THE EFFECT OF SOIL GRADATION AND ADDITION OF NATURAL FIBRES ON THE MECHANICAL PROPERTIES AND FREEZE-THAW DURABILITY OF ON-SITE MANUFACTURED COMPRESSED EARTH BLOCKS

by

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Abstract

Implementation of sustainable materials is becoming an imperative consideration in modern building because of the impact of the construction industry on climate change patterns. Building with earth is an ancient technique common in many warm regions and developing countries due to its low cost, and is garnering attention for applications in cold regions due to its favorable hygrothermal properties, ease of use, and low embodied energy.

The compressed earth blocks (CEBs) in this project were manufactured on-site by an experienced builder in Cobourg, Ontario, Canada using a combination of various soil gradations and locally sourced natural fibres (Phragmites, straw, switchgrass, and rice hulls). Approximately 280 CEBs were tested in direct compression and three-point bending at ambient conditions, saturated conditions, and after being subjected to six and twelve freeze-thaw conditioning cycles.

Results showed that blocks constructed with about 20% gravel particles had up to a 29.3% increase in compressive strength and up to a 71.4% increase in flexural strength than blocks constructed with soil containing only sand, silt, and clay particles.

The addition of natural fibres was more beneficial for the compressive strength. In general, blocks produced with the larger quantities of fibres had significantly reduced compressive and flexural strengths than the blocks produced with lower quantities of fibres. The addition of 0.5% of Phragmites fibres resulted in a strength of 7.5 ± 0.34 MPa when added in combination with the gravel particles. The corresponding flexural strength of this block type was 1.56 ± 0.36 MPa which was 11.4% less than the flexural strength obtained using gravel particles and no fibres. Blocks produced with 0.125% straw achieved the highest compressive strength of 8.96 ± 0.71 MPa and blocks produced without fibres had the highest flexural strength of 1.34 ± 0.23 MPa of that investigation.

After subjecting the CEBs to six and twelve freeze-thaw cycles, the blocks showed strength retentions of up to 140% for both the compressive and flexural strengths. The moisture absorbed by the blocks during the cycling process appeared to have allowed for additional curing of the blocks, resulting in the increased capacity of the CEBs.

Co-Authorship

Dr. Mark Green (Queen's University) provided insight and guidance as to test procedures and other considerations throughout the duration of the thesis. He reviewed Chapters 1 to 5 in this thesis and provided intellectual insights into interpreting the results.

Dr. Salah Sarhat (Queen's University) assisted with the design and fabrication of the compressed earth blocks at Fifth Wind Farm and assisted in performing tests in compression and three-point bending in the laboratory. He reviewed Chapters 1 to 5 in this thesis and provided intellectual insights into interpreting the results.

Md. Yusuf and Sheikh Hamza Rizwan (Queen's University) assisted in performing various tests in compression and three-point bending in the laboratory. Katrina Schmid (Queen's University) assisted in performing the compression tests on one-block and four-block prisms (Chapter 3), and Branna MacDougall (Queen's University) assisted in performing the compression and three-point bending tests for blocks not subjected to freeze-thaw cycles (Chapter 4).

The results presented in Chapter 3 were obtained during work completed for an undergraduate thesis project. The undergraduate thesis work included testing the four block types in compression and in flexure, in the air-dry and saturated states. In the undergraduate thesis only the fine soil blocks with and without fibres were discussed in terms of saturated flexural strength. The results provided in Chapter 3 include substantially more detailed analyses regarding the effect of the soil gradation on the compressive and flexural strength of the CEBs, the effect of the aspect ratio correction factors on estimated wall strength, the effect of fibres on the compressive and flexural strength of the CEBs, and the effect of block saturation on the compressive and flexural strength of the CEBs. Chapter 3 also proposes an equation to relate compressive and flexural strength, which was not included in the undergraduate thesis paper.

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Chapter 1

Introduction

1.1 General

The production of carbon dioxide (CO_2) and other greenhouse gas (GHG) emissions by the building and construction industry are some of today's leading causes of climate change. The building sector contributes 40% of the global energy and material consumption and 33% of the GHG emissions (UNEP 2009). To mitigate the damages done by conventional industrial building practices, sustainable development and green building practices are becoming imperative considerations in the built environment.

Conventional building materials such as steel and concrete are more harmful to the environment when compared with innovative and sustainable alternatives such as timber, earth, and straw. In fact, earth construction is becoming an increasingly relevant building technique as society becomes more aware of the importance of sustainable building practices. A form of this building system is a compressed earth block (Figure 1-1) which is a masonry unit comprised of compacted earth (Mak, MacDougall and Fam, The Mechanical Characteristics of On-Site Manufactured Compressed Earth Blocks: The Effects of Water Repellent and Other Additives 2015).

Figure 1-1: Photograph of compressed earth block

Compressed earth blocks (CEBs) generally contain soil as the main ingredient. Additives such as cement, lime, and fibres reinforcement may be added to improve performance.

1.1.1 Benefits of CEB Construction to Indigenous Health and Lifestyle

For most of Canada, a healthy lifestyle and safe housing is a given, but for Indigenous communities, especially those located in rural and remote northern locations, many necessities are denied and access to adequate housing is virtually impossible. Since 2006, the Indigenous population in Canada has grown by 42.5%, which is more than four times the growth rate of the non-Indigenous population over the same period (Statistics Canada 2017). Indigenous Peoples are the fastest growing segment of the Canadian population, and many communities are struggling to provide adequate on-reserve housing (Indigenous Corporate Training Inc. 2018). Figure 1-2 shows two houses located on two different First Nation communities in Canada.

a) b)

Figure 1-2: Photographs showing the housing conditions in two Northern Ontario communities: a) Sandy Bay First Nation (Lambert 2016), and b) Pikangikum First Nation (Stastna 2011)

Unfortunately, the houses pictured in Figure 1-2 are just two out of the countless others across Canada that currently exist in this condition. Mould is a frequent health concern due to poorly constructed and overcrowded houses. Overcrowding, defined as having more than one person per room (Kelly-Scott and Smith 2015), presents significant health risks, social issues, and moisture buildup which decreases the lifespan of the building (Indigenous Corporate Training Inc. 2018). A study conducted in 2017 compared the relevance of whether a First Nation identity is associated with higher odds of hospitalization for respiratory conditions relative to non-Indigenous persons. The study concluded that housing conditions were significantly related to rates of hospitalization for respiratory tract infections and asthma. The study also concluded that income differences between First Nations and non-Indigenous households could have a larger impact on the hospitalization statistics for respiratory conditions (Carrière, Garner and Sanmartin 2017). These housing problems have the devastating potential to exacerbate the effects of the COVID-19 pandemic in Indigenous communities in Canada in the way that it has affected low income and racialized communities in cities. Indigenous communities in Brazil are already experiencing some of these deadly effects (Wallace 2020).

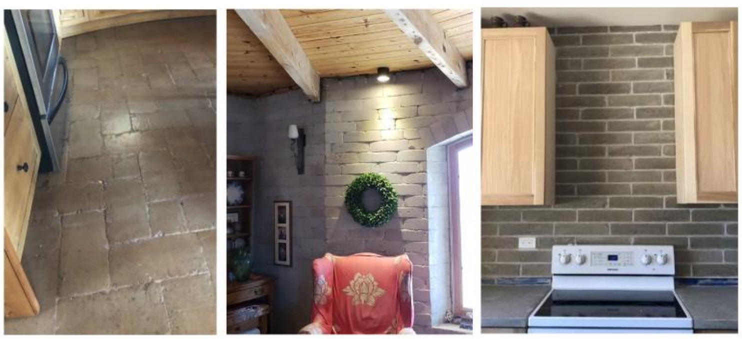
The use of on-site materials allows for the potential to construct more homes, while lowering transportation costs and carbon emissions. Building with earth can be done without the use of high technology tools, which presents an incredible opportunity to engage the community in green building technologies and create employment opportunities.

1.1.2 Practical Application of Building with CEBs

The owners at Fifth Wind Farm in Cobourg, Ontario, Canada have been very active in the sustainable building movement for many years. The farm accepts individuals from all over the world to provide labour at the farm in exchange for accommodations, meals, and education on sustainable building practices. Fifth Wind Farm currently has two buildings on site that were constructed using the earth blocks as load bearing and non-load bearing walls, floor tiles, window arches, fire separation walls, and outdoor paving blocks. One of the homes (Figure 1-3) uses ancient sacred geometry called "squaring of the circle" to bring a holistic component to the home. A holistic approach typically involves considering the whole person (mind, body, and spirit) as opposed to just the physical aspects.

Sacred geometry stems from the idea that certain geometric shapes and proportions represent symbolic and sacred meanings. In the "squaring of the circle", the perimeter of the square is equal to the circumference of the circle and the radius of the circle creates the height of the pyramid (Wiersma 2018). The circle in the square concept is shown in Figure 1-3, where a circle is clearly seen protruding from the sides of the square exterior.

a)



b)

Figure 1-3: Building constructed with CEBs at Fifth Wind Farm: a) exterior and interior views of a house built based on the "squaring of the circle" concept, b) using CEBs in flooring, walls and arches, and fire walls

Since the primary function of a building or home is to provide shelter from the elements, it is common to overlook how the interior of a building makes the inhabitants feel. By incorporated the "squaring of the circle" into the home design, the hope is that the inhabitant's mental and spiritual wellness is as much of a priority as physical well-being since the design creates a harmonic balance within the space.

The earth material creates housing that offers comfortable temperatures that maintain warm conditions in winter and cool conditions in summer, and reduces humidity fluctuations, similar to in a stabilized rammed earth test building (Allinson and Hall 2010). From a health and wellness perspective, using earth material has many benefits when compared to industrialized building materials. Compressed earth blocks have the same electromagnetic properties as human beings themselves, thus creating a synergy between humans and their environment (Dupuy 1999). Not only does this benefit the physical health of an individual, but this synergy brings spiritual meaning to humans "living in" the earth. In the beliefs of many Indigenous cultures it is said that all humans were created from Mother Earth, who must be treated with love and respect. It is also important to remember that nature can survive without the assistance of humans, but humans rely on the earth to live. For example, a tree can grow on its own and a river can flow on its own, but humans need both oxygen and water to survive. By using the Earth to build homes where Mother Earth is literally providing shelter to humans from the environment, the spiritual relationship that society has with the environment is strengthened. Building with earth not only provides tangible health benefits, it can improve the mental well-being of its inhabitants and provide a healthy, safe, and cost-effective solution to the inadequate housing crisis currently experienced in many Northern Indigenous communities in Canada.

