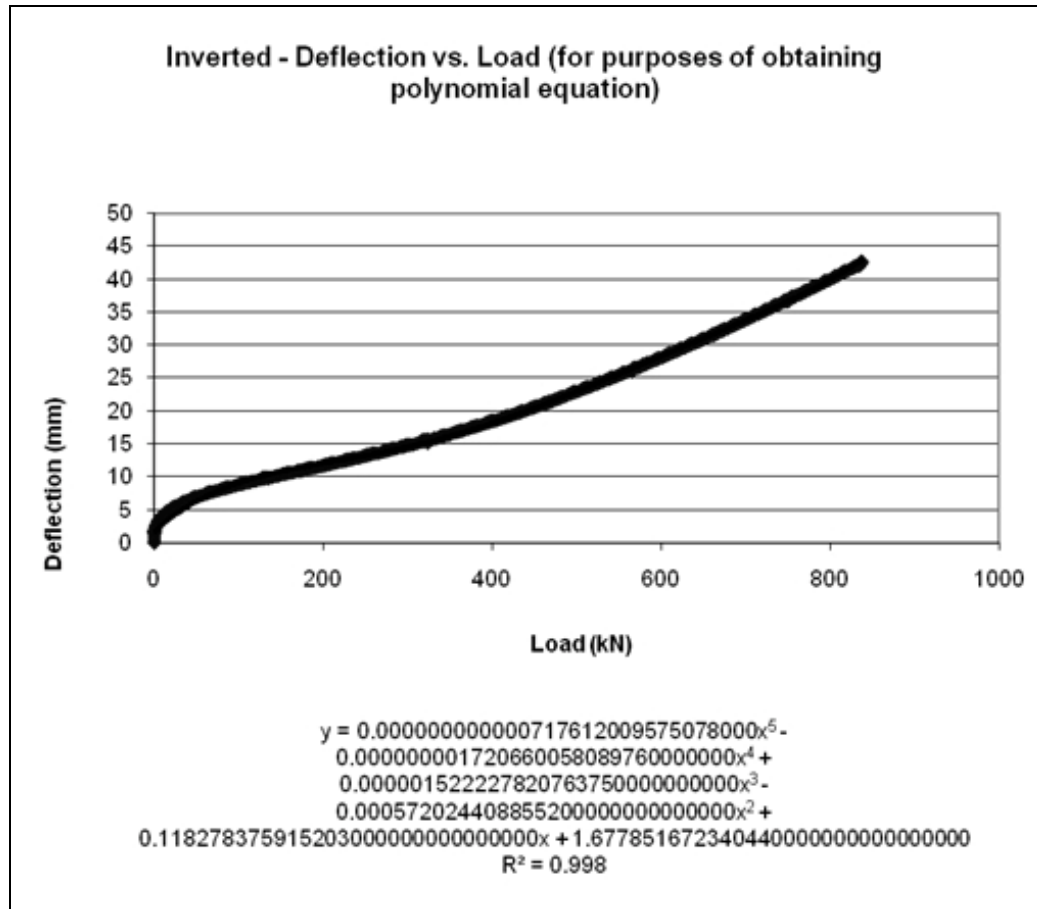


Figure D.1: Loading plate deflection versus load response.

## Appendix E

### Summary of Earthbag Test Results

**Table E.1: Summary of Earthbag Testing – Ultimate load, deformation, stress, stiffness and load per metre for all earthbag specimens.**