There are other companies in Canada, such as Building Alternatives in Winnipeg, Manitoba (Building Alternatives Inc. 2020) that offer services involving sustainable building materials like rammed earth, compressed earth blocks, and straw bales. However, the work that Fifth Wind Farm is doing to create architectural beauty from earth block construction in addition to structural integrity is unmatched.

1.2 Objectives

The objectives of this thesis are as follows:

1. To determine the compressive and flexural strengths of on-site manufactured CEBs with different soil gradations and different natural fibre types and quantities.
2. To determine an empirical relationship between the compressive and flexural strengths of on-site manufactured CEBs.
3. To determine the effect of block saturation on the compressive and flexural strength of on-site manufactured CEBs with different soil gradations and different natural fibre types and quantities.
4. To determine the effect of prism aspect ratio on the compressive strength of on-site manufactured CEBs when used in combination with appropriate correction factors from the literature. Prism aspect ratio correction factors are used to estimate wall strength when presented with measured strengths of individual blocks or prisms of two.
5. To determine if testing CEB prisms unbonded will provide compressive strengths that are comparable to testing bonded prisms. Determining the compressive strength of CEB masonry made with low strength mortar from unbonded prisms avoids the complexities of handling bonded CEB prisms.
6. To determine the freeze-thaw resistance and durability of on-site manufactured CEBs with different fibre types and quantities.

1.3 Thesis Outline

This thesis is presented in manuscript format and is separated into two phases of field investigations, which aim to identify how CEBs manufactured in-situ can be improved for building in cold climates and remote regions. Both investigations follow very similar block production and laboratory testing procedures, however, each investigation includes its own experimental method section to ensure a coherent discussion. A brief outline of each chapter is as follows:

Chapter 1: A general introduction to the need for sustainable building practices such as earth block construction, and how similar methods can be implemented in northern and remote communities to mitigate negative impacts of the on-reserve housing crisis.

Chapter 2: A review of relevant literature including typical ingredients and additives used in earth block construction, generally accepted testing procedures, and other applications of earth building.

Chapter 3: This chapter presents an experimental investigation into the compressive and flexural performance of on-site manufactured CEBs, produced using different soil gradations and different quantities of locally sourced (invasive) Phragmites fibres. This chapter is considered the preliminary phase of this thesis and aims to gain more insight as to how natural fibres affect the mechanical properties of the CEBs.

Chapter 4: This chapter presents an experimental investigation into the compressive and flexural performance and freeze-thaw durability of on-site manufactured CEBs, produced with different quantities of locally sourced straw, switchgrass, and rice hull fibres. This chapter is the second phase of this thesis and provides a more detailed investigation, based on the findings in Chapter 3, of the effect of varying fibre type and quantity on the mechanical properties and durability of CEBs in cold climates.

Chapter 5: This chapter presents a summary of the conclusions drawn from the results of previous chapters and provides suggestions on the direction of future research.

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Chapter 2

Literature Review

2.1 Compressed Earth Blocks (CEBs)

While traditional adobe and clay-fired brick practices have been around for many years, modern earth construction is a relatively new concept in Canada. There are many advantages to using CEBs as a building material. In addition to their favourable hygroscopic properties, other benefits of using CEBs versus steel or concrete include: lower costs, faster and easier construction, use of local materials, no direct environmental pollution, low embodied energy, and reduced carbon dioxide emissions (Shehu Waziri, Alhaji Lawan and Ma'aji Mala 2013).

2.1.1 Behaviour of Unstabilized CEBs

Blocks constructed from plain soil are defined as unstabilized compressed earth blocks. Depending on the type of soil and method of compaction used (manually or mechanically pressed) it is possible to manufacture unstabilized compressed earth blocks, but unstabilized earth is not commonly used in the construction of on-site buildings. Furthermore, typical values of compressive strength of manually pressed CEBs are in a range of 2-3 MPa, which restricts use to one-storey buildings (Mostafa and Uddin 2015).

The main benefit of using unstabilized CEBs versus chemically stabilized CEBs (with cement, lime, etc.) is increased environmental wellness. Unstabilized CEBs have much lower embodied energy and better potential for recycling demolition waste at the end of a building's service life (Bruno, et al. 2015). At ambient conditions, however, unstabilized CEBs have significantly lower strength than stabilized CEBs [(Bogas, Silva and Gomes 2018), (Eko, et al. 2006)] and when exposed to moisture from the environment (rain, freeze-thaw, humidity) have zero strength and will essentially disintegrate (Mak, MacDougall and Fam 2015).

Standard practice for manufacturing compressed earth blocks consists of compacting moist soil in a mould under pressures that range from 5 MPa to 25 MPa [(Bruno, et al. 2015), (Sitton, Zeinali, et al. 2018), (Dupuy 1999)]. An alternative compaction method compresses unstabilized soil at higher pressures (25 MPa - 100 MPa) for a longer period of time to allow pore water pressures to fully dissipate (Bruno, et al. 2015). The adoption of this second compaction method results in mechanical properties of unstabilized CEBs that can compete with those of stabilized earth and standard masonry bricks. The large pressures required to achieve these results, however, exceed the capacity of most standard CEB equipment, including the AECT 3500 Compressed Earth Block Machine used to produce the CEBs tested in this thesis. Therefore, a small quantity of chemical stabilizer was used to provide adequate strength and water resistance [(Mak, MacDougall and Fam 2015), (Hallal, Sadek and Najjar 2018)] thereby slightly increasing the environmental impact.

2.1.2 Chemically Stabilized CEBs

Past research has shown that the addition of chemical additives, referred to as binders or stabilizers, can significantly improve the mechanical properties and durability of the CEBs in both wet and dry conditions [(Mak, MacDougall and Fam 2015), (Hallal, Sadek and Najjar 2018)]. Typical stabilizers include Portland cement, hydrated lime, or metakaolin (Mak, MacDougall and Fam 2015). Research has also been conducted on the use of an activated industrial by-product (ground granulated blast-furnace slag) as an earth block binder (Deboucha and Hashim 2011). Many studies have concluded that increasing the water content of the CEBs decreases the compressive strength. A previous study looked at the effect of adding a commercial silane/siloxane water-repellent admixture (Plasticure) to the CEBs to improve the performance of the CEBs when saturated (Mak, MacDougall and Fam 2015).

The study found that the addition of Plasticure had no significant impact on the dry strength of the CEBs. The wet strength was significantly stronger with the inclusion of Plasticure than without due to the ability of the Plasticure to repel water absorption.

The type and quantity of stabilizer required for CEB construction cannot be generalized without taking into consideration the chemical and mineralogical composition of the soil. The effects of stabilization from mineral binders are strongly dependent on the type of soil (Ouedraogo, et al. 2020). A study by Nagaraj, Rajesh, and Sravan found that using cement alone as a stabilizer would yield satisfactory results only when there was a lower clay content in the block (around 13%), and that soils with higher proportions of clay can still be favourably used in the preparation of stabilized CEBs by using lime in combination with cement (Nagaraj, Rajesh and Sravan 2016). Other past studies have found that adding a cement-lime mix stabilizer at a 1:1 ratio at an optimal range of 4-8% by weight resulted in higher strength and durability of the blocks than using a lower lime ratio or using cement alone [(Mak, MacDougall and Fam 2015), (Hallal, Sadek and Najjar 2018), (Nagaraj, Rajesh and Sravan 2016), (Bahar, Benazzoug and Kenai 2004)].

2.1.3 Soil Gradation in CEB Production

Most of the literature focused on the gradation of the soil in terms of clay content. There is limited research on the effect of the soil aggregate particle size on the mechanical properties of CEBs, in terms of coarse-grained particles versus fine-grained particles, which will be further examined in this study. According to Dupuy (Dupuy 1999) and Hallal, Sadek, and Najjar (Hallal, Sadek and Najjar 2018), soils that are suitable for earth construction should be composed of a mixture of gravel, sand, silt, and clay particles. These studies used the traditional particle-size distribution criteria to classify the soil components as follows: gravel particles are smaller than one-sixth of the least specimen dimension and larger than 4.75 mm, sand particles are smaller than 4.75 mm and larger than 75 μm, silt particles are smaller than 75 μm and larger than 2 μm, and clay particles are smaller than 2 μm (Hallal, Sadek and Najjar 2018). Nagaraj, Rajesh, and Sravan argue that soils available in nature are not suitable to prepare stabilized CEBs and suggest reconstituting of the soil such that sand, silt and clay are present in certain proportions (Nagaraj, Rajesh and Sravan 2016). For blocks that are manufactured on-site this may not be a viable option. Other alternatives should be considered such as the type and quantity of additives used, which has been shown to have a larger effect on the performance of the blocks when compared to the sand content of the soil (Seco, et al. 2017).

2.2 Types of Fibre Reinforcement

Natural fibre types are characterized by three main categories: animal fibres, plant fibres, and mineral fibres (Zhang, et al. 2016). The fibres used in this thesis (Phragmites, straw, switchgrass, and rice hulls) were selected based on regional availability (Charlet 2012) and are categorized into the "plant fibre" category, which is broken down further into wood versus non-wood fibres. Straws (including rice straw/hulls) and grasses are categorized under "non-wood plant" fibres (Zhang, et al. 2016).

Plant fibres and aggregates have been added to earth mixes for thousands of years to enhance performance, but scientific investigations began only very recently. The main advantage of adding plant aggregates or fibres to earth construction materials (such as extruded brick, adobe, CEBs, earth plasters, rammed earth, cob, wattle, and daub) over other options is to improve thermal insulation and save energy. Thermal conductivity is directly linked with the density of the material, which decreases as the aggregate or fibre content increases (Loborel-Preneron, et al. 2016). The sustainability, recyclability, and availability of natural fibres also makes them an attractive addition to improve the performance of CEBs (Zhang, et al. 2016), however the net impact of chemical reactions on the strength properties of the natural fibre CEBs needs to be further investigated (Donkor and Obonyo 2016).

Another type of natural fibre that has not been extensively studied for use in CEB construction is Phragmites Australis (common reed). Two forms of Phragmites exist in the Great Lakes region: invasive and native. The fast-growing invasive form of Phragmites is an extreme threat to native ecosystems due to the plant's ability to outcompete native wetland plants for resources and dominate the ecosystem (Bourgeau-Chavez, et al. 2013). If proven to be successful, the benefits of using the invasive form of Phragmites in CEB construction will be two-fold. The fibres will provide a natural solution to the inadequate tensile capacity of the stabilized CEBs in building, and the negative impacts of the fast-growing invasive species on the Great Lakes wetlands and its ecosystem will be reduced.

Several investigations [(Khedari, Watsanasathaporn and Hirunlabh 2005), (Galán-Marín, Rivera-Gómez and Petric 2010), (Taallah, et al. 2014), (Mostafa and Uddin 2015)] have been conducted on the implementation of natural fibres in the production of CEBs in the past two decades. Test results by Khedari et al. (Khedari, Watsanasathaporn and Hirunlabh 2005) showed that adding coconut fibre at a ratio of 20% of the cement weight can reduce the thermal conductivity and weight of the soil-cement block while retaining comparable compressive strength to commercial soil–cement blocks. Galán-Marín et al. (Galán-Marín, Rivera-Gómez and Petric 2010) used a combination of alginate as the stabilizer and sheep wool fibre as reinforcement, which was found to double the compressive resistance. Better results were obtained with a lower quantity of wool. Taallah et al. (Taallah, et al. 2014) found that a higher dry compressive strength of CEBs could be achieved with the addition of 0.05% date palm fibre content, 8% cement content and a compaction pressure of 10 MPa. Mostafa and Uddin (Mostafa and Uddin 2015) studied the effect of banana fibres on the compressive and flexural strength of CEBs. The highest flexural and compressive strength values for the utilization of banana fibres were recorded with 50 mm fibres and 0.35% fibre content by weight. Finally, plant aggregates have a similar effect on the mechanical properties of the CEBs as other natural fibres (Donkor and Obonyo 2016).

Donkor and Obonyo (Donkor and Obonyo 2016) studied the mechanical properties of CEBs reinforced with polypropylene (synthetic) fibres. These fibres led to an improved performance in resisting cracks and crack propagation and an increase in tensile strength of the CEBs. The test results showed that very low percentages of polypropylene fibres are needed to achieve optimal performance of fibre reinforced soil blocks, with an optimum fibre content ranging between 0.4% and 0.8% by weight.

2.3 Method of CEB Production

The method in which the blocks are manufactured greatly affects the ultimate strength and performance of the blocks. Unlike much of the previous research, the blocks in this investigation were not being manufactured in a lab where various parameters can be controlled. Since the on-site manufacturing process is limited by what materials and equipment the builder has available on-site, variability in the gradation of the soil (clay, sand, silt, and gravel content) and measured moisture content can affect the blocks. While this may not be ideal, it is realistic to the unique application of these CEBs, which is to use locally sourced materials on-site to build sustainable homes.

Lab manufactured CEBs are generally produced using manual presses that rely on leverage to achieve proper compaction (Sitton, Zeinali, et al. 2018) which can result in variations of compaction pressure from block to block. Using heavy machinery such as a one-yard concrete mixer and an AECT 3500 Compressed Earth Block Machine allows for well-combined mixes and consistent compaction from block to block.

2.4 Freeze-Thaw Conditioning

In various other parts of the world, earth is being used as low-cost and sustainable alternatives to conventional building materials such as concrete and steel. Regions in Bangladesh, Belgium, Egypt, Honduras, USA, Nigeria, and Mexico are looking at ways to increase the performance of CEBs to expand their use and potentially construct larger homes and buildings [(Islam, et al. 2016), (Mango-Itulamya, et al. 2019), (Sameh 2014), (Brown 2014), (Bowen 2017), (Hughes 2015), (Egenti, Khatib and Oloke 2014), (Trujillo 2016)]. Nevertheless, knowledge is lacking on the practical applications of building with CEBs in cold climate regions such as Canada where temperatures can reach well below freezing.

As Mak, MacDougall, and Fam (2016) discussed, there have been conflicting opinions over the appropriate method to determine masonry resistance to freeze-thaw cycles. The authors presented an analysis of various standards [(Butterworth and Baldwin 1964), (Fagerlund 1977a), (Fagerlund 1977b), (Straube, Schumacher and Mensinga 2010)] which have been proposed for compacted soil-cement mixtures, such as those of cement-stabilized compressed earth blocks, and discussed the applicability of these methods in real-life situations. For example, Butterworth and Baldwin (1964) concluded that specimens passing ASTM and CSA standards (which require boiling the blocks for five hours to increase water penetration) did not necessarily prove their durability to freeze-thaw cycles in real life. The concept of a critical saturation level, proposed by Fagerlund (1977a, b) and supported by Straube (Straube, Schumacher and Mensinga 2010), states that below a critical saturation level, freeze-thaw cycling would not damage masonry because water would be able to fully expand within pores. Since the critical saturation limit can vary greatly and is highly dependent on the material, Mak, MacDougall, and Fam (2016) argued that the method proposed by Straube, Schumacher, and Mensinga (2010) was less applicable for soil-based systems. The authors explained that CEBs are known to breathe when they absorb and release moisture in the air which causes complications for designing a procedure based on block saturation level. Therefore, they suggested following a modified version of ASTM D560 (ASTM 1996) which represents the most realistic freeze-thaw scenario for soil-cement based materials, such as compressed earth, in which moisture absorption is governed by capillary action and relative humidity as opposed to full submersion (Mak, MacDougall and Fam 2016). Since the CEBs used in this study were manufactured at the same location using the same equipment and were tested using the same lab facilities as the CEBs used in Mak, MacDougall, and Fam's (2016) study, the same procedure for determining the freeze-thaw durability of CEBs will be used.

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Chapter 3

Compressive and Flexural Strength of On-Site Manufactured Compressed Earth Blocks: The Effect of Soil Gradation and Phragmites

3.1 Introduction

Earth construction is becoming increasingly relevant in modern building as society becomes more aware of the importance of sustainable building. Traditionally, the concept of earth building stems from Mexican Pueblo housing designs, which use adobe bricks as the main building material (Wiersma and Wiersma 2018). Mud brick (adobe) houses have been discovered in Russian Turkestan dating from 8000 to 6000 BC, and rammed earth foundations have been discovered in Assyria dating from ca. 5000 BC (Minke 2006). A modern form of this ancient building system is a compressed earth block (CEB), which is a masonry unit consisting of compacted earth (Mak, MacDougall and Fam 2015). CEBs are being considered for building in cold climate conditions due to their low thermal conductivity (Smigelski 2016) and capacity to balance air humidity in buildings (Loborel-Preneron, Aubert, et al. 2016), thus creating a sustainable building solution. In addition to their favourable hygroscopic properties, other benefits of using CEBs versus steel or concrete include: lower costs, faster and easier construction, use of local materials, no direct environmental pollution, low embodied energy, and reduced carbon dioxide emissions (Shehu Waziri, Alhaji Lawan and Ma'aji Mala 2013).

3.1.1 Objectives

Previous studies have shown that the addition of a cementitious stabilizer, as well as a reinforcing fibre, can improve CEB properties [(Loborel-Preneron, Aubert, et al. 2016), (Donkor and Obonyo 2016)]. These studies, however, were conducted in laboratory settings. There is a lack of research regarding the mechanical characteristics of on-site manufactured CEBs when faced with the various challenges of manufacturing blocks on-site to be used in local construction. The objectives of this project were to determine the effect of the soil gradation particle size and the addition of invasive Phragmites on the compressive and flexural strength of on-site manufactured CEBs at air-dry and saturated states. This is a unique aspect of research considering that much of the previous literature investigated the mineralogical properties of the soil in terms of clay and sand content. This investigation examined the effect of having a coarsely graded sand versus a finely graded sand added as aggregate, and how this change in gradation affected the performance of the CEBs. Additionally, the effect of adding Phragmites fibres on the performance of CEBs has not yet been examined in the literature. Furthermore, a review of previous studies indicated that the relationship between the compressive strength and flexural tensile strength of CEBs has not yet been studied. This chapter aims to derive an accurate formula to estimate the flexural tensile strength of CEBs from the compressive strength. The formula is derived from statistical analysis of a database of test results collected from the literature along with the test results of the current investigation.

Another objective of this investigation was to determine the effect of aspect ratio on the compressive strength of unbonded (no mortar) CEB prisms. The purpose of this specific aspect of the study is to ensure accurate strength values when comparing two-block prisms tested in the lab to how the CEBs will perform in larger prisms (i.e. as part of a wall system for a house). The effect of testing unbonded prisms was also compared with a previous study that used a thin, low-strength mortar to bond the CEBs and were tested in this configuration.

Finally, this investigation tested the CEBs saturated in three-point bending and in direct compression, whereas previous literature has only considered the effect of block saturation on the compressive strength.

3.2 Experimental Method

An experimental investigation was conducted to determine the mechanical properties of on-site manufactured CEBs. The following section outlines the materials and fabrication method used to construct the test specimens as well as the test setups used to perform the investigation.

3.2.1 Test Specimens

Four different mix designs constituted the test matrix. The CEBs were cast using a mixture of soil, cement stabilizer, hydrated lime, and natural fibres. The block constituents are discussed further in Section 3.2.2 and material quantities are listed along with other block properties in Table 3-1.

Table 3-1: CEB composition and properties

Mix Design Code	Ingredients			Dimensions (mm)			Physical Properties	
	Soil Gradation	Fibre Type	Fibre Quantity (% by weight)	Length	Width	Height	Density (kg/m^3)	Water Absorption (%)
0	Coarse	-	-	355	179.5±0.7	78.1±1.6	2082±66	8.8
0Ph	Coarse	Phragmites	0.50%	355	179.6±0.5	78.7±1.7	2022±35	8.3
1	Fine	-	-	355	179.5±0.6	78.3±0.7	1990±16	10.7
1Ph	Fine	Phragmites	0.50%	355	179.5±0.7	78.5±1.1	1963±7	11.1

The length, width, and height values in Table 3-1 are shown as average value of all blocks tested in that block type along with the standard deviation of those measured values. The density values are shown as average values of three samples with standard deviation. Only two samples were measured for water absorption and so only the average of the two measurements are presented.

3.2.2 Materials

Clay soil, found in most parts of southern Ontario, was used as the main ingredient in the CEBs and was locally sourced for on-site fabrication. The soil was dug from the farm and was processed using a

1-inch (25 mm) filter to screen out large rocks, creating what will be herein referred to as coarse soil gradation. Approximately half of the coarse soil was set aside, and a hammer mill was used to break up the remaining soil into a fine powder, which will be herein referred to as fine soil gradation. Figure 3-1 show samples of the soils used in manufacturing of the CEBs in the current investigation. Tests conducted by a commercial testing lab (Hamilton 2005), including X-ray diffraction and X-ray fluorescence analysis, indicated that the clay contents were 23.3% clay-sized particles by mass for the coarse soil gradation and approximately 27% clay-sized particles by mass for the fine soil gradation. The clay-sized particles are composed mostly of calcium carbonate (calcite). No ball clay or kaolinite was detected. The densities of both soil types were determined in the lab by measuring the weight of soil in a known volume cylinder. Three samples were measured, and the results are presented as average values of the three samples with the associated standard deviations. The coarse-grained soil had a density of 1644 ± 17 kg/m^3 and the fine-grained soil had a density of 1569 ± 15 kg/m^3.