| Test | Ult. Load (kN) | Earthbag Deformation |             |              |              |              | Stress at Ult. (MPa) | Stiffness at Ult. (kN/mm) | Load per Metre (kN/m) |
|------|----------------|----------------------|-------------|--------------|--------------|--------------|----------------------|---------------------------|-----------------------|
|      |                | @ Ult. (mm)          | @ 50kN (mm) | @ 100kN (mm) | @ 200kN (mm) | @ 300kN (mm) |                      |                           |                       |
| SG1  | n/a            | n/a                  | 27.58       | 48.58        | 91.06        | n/a          | n/a                  | n/a                       | n/a                   |
| SG2  | n/a            | n/a                  | 35.15       | 51.26        | 80.81        | n/a          | n/a                  | n/a                       | n/a                   |
| SG3  | 310.83         | 144.74               | 37.71       | 62.25        | 106.66       | 141.36       | 1.10                 | 2.15                      | 489.50                |
| SG4  | 420.99         | 140.22               | 27.10       | 45.77        | 86.17        | 111.33       | 1.49                 | 3.00                      | 662.98                |
| SG5  | 341.30         | 109.90               | 28.51       | 45.40        | 78.81        | 103.33       | 1.21                 | 3.11                      | 537.48                |
| SG6  | 840.00         | 118.02               | 20.60       | 31.67        | 51.85        | 71.74        | 2.98                 | 7.12                      | 1322.83               |
| SG7  | 838.91         | 105.15               | 16.31       | 26.01        | 44.92        | 62.85        | 2.97                 | 7.98                      | 1321.12               |
| MG1  | 501.30         | 165.53               | 33.65       | 55.29        | 93.28        | 117.86       | 1.39                 | 3.03                      | 669.02                |
| MG2  | 714.55         | 165.22               | 28.12       | 44.72        | 81.44        | 107.33       | 1.98                 | 4.32                      | 953.62                |
| MG3  | 630.00         | 186.35               | 34.27       | 59.66        | 99.22        | 126.57       | 1.74                 | 3.38                      | 840.78                |
| MG4  | 785.20         | 161.37               | 29.98       | 44.23        | 72.65        | 93.93        | 2.17                 | 4.87                      | 1047.91               |
| MG5  | 841.90         | 145.70               | 23.82       | 35.83        | 56.93        | 77.25        | 2.33                 | 5.78                      | 1123.58               |
| SS1  | 840.00         | 99.75                | 35.45       | 47.00        | 61.13        | 72.52        | 2.98                 | 8.42                      | 1322.83               |
| SS2  | 841.90         | 53.22                | 14.06       | 21.02        | 32.71        | 42.33        | 2.98                 | 15.82                     | 1325.83               |
| MS1  | 841.90         | 77.44                | 32.32       | 42.12        | 54.77        | 63.73        | 2.33                 | 10.87                     | 1123.58               |
| MS2  | 841.90         | 87.60                | 35.25       | 47.98        | 63.86        | 74.86        | 2.33                 | 9.61                      | 1123.58               |
| ST1  | 841.90         | 76.17                | 21.09       | 33.42        | 49.02        | 60.80        | 2.98                 | 11.05                     | 1325.83               |
| ST2  | 842.40         | 63.83                | 12.79       | 22.78        | 37.78        | 49.57        | 2.98                 | 13.20                     | 1326.61               |
| MT1  | 841.55         | 94.86                | 36.03       | 49.64        | 66.40        | 77.89        | 2.33                 | 8.87                      | 1123.11               |
| MT2  | 841.99         | 82.52                | 25.39       | 39.19        | 56.15        | 67.93        | 2.33                 | 10.20                     | 1123.70               |
| G6-1 | 127.88         | 120.27               | 35.64       | 69.95        | n/a          | n/a          | 0.45                 | 1.06                      | 201.39                |
| G6-2 | 100.20         | 118.45               | 40.09       | 118.00       | n/a          | n/a          | 0.35                 | 0.85                      | 157.79                |
| G6-3 | 100.20         | 104.37               | 41.11       | 104.37       | n/a          | n/a          | 0.35                 | 0.96                      | 157.79                |
| G9-1 | 78.66          | 121.37               | 61.77       | n/a          | n/a          | n/a          | 0.28                 | 0.65                      | 123.87                |
| G9-2 | 91.41          | 112.24               | 49.17       | n/a          | n/a          | n/a          | 0.32                 | 0.81                      | 143.95                |
| G9-3 | 77.34          | 114.02               | 60.74       | n/a          | n/a          | n/a          | 0.27                 | 0.68                      | 121.80                |