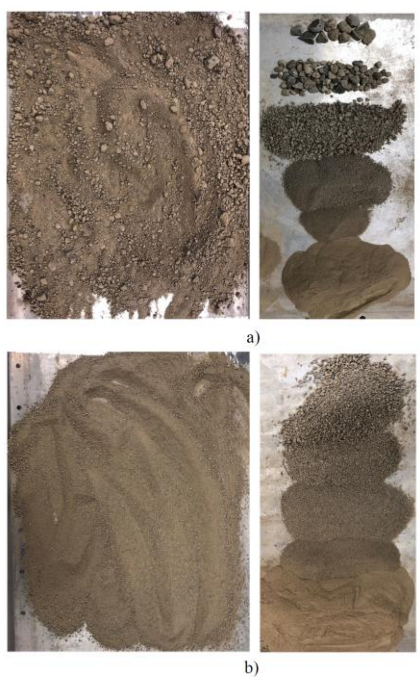

Figure 3-1: Samples of soil used in producing the CEBs before and after sieving: a) coarse soil, and b) fine soil

A sieve analysis was completed on both soil gradations following the standard test procedure outlined in ASTM D6913 (ASTM 2019) and the soil was classified as clayey sand as defined by ASTM D2487 (ASTM 2019). The coarse soil sieve analysis was completed using sieve sizes ranging from No. ½ (12.5 mm) to No. 100 (150 μm), and the fine soil sieve analysis was completed using sieve sizes ranging from No. 4 (4.75 mm) to No. 100 (150 μm) as shown in Figure 3-2. The clay contents (smaller than 2 μm) were measured in a commercial lab (Hamilton 2005). It can be noted in Figure 3-2 that the coarse-grained soil was composed of gravel, sand, silt, and clay particles, while the fine-grained soil did not include any gravel particles. About 80% of the coarse-grained soil particles passed through the No. 4 sieve (4.75 mm), while 100% of the fine-grained soil passed through this sieve. It can also be observed from Figure 3-2 that approximately 34% of the coarse-grained soil particles passed the No. 100 sieve (150 μm) versus 39% for the fine-grained soil. The clay contents were 23% and 27% for the coarse and fine soils, respectively, as stated earlier. As such, the main differences between the two types of soils used in this investigation were grading and the presence of gravel particles in the coarse soil.

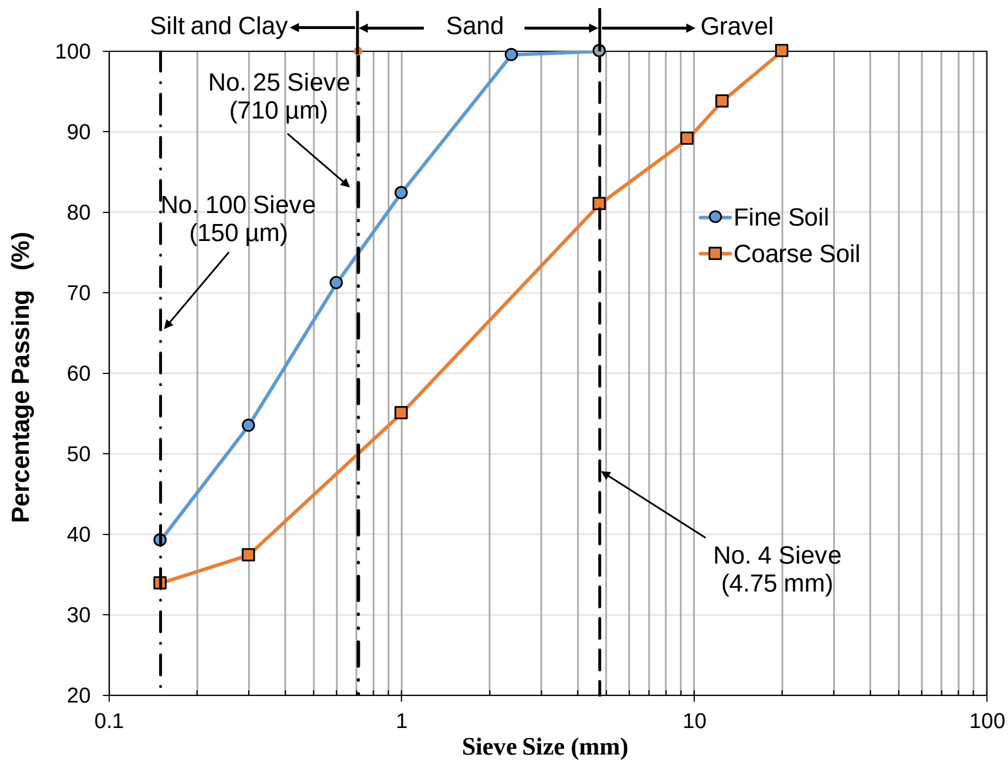

Figure 3-2: Results from coarse-soil and fine-soil sieve analysis

From a combination of previous literature [(Mak, MacDougall and Fam 2015), (Hallal, Sadek and Najjar 2018), (Nagaraj, Rajesh and Sravan 2016), (Bahar, Benazzoug and Kenai 2004)] and local expertise trial-and-error (Wiersma and Wiersma 2018) it was determined that adding a 1:1 cement: lime chemical stabilizer at 5% by weight (2.5% Type 1 Portland cement and 2.5% hydrated dolomite lime) was sufficient to stabilize the clay soil and prevent the blocks from eroding during adverse weather conditions. The stabilizer was added in the same quantity to all block mixes. Invasive Phragmites sourced near the fabrication site were added to the blocks at 0.5% by weight and were added to both the coarse soil mix and the fine soil mix. The Phragmites arrived at the lab as long, tapered, tubular reed fibres with end diameters of 1.5 mm at the narrowest end and 7.5 mm at the widest end and were cut in the lab using a paper cutter. The long reeds were cut into smaller pieces such that an aspect ratio (length/diameter) of 10 was maintained. Although the term "fibre" was used to describe the Phragmites they are not small thread-like fibres but are larger, more woody fibres. The final fibre product had either a tubular diameter or flat thickness ranging between 1.5 mm to 7.5 mm and length ranging from 1.5 cm to 7.5 cm. Blocks were also produced without the fibres for both the coarse soil mix and the fine soil mix, creating the four mix designs used in this investigation. The density of the cut fibres was measured by weighing a known volume cylinder with and without the fibres and calculating density based on those values. The measured density of the Phragmites fibres was determined to be 87 $\pm$ 1.5 kg/m^3 which is the average value of five tests shown with corresponding standard deviation. It is important to know the density of the fibres for the mix design, so that the correct weight of soil, fibres, cement, and lime can be added to achieve the desired quantity of constituents.

3.2.3 Fabrication of Earth Blocks

All blocks were manufactured on-site by an experienced builder in Cobourg, Ontario, Canada. The process of manufacturing the CEBs used in this investigation was not a laboratory procedure. The following section provides a detailed procedure (including figures) to give enough information for other researchers and builders to be able to produce similar work. The soil, cement, lime, and fibres were combined using a mechanical one-yard mixer (see Figure 3-3a) and water was added until the desired consistency was reached. The optimum moisture content was found to be around 6.5%. The moisture content was checked by inserting the prongs of a moisture sensor into the mix until the sensor read 6.5%. The consistency of the mix was checked by hand. If a handful of material retained its shape after being compressed, the desired consistency was been met, as shown in Figure 3-3b. The blocks were mechanically compressed using an AECT 3500 Compressed Earth Block Machine (see Figure 3-3c). Blocks were cross stacked in single stacks on the floor immediately after production and were left outside uncovered for about four hours after which the blocks were covered with plastic sheets. The blocks were left outside covered for one day, and then were moved to be stored in a covered barn on the farm where a temperature of 20°C and humidity of 60% were maintained for 120 days prior to transportation to the lab. Because of manufacturing constraints, there was a slight variation of block height, typically ranging from 75 mm to 80 mm. To circumvent this inconsistency in block height in future work, the soil mixture should be weighed prior to compression to ensure the same amount of soil is being used in each block. Also, the pressure and duration should remain constant for the entire batch of blocks during production to ensure as much consistency as possible. After the blocks were removed from the hydraulic press they were transported by hand to where they were stacked and dried. More than 94% of the blocks were manufactured intact without any damage. However, because the blocks were still wet during this process, small parts of the blocks (especially at the corners) crumbled away resulting in loss of surface area in some of the CEBs (less than 6%). Also, pre-cracks formed in some of the fibre reinforced CEBs during the process of transporting and stacking.

Figure 3-3: On-site manufacturing of CEBs at Fifth Wind Farm: a) adding soil, lime, cement, and fibres to mixer, b) adding water to mixture, c) compression of the CEBs

3.2.4 Test Setup

A combination of compression and flexural tests were performed on air-dry and saturated CEBs, as shown in Table 3-2. The block type in Table 3-2 indicates whether the block was produced with fine or coarse soil and whether fibres were added. The coarse and fine blocks are represented by 0 and 1, respectively. If Phragmites were added to the blocks, "Ph" follows the numeral. Test repetitions were selected based on availability of blocks. For example, because the four-block prisms require more blocks per test repetition than the one-block and two-block prisms, only two test repetitions were completed due to availability of the CEBs.

Table 3-2: CEB test repetitions and arrangements

Block Type	Compression						Flexure	
	Dry			Wet			Dry	Wet
	1-Block	2-Block	4-Block	1-Block	2-Block	4-Block		
0	3	3	2	-	3	-	4	3
0Ph	3	3	2	-	3	-	4	3
1	3	3	2	-	3	-	4	3
1Ph	3	3	2	-	3	-	4	3
Blocks Tested	12	24	32	-	24	-	16	12
Total	120							

Blocks tested in compression at the air-dry state were tested in three prism configurations: one-block, two-block, and four-block. Only the two-block prism configuration was tested in the saturated state. The two-block prism configuration is the most generally accepted method of determining prism strength and testing the other prism configurations while saturated would not have contributed to either the knowledge of how the unbonded prisms behaved while saturated, or the effect of increasing and decreasing aspect ratio on the performance of unbonded prisms. Blocks were tested in both the air-dry state and saturated state for all flexure tests. Based on Table 3-2, 120 CEBs were tested in this investigation.

3.2.5 Unconfined Compression

CEBs are commonly tested with the same standards as concrete and clay-fired brick masonry (Mak, MacDougall and Fam 2015). A Forney Testing Machine with capacity of 2224 kN, shown in Figure 3-4a, was used to test the CEBs in uniaxial compression. The CEBs were stacked unbonded, in prisms of two, and tested under uniaxial compression in accordance with ASTM C140 (ASTM 2018) and ASTM C1314 (ASTM 2018). The prisms were capped with 3 mm thick plywood sheets.

a) b)

Figure 3-4: a) Uniaxial compression test setup, b) Three-point bending test setup

In addition to testing the blocks in two-block prisms, the tests were also performed with one-block and four-block prisms (Figure 3-5). The results from the one-block and four-block tests will provide insight to how the CEBs will behave when the aspect ratio of the prisms is adjusted.

a) b)

Figure 3-5: Compression test setup for a) one-block and b) two-block prisms

Compressive force was applied at rates ranging from 0.05-0.25 MPa/s until failure as determined in a previous study by Mak, MacDougall, and Fam using similar on-site manufactured CEBs (Mak, MacDougall and Fam 2015). The dry two-block prisms were tested at the standard rate of 0.25 MPa/s, however, the loading rate had to be adjusted for some of the other tests. For example, the four-block prisms (both wet and dry) and all the wet tests for all prism heights had to be loaded at lower rates (in the aforementioned range) because of the much softer nature of the CEBs and lower compressive strengths achieved. The compressive strength, f_{CEB} of the prism was calculated using Equation 1.

$$f_{CEB} = \frac{P_{failure}}{A} \tag{1}$$

where f_{CEB} is the ultimate compressive strength of the prism (MPa), $P_{failure}$ is the peak load at failure (N), and A is the original surface area to which the load was applied (mm^2).

3.2.6 Flexure

The tests were conducted according to ASTM C67-07 (ASTM 2007) with a modification from loading the block at third points to loading the block at the midpoint as shown in Figure 3-4b. Load was applied through a steel plate and roller placed on the block at the midpoint. The CEBs rested on two steel plates and rollers positioned 25 mm from each end of the blocks. The dimensions of each block were measured and recorded before each test, and lines were drawn at the centre of each dimension to ensure symmetrical loading. The blocks were loaded at a rate of 0.25 mm/min until failure, and the peak applied load was recorded in kN for each sample.

The flexural strength of the blocks, fr_{CEB} was calculated using Equation 2. The moment induced at the mid-span (M) of the block was calculated given the peak applied force using Equation 3, and the moment of inertia ($I_{N/A}$) of each block was calculated given the measured width and height of the CEBs using Equation 4.

$$fr_{CEB} = \frac{M*C}{I_{N/A}} \tag{2}$$

where,

$$M = \frac{P_{failure}*L}{4} \tag{3}$$

$$I_{N/A} = \frac{bh^3}{12} \tag{4}$$

and C is the distance from the neutral axis to the extreme fibre in tension (half the block thickness).

3.2.7 Saturated CEB Tests

Blocks were fully submerged in water for 24 hours and tested afterwards in compression and flexure using the procedures detailed in Section 3.2.5 and Section 3.2.6. The blocks were tested wet 24 hours after removal from water to allow excess surface water to evaporate while still ensuring the block was completely saturated. The amount of water absorbed by the blocks during the 24-hour soaking period was determined by weighing the block after it had been tested to failure and then again after oven-drying.

3.3 Experimental Results and Discussion

Multiple samples were tested for each type of block used in this investigation. The results of each test have been reported as average values with the associated standard deviation, indicated by the "±" symbol following the average value. A complete summary of all the test results is provided in Appendix A.

3.3.1 Unconfined Compression Failure Modes

Figure 3-6 summarizes the measured prism strength for each of the four block types in the two-block prism configuration at air-dry state, as well as at saturated state. Mean values are shown with error bars to denote maximum and minimum measured values.

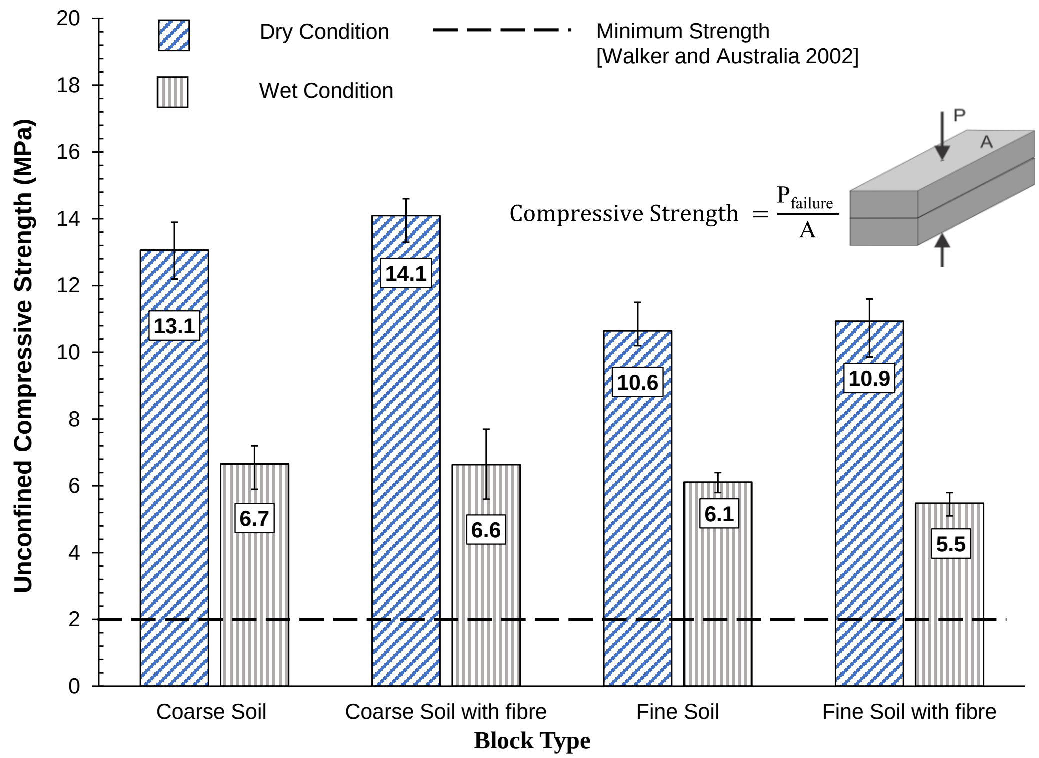

Figure 3-6: Unconfined compressive strength for 2-block prisms

According to ASTM C1314, masonry blocks and bricks mainly demonstrate a splitting mode of failure by a conical break or cone and shear failure mechanism when loaded in compression (ASTM 2018). From Figure 3-7, the CEB prisms failed by web splitting cracks throughout the length of the blocks.

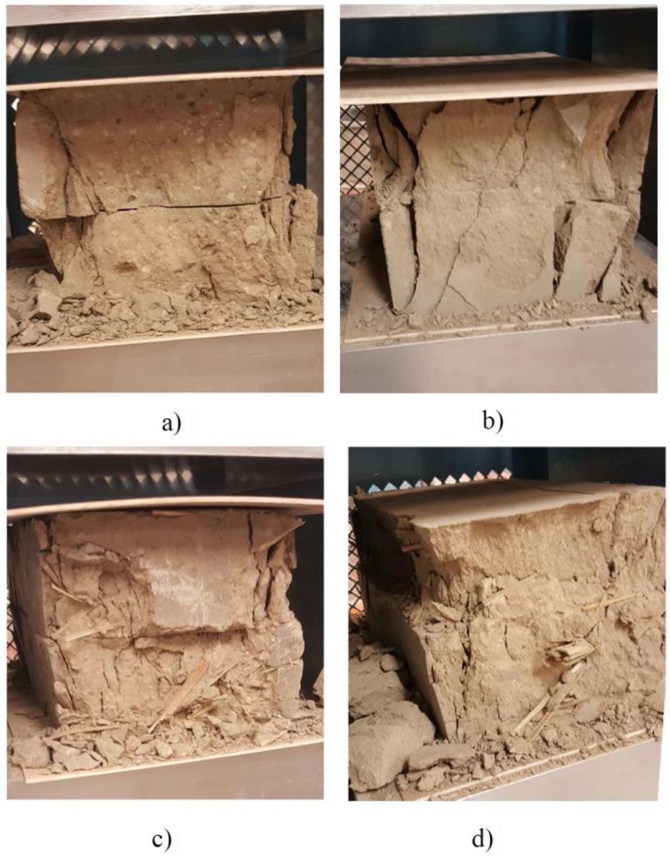

Figure 3-7: Compression failure modes of CEBs tested at air-dry state: a) coarse soil without Phragmites, b) fine soil without Phragmites, c) coarse soil with Phragmites, d) fine soil with Phragmites

The degree of damage (the number and width of cracks) was higher in fine soil blocks compared coarse soil blocks, and lower in fibre reinforced blocks compared to unreinforced blocks. To further explore these differences in the degree of damage, close-up photos were taken for failure surfaces of different CEBs prisms (see Figure 3-8). It can be observed in Figure 3-8a that the texture of the failure surface in a coarse soil block was rough and the gravel particles were either crushed or pulled out from the soil matrix. The texture of the failure surface in the fine soil block, however, was smooth with the large particles of the soil remaining uncrushed (cracked), as shown in Figure 3-8b.