## Appendix F

### Polypropylene Tensile Test Report

Page 1 of 2



#### ANALYSIS REPORT SCC Accreditation No.: 40

Mr Bryce Daigle  
Queen's University

Date: August 1, 2008  
Report: S492-008-28735A

|                                     |   |   |
|-------------------------------------|---|---|
| IDENTIFICATION:                     | Bag: .  | Received: July 16, 2008                             |
| STANDARD:                           |   |   |
| TEST:                               | Tensile Properties of Geotextiles by the Wide-Width Strip Method  | ASTM D4595 - 05                                     |
| TEST CONDITIONS:                    | Conditioned sample(s) (21°C, 65 % R.H.); Dry sample(s);<br>6 test specimens per machine direction; Specimen width: 200 mm;<br>Apparatus used: Dynamometer with a Constant Rate of Extension (CRF); Speed: 10 mm/min |   |
| Breaking Strength (kN/m):           | 6.8<br>6.7  | 6.9<br>6.8<br>6.3<br>6.7<br>0.2<br>3.2              |
| Breaking Strength (lb/in):          | 38.8<br>38.3  | 39.4<br>38.6<br>38.7<br>35.8<br>38.3<br>1.3<br>3.3  |
| Elongation at break (%):            | 27.3<br>29.6  | 29.8<br>28.5<br>29.7<br>29.0<br>29.0<br>1.0<br>3.3  |
| Strength at 5% elongation (kN/m):   | 2.7<br>1.7  | 2.4<br>2.5<br>2.1<br>2.1<br>2.3<br>0.4<br>15.8      |
| Strength at 5% elongation (lb/in):  | 15.1<br>9.5   | 13.5<br>14.0<br>12.0<br>11.9<br>12.7<br>2.0<br>15.6 |
| Strength at 10% elongation (kN/m):  | 4.3<br>3.5  | 4.1<br>4.2<br>3.8<br>3.7<br>3.9<br>0.3<br>8.0       |
| Strength at 10% elongation (lb/in): | 24.6<br>19.8  | 23.4<br>23.7<br>21.8<br>21.1<br>22.4<br>1.8<br>8.1  |
| CROSS DIRECTION                     | --  |   |
| Breaking Strength (kN/m):           | 6.6<br>6.8  | 6.8<br>7.0<br>7.0<br>6.9<br>6.9<br>0.2<br>2.2       |
| Breaking Strength (lb/in):          | 37.6<br>38.8  | 38.7<br>40.2<br>39.9<br>39.5<br>39.1<br>0.9<br>2.4  |
| Breaking Strength (kN/m):           | 6.6<br>6.8  | 6.8<br>7.0<br>7.0<br>6.9<br>6.9<br>0.2<br>2.2       |
| Breaking Strength (lb/in):          | 37.6<br>38.8  | 38.7<br>40.2<br>39.9<br>39.5<br>39.1<br>0.9<br>2.4  |

Prepared by:

*Jonathan Trudel*  
Jonathan Trudel, Tech.  
Technician

Approved by:

*Eric Blond*  
Eric Blond, Eng., M.Sc.A.  
Vice-President  
Date: August 1, 2008

**\*\*For any information concerning this report, please contact Eric Blond\*\***

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**ANALYSIS REPORT**  
**SCC Accreditation No.: 40**

Mr Bryce Daigle  
**Queen's University**

Date: August 1, 2008  
 Report: S492-008-28735A

|                                     |  |                         |      |      |      |                 |      |      |  |
|-------------------------------------|--|-------------------------|------|------|------|-----------------|------|------|--|
| IDENTIFICATION:                     |  | Bag: .                  |      |      |      |                 |      |      |  |
|                                     |  | Received: July 16, 2008 |      |      |      |                 |      |      |  |
| STANDARD:                           |  |                         |      |      |      |                 |      |      |  |
| TEST:                               | Tensile Properties of Geotextiles by the Wide-Width Strip Method                                     |                         |      |      |      | ASTM D4595 - 05 |      |      |  |
| RESULTS (CONT):                     | Individual Data  |                         |      |      |      | Avg.            | S.D. | % CV |  |
| Elongation at break (%):            | 25.6   | 26.6                    | 28.6 | 27.1 | 27.5 | 26.9            | 1.1  | 4.2  |  |
|                                     | 25.7   |                         |      |      |      |                 |      |      |  |
| Strength at 5% elongation (kN/m):   | 2.1  | 2.2                     | 2.1  | 2.1  | 2.1  | 2.1             | 0.0  | 1.9  |  |
|                                     | 2.1  |                         |      |      |      |                 |      |      |  |
| Strength at 5% elongation (lb/in):  | 12.1   | 12.3                    | 12.0 | 11.8 | 12.0 | 12.1            | 0.2  | 1.5  |  |
|                                     | 12.2   |                         |      |      |      |                 |      |      |  |
| Strength at 10% elongation (kN/m):  | 3.9  | 3.9                     | 3.9  | 3.9  | 3.9  | 3.9             | 0.0  | 0.0  |  |
|                                     | 3.9  |                         |      |      |      |                 |      |      |  |
| Strength at 10% elongation (lb/in): | 22.2   | 22.5                    | 22.2 | 22.0 | 22.2 | 22.2            | 0.2  | 0.7  |  |
|                                     | 22.2   |                         |      |      |      |                 |      |      |  |
| REMARKS:                            | Machine direction was assumed to be in the longer direction of the bag (opening perpendicular to MD) |                         |      |      |      |                 |      |      |  |

Prepared by:

*Jonathan Trudel*  
 Jonathan Trudel, Tech.  
 Technician

Approved by:

*Eric Blond*  
 Eric Blond, Eng., M.Sc.A.  
 Vice-President

Date: August 1, 2008

**\*\*For any information concerning this report, please contact Eric Blond\*\***

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