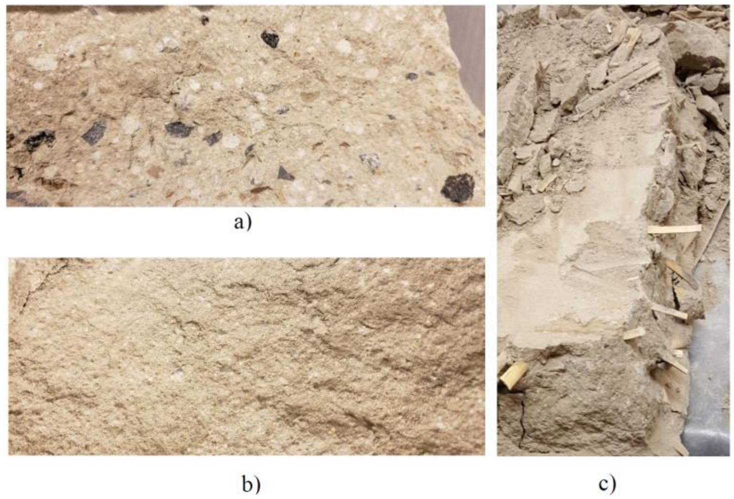

Figure 3-8: Texture of failure surfaces of CEBs tested in compression at air-dry state: a) coarse soil without Phragmites, b) fine soil with Phragmites, c) typical coarse or fine soil with Phragmites

The increased roughness of the cracked surface of the blocks with coarse soil with the gravel particles being crushed or pulled out created more resistance that helped the coarse soil block undergo less damage when loaded in compression compared to the fine soil block. For the fibre reinforced blocks, the failure surfaces contained Phragmites fibres that mainly pulled out (and sometimes fractured), indicating a crack bridging mechanism provided by the fibres. This bridging mechanism led to less damage in the fibre reinforced CEBs compared to the unreinforced blocks for both coarse and fine soils.

3.3.2 Effect of Soil Gradation and Fibres on Compressive Strength at Air-Dry State

The type of soil used in the blocks had a larger effect on the compressive strength of the blocks than the addition of Phragmites. Figure 3-6 shows that the stress range for the coarse soil block type is outside of the fine soil block type, which may indicate a significant difference. To confirm this hypothesis, a two-sample t-Test assuming unequal variances was performed to determine if there was a significant difference between the data. The null hypothesis was that the means of the two populations were equal. The null hypothesis was rejected if the P-value from the t-Test was less than the significance level ($\alpha = 0.05$), indicating a significant difference between the means of the two populations. The results of the t-Test showed that the difference in compressive strength between the coarse soil and fine soil blocks without fibres was statistically significant at the 95% confidence level. The difference in compressive strength between the coarse soil and fine soil blocks with fibres was also found to be significant at the 95% confidence level.

The compressive strength increased 23.5% from the use of fine soil to coarse soil for the unreinforced blocks and 28.8% from the use of fine soil to coarse soil for the blocks reinforced with Phragmites. This increase can potentially be attributed to the presence of a range of aggregate sizes in the coarse soil mixture that created a stronger bond in the mix, resulting in higher strengths being achieved. Furthermore, having larger particle sizes bonded by the cement and lime to the rest of the soil mixture in the blocks provided an additional resistance mechanism (aggregate interlock) that helped to limit crack propagation leading to higher strength.

An increase in compressive strength of 7.8% was achieved for the coarse-grained soil with the addition of Phragmites. The fine-soil block strength increased only by 2.7% with the addition of Phragmites. Figure 3-6 shows that there is likely no statistical significance between the strength of the blocks with Phragmites and the unreinforced blocks. The average strength of blocks composed of fine soil with Phragmites was higher than that of unreinforced, fine soil blocks, but the variation associated with each value places these results in the same strength range. This is also the case for the coarse soil block types indicating that there was likely no statistical significance between these values. To confirm this hypothesis, a t-Test was performed using the same method as previously described. The results of the t-Test found that the difference in compressive strength of the coarse-soil blocks with and without fibres was not statistically significant at the 95% confidence level. The results also showed that the difference in compressive strength of the fine-soil blocks with and without fibres was not statistically significant at the 95% confidence level.

Australia's Earth Building Handbook requires a minimum dry compressive strength of 2.0 MPa (Walker and Australia 2002), while the International Building Code requires a dry compressive strength of 2.07 MPa (International Code Council 2006). Australia's Earth Building Handbook sets out principles of accepted good practice and recommended design guidelines for lightly loaded, primarily single and two-storey buildings constructed using unbaked earthen walls and floors, similar to those used in this thesis (Walker and Australia 2002). The strengths of all the block types in this investigation exceeded these minimum values. Mak et al. found that the 28-day compressive strength for CEBs made out of coarse-grained soils with the addition of 5% cement stabilizer and no fibre reinforcement was 12.2 MPa (Mak, Maracle and MacDougall 2015). This was less than the 120-day compressive strength of the coarse-grained soil specimens both with and without fibre reinforcement tested in this investigation. The same production method used in the Mak et al. study was followed in the current investigation apart from the curing time. The higher strengths observed in the current investigation can be attributed to the longer curing time.

3.3.3 Effect of Block Saturation on Compressive Strength

Blocks that were completely submerged in water for 24 hours were weighed before and after submersion to determine the percentage of water absorbed at time of testing. The water absorption of the coarse-grained blocks was approximately 8-9% and the fine-grained blocks approximately 10-11%. The water absorption of all block types can be found in Table 3-1.

The compression failure mode of CEB prisms tested in the saturated state was similar to that of prisms tested in the air-dry state (See Figure 3-9). The wet strength of both the coarse-grained block types was approximately half the dry strength. The unreinforced coarse-grained soil had a wet strength of

6.6 ± 1.1 MPa while the coarse-grained soil with Phragmites had a wet strength of 6.7 ± 0.7 MPa. The wet compressive strengths of both fine-grained samples were slightly lower than those of the coarse-grained samples. The average values for the unreinforced and reinforced blocks were 6.1 ± 0.26 MPa and 5.5 ± 0.36 MPa, respectively. This represents a reduction in wet strength of 9% from the coarse soil block without fibre and a reduction in wet strength of 17% from the coarse soil block with fibre. Also, the addition of fibres in the fine-soil blocks caused a reduction in wet strength of 10% when compared with the fine-soil blocks without fibres. These results were consistent with findings by other researchers [(Walker 1997), (Mak, MacDougall and Fam 2015)] who observed that the reduction in compressive strength of CEBs while saturated ranged between 40% and 60%.

Figure 3-9: Compression failure modes of CEBs tested after saturation: a) without Phragmites, and b) with Phragmites

The reason for this decrease in strength in the saturated state can be attributed to pore water pressures, reduced bond between stabilizers (cement/lime) and the rest of the soil, and liquefaction of un-stabilized clay minerals (Walker 1997). These effects combined to cause a decrease in the internal friction of the CEB matrix. In natural clay-based stones, the reduction in strength at saturated conditions compared to dry conditions was ascribed mainly to the presence of clay fractions that swelled due to the presence of water and decreased the internal friction of the stone [(Verstrynge, et al. 2014), (Erguler and Ulusay 2009)]. Further investigation is needed to explore the effect of water saturation on the bond between hardened stabilizers (cement/lime) with the other particles of the CEB mixture. The test results showed that it is important to protect CEB buildings from water penetration (i.e. by plastering CEB walls and coating or laminating CEB floors). Mak et al. (Mak, MacDougall and Fam 2015) found that using Plasticure in CEBs reduced the amount of water absorbed by 60-80% and improved the wet compressive strength of CEBs. It was apparent that when the blocks were fully saturated they were not nearly as strong as the air-dry counterparts; however, it is once again important to note that even the saturated strength values still exceeded the Australian Earth Building Handbook requirement of 2.0 MPa (Walker and Australia 2002).

3.3.4 Effect of Prism Configuration on Compressive Strength

Figure 3-10 shows the air-dry compressive strength of each block mix in the one-block, two-block, and four-block prisms. The first thing to note is that, as the aspect ratio (ratio of h/t in Figure 3-10) increased, the variation in strength both between both block types and test repetitions decreased.

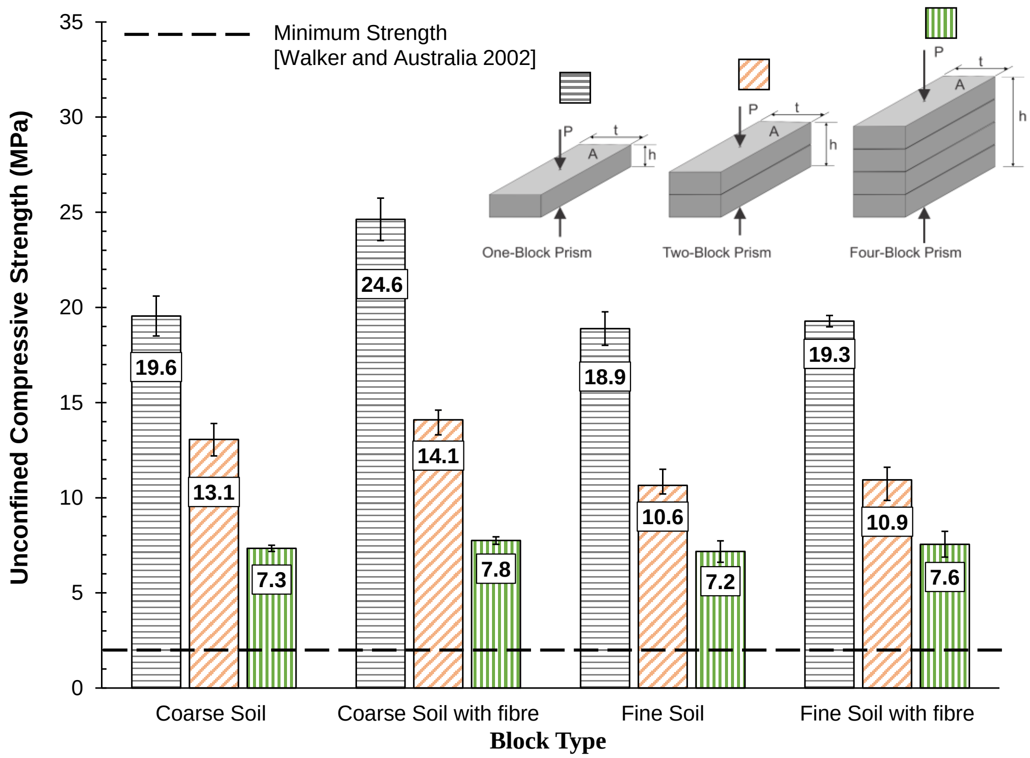

Figure 3-10: Air-dry uncorrected compressive strength of three prism configurations

There was more variability in strength when considering a single block than with the multi-block tests. The next thing to note was that the single block prisms had a much higher individual unit strength than the two-block and four- block prisms, as expected, which was accounted for by using aspect ratio correction factors. It is clear from Figure 3-11 that failure modes of one-block and four-block prisms were similar to those of the two-block prisms. The failure occurred from the development of web splitting cracks throughout the length of the blocks. The effect of gravel particles reducing the degree of damage in coarse soil blocks compared to that of fine soil block was still evident. The effect of fibres in bridging the splitting cracks in reinforced blocks was evident as well.

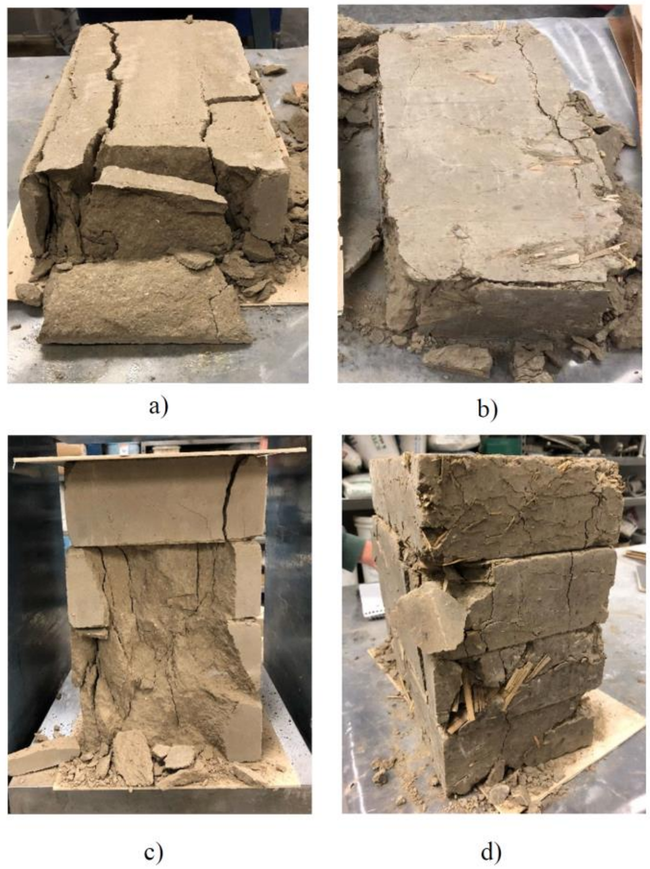

Figure 3-11: Compression failure modes of CEBs in one-block and four-block prisms: a) and c) fine soil without Phragmites, b) and d) fine soil with Phragmites

3.3.5 Aspect Ratio Correction Factors

The determination of compressive strength of masonry structural elements involves testing bonded (mortared) prisms built from the same materials used in the construction of the structure. It is well known that the measured compressive strength decreases as the aspect ratio (*h/t*) increases, though above a certain height the effect of aspect ratio becomes marginal. Aspect ratio correction factors are used to convert all the measured prism strength values to an equivalent prism size with an aspect ratio greater than five to accurately compare the strengths. This limit is based on the philosophy that taller prisms provide more representative strengths of in-situ masonry. There are two methods of determining correction factors based on aspect ratio; Krefeld (Krefeld 1938) brick masonry prisms and Heathcote and Jankulovski (Heathcote and Jankulovski 1992) for soilcrete block prisms. Although both methods are based on nonlinear relationships between the correction factor and the aspect ratio, it is important to note that Krefeld correction factors are given for specific aspect ratio values. Other Krefeld correction factors can be linearly interpolated between these values as follows:

$$K_a = \begin{cases} 0 - 0.5 \; for \; 0 \leq A_r \leq 0.4 \\ 0.5 - 0.6 \; for \; 0.4 \leq A_r \leq 0.7 \\ 0.6 - 0.7 \; for \; 0.7 \leq A_r \leq 1.0 \\ 0.7 - 0.85 \; for \; 1.0 \leq A_r \leq 3.0 \\ 0.85 - 1.0 \; for \; 3.0 \leq A_r \leq 5.0 \\ 1.0 \; for \; A_r > 5.0 \end{cases} \tag{5}$$

where, K_a denotes the calculated correction factor and A_r denotes the aspect ratio.

The Heathcote and Jankulovski correction factors can be calculated using the following equation:

$$K_a = 10.1\left(8.9 + \frac{8.0}{A_r^{1.2} - 0.061}\right)^{-1} \tag{6}$$

A plot of unconfined compressive strength versus aspect ratio is shown in Figure 3-12. The figure covers a range of results including those from this investigation that are unbonded, with the addition of some bonded data from an investigation completed by Tattersall (Tattersall 2013). All results in Figure 3-12 include blocks produced at the same site with 2.5% cement and 2.5% lime. The prism series tested by Tattersall was composed of three coarse soil CEBs with a 5 mm thick layer of low strength soil slurry mortar between the blocks.

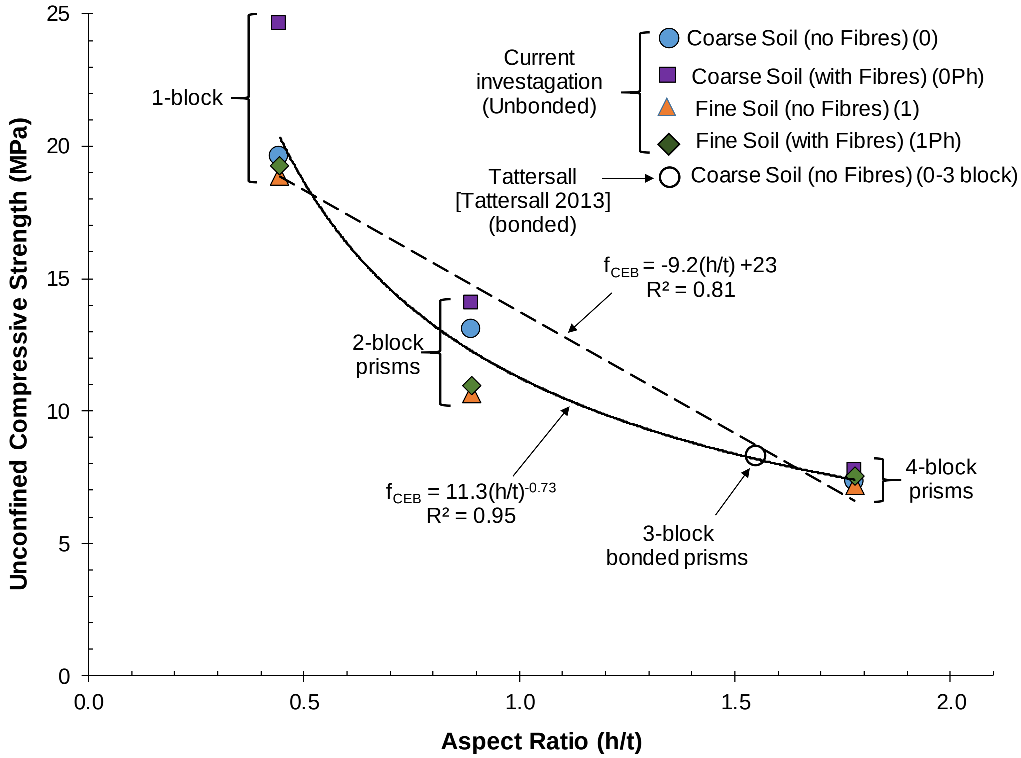

Figure 3-12: The effect of aspect (*h/t*) ratio on compressive strength of CEB prisms

It can be observed from Figure 3-12 that a non-linear trend (with a correlation coefficient of 0.95) can better represent the relationship between the compressive strength of unbonded CEB prisms and the h/t ratio than a linear trend (with a correlation coefficient of 0.81). This non-linear trend shows that it is appropriate to use the Krefeld (Krefeld 1938) and Heathcote and Jankulovski (Heathcote and Jankulovski 1992) correction factors for unbonded CEB prisms. It was also observed from Figure 3-12 that the four-block prisms had much lower variability than the other prism heights. This can be attributed to the fact that when more blocks are included in the prism the strength is less dependent on individual block strength. For example, a block tested in the one-block prisms may obtain less strength depending on degree of damage than if that same block was included in the four-block prism because the other three blocks will also share the load. Therefore, the strength values obtained for the four-block prisms are less sensitive to increases or decreases in strength due to inconsistent block damage.

Figure 3-13 shows a plot of both the uncorrected and corrected strengths (using Equations 5 and 6) for all prism types tested at air-dry state in this investigation along with Tattersall's results. A summary of the uncorrected and corrected strengths is presented in Appendix A.

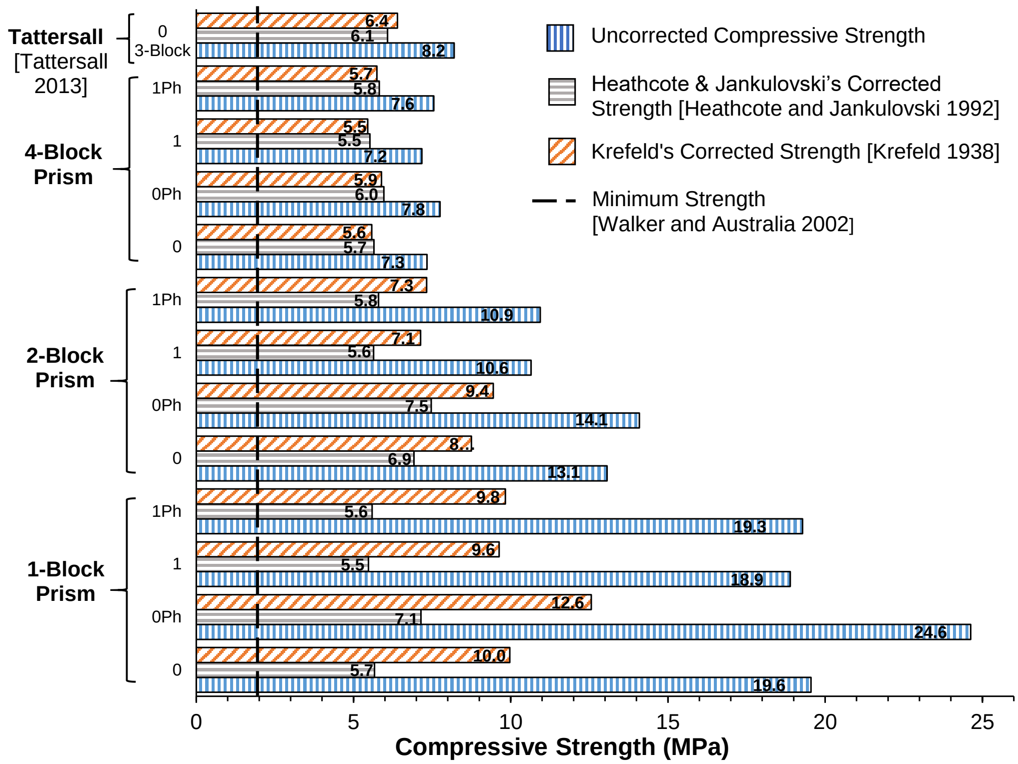

Figure 3-13: Uncorrected and corrected compressive strengths for all block types and prism configurations tested using Heathcote & Jankulovski and Krefeld's methods

The unconfined compressive strengths of single blocks were much higher than those for two-block and four-block prisms when examining measured strengths for any of the tested series (coarse or fine soil, with or without fibres). However, when the appropriate correction factors were applied, the corrected strengths of the four-block prisms fell into a very close range (5.5 – 6.0 MPa). The difference between the Krefeld and Heathcote and Jankulovski correction factors was more apparent for the one-block and two-block prisms, with the Krefeld method consistently predicting higher strengths than Heathcote and Jankulovski. It is also interesting to note that the difference in predicted strengths between the two methods increased as prism height decreased. For example, the difference in predicted strengths between both methods was much greater for the one-block prisms than the two-block prisms, and the difference in predicted strengths was much greater for the two-block prisms than the four-block prisms. Although both methods are based on non-linear relationships, Heathcote and Jankulovski present an equation which is valid for all aspect ratios whereas linear interpolation must be used between two given aspect ratios for Krefeld's method. Using an equation results in slightly more accurate (and conservative) strength values (as shown from Figure 3-13) than having to linearly interpolate. While both methods are technically correct, Heathcote and Jankulovski's method is more appropriate. It is also important to note that while the correction factors reduced the measured strength of the blocks substantially, the corrected compressive strengths for all blocks still exceeded the Australian Earth Building Handbook's minimum requirement of 2.0 MPa (Walker and Australia 2002).

It is interesting to note from Figure 3-12 that the average compressive strength of the bonded prisms tested by Tattersall (Tattersall 2013) landed on the trend line of the results of the unbonded prisms tested in the current investigation. Furthermore, it can be seen in Figure 3-13 that the corrected strength of Tattersall prisms using Equation 6 (6.1 MPa) was close to the corrected strengths of corresponding unbonded prisms tested (made with coarse soil without fibres) in the current investigation (5.7 MPa, 6.9 MPa, and 5.5 MPa for one-block, two-block, and four-block prisms, respectively). This comparability in corrected strengths of bonded and unbonded prisms can be attributed to the fact that compressive strength of CEB masonry prisms depends mainly on the compressive strength of the unit and, to a lesser degree, on the compressive strength of the mortar layer (Sajanthan, Balagason and Sathiparan 2019). As such, the use of thin (5 mm thickness), low strength soil slurry mortar in the construction of Tattersall's prisms had only a marginal effect on the compressive strength of the bonded prisms compared to those of the unbonded prisms tested in the current investigation. This finding needs to be further explored to prove the possibility of determining the compressive strength of CEB masonry from unbonded prisms avoiding the complexities of handling CEB bonded prisms. Despite being approximate, such an approach might lead to a reasonable estimation of the compressive strength of CEB masonry, given the fact that the common practice in CEB construction is to use thin, low strength mortar [(Wiersma and Wiersma 2018), (Tattersall 2013)].

Similar to the findings in this investigation regarding the compressive strength of unbonded masonry prisms, other investigations by Sturm and Ramos, and Silva et al. found that the compressive strength of interlocking CEB prisms was also dependent on aspect (h/t) ratio [(Sturm and Ramos 2015), (Silva, et al. 2015)]. Testing the CEBs without bonding mortar would be very representative of wall strength when constructed with interlocking CEBs, which do not require the use of mortar. Further investigation is required to prove the possibility of estimating wall strength (corrected strength) of interlocking CEBs from single block compressive strength, such as what can be done with unbonded masonry prisms.

3.3.6 Flexural Strength Failure Modes

All CEBs tested in three-point bending in this investigation failed in pure flexure. Shear cracks were observed in some of the samples; however, the main failure mechanism was flexural cracking at the midspan of the block. There appeared to be no noticeable cause for the occurrence of shear cracks, and they likely developed due to how the load was being distributed given the development of pre-cracks near the supports. Figure 3-14 shows typical flexural failure modes of CEBs with and without Phragmites fibres.

a)

b)

Figure 3-14: Flexural failure modes of CEBs: a) coarse soil without Phragmites, b) coarse soil with Phragmites

The unreinforced CEBs experienced sudden failure shortly after the formation of a single vertical crack during loading in three-point bending, and total separation of the cracked pieces occurred. Failure of fibre reinforced CEBs, on the other hand, was more gradual. Minor cracks developed near the main flexural crack and total separation of cracked pieces did not occur. The fibres near the crack zone were observed to bridge the cracks and slow crack propagation, where the term "bridging" refers to a transfer of tensile stresses from the fractured section of soil matrix to the fibres. This stress-transfer action resulted in a more gradual failure suggesting an improvement in deformability of the fibre reinforced CEBs.

3.3.7 Effects of Soil Gradation and Fibres on Flexural Strength at Air-Dry State

Figure 3-15 summarizes the flexural strengths of all four block types at air-dry and saturated conditions. The average flexural strength increased 15% from the use of fine soil to coarse soil for unreinforced blocks and 32% from the use of fine soil to coarse soil for fibre reinforced blocks. This increase in the average flexural strength of coarse soil CEBs compared to that of fine soil blocks can be ascribed mainly to the presence of gravel particles that provided an additional resistance mechanism (aggregate interlock) that helped to limit the crack propagation and widening, resulting in higher flexural capacity. It is worth noting that the lower bound stress values for the coarse-grained block types roughly coincide with the upper bound stress values for the fine-grained block types. This indicated that there was likely no statistical significance between the coarse soil blocks (with and without fibre) and the fine soil blocks (with and without fibre) in three-point bending. However, a t-Test was performed to test this hypothesis. The results of the t-Test showed that only the difference in flexural strength between the coarse-soil blocks with fibres and the fine-soil blocks with fibres was statistically significant, indicating that the use of coarse soil significantly increased the flexural capacity of the blocks when added in combination with the Phragmites fibres compared to the fine soil blocks.

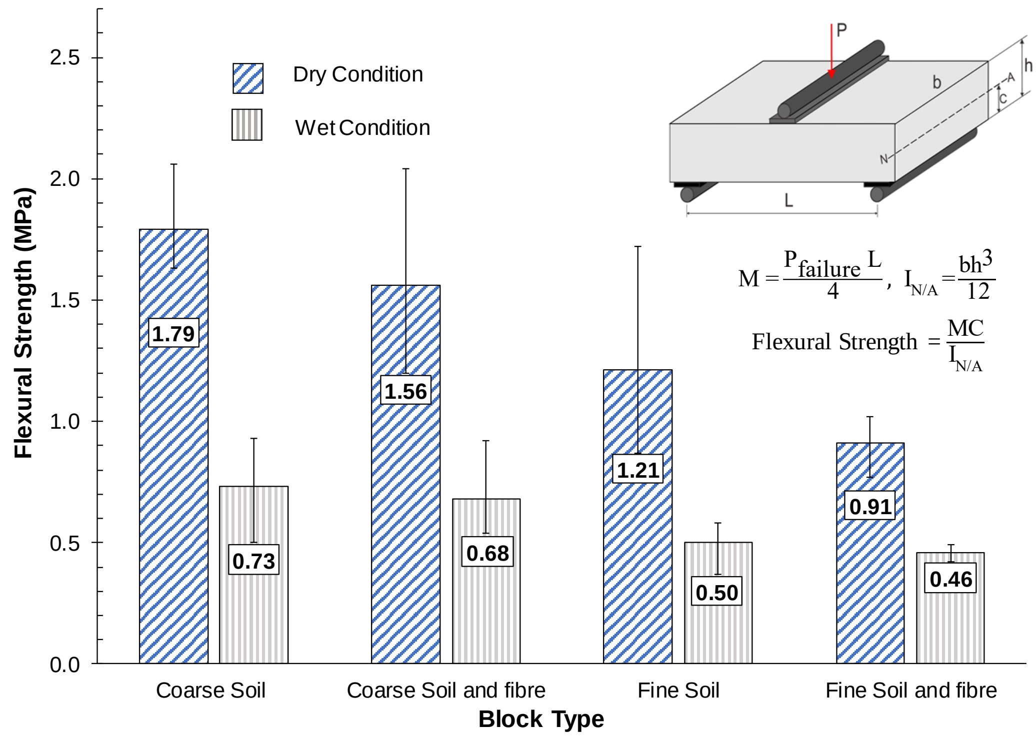

Figure 3-15: Flexural strengths for wet and dry tests for all four block types

One of the initial expectations of this investigation was that the Phragmites would improve the flexural properties of the CEBs by bridging cracks during loading and thus extending the peak load carrying capacity. However, the addition of Phragmites fibres caused reductions in the average flexural strengths by about 13% for the coarse soil blocks and 25% for the fine soil blocks. The reduction in flexural capacity seen with the addition of Phragmites is possibly due to the size (diameter or width) of the fibres, inadequate bond between the fibres and the soil matrix, and the formation of pre-cracks during block production. The inadequate bond between the fibres and the soil matrix impeded bond capabilities, and therefore instead of acting as reinforcement to the CEB, the fibres created points of weakness and they pulled out of the block when loaded. If a better bond between the fibres and the block matrix can be achieved, then an optimum aspect ratio and quantity of fibre may be possible to improve the flexural capacity of the blocks. The pre-cracks developed during the manufacturing process resulted in an initial lower flexural strength than could have been achieved with an uncracked section. The results of the current investigation agreed well with the test results of a study conducted by Donkor and Obonyo (Donkor and Obonyo 2016) who considered the effects of polypropylene fibres in earth blocks. Their study concluded that the polypropylene fibres did improve post-crack performance of the blocks, however both fibre pullout and fracture were observed during specimen testing (Donkor and Obonyo 2016). Their observation was similar to what was observed in this investigation, where the natural invasive Phragmites pulled out of the block because of a lack of adequate bond between the soil mixture and the fibres. The peak flexural strength of the CEBs with no fibre reinforcement determined by Donkor and Obonyo (Donkor and Obonyo 2016) was found to be 0.47 $\pm$ 0.03 MPa which was 72% less than the flexural strength of the coarse-grained unreinforced blocks tested in this investigation and 61% less than that for the fine-grained unreinforced blocks tested in this investigation. The highest flexural strength in Donkor and Obonyo's (Donkor and Obonyo 2016) experiment occurred at a fibre content of 0.6% and was found to be 0.84 $\pm$ 0.12 MPa which represented an increase in flexural strength of 79% when compared with the unreinforced blocks tested in their investigation. It is interesting to note that in their investigation the addition of fibres improved the flexural capacity of the CEBs when added in quantities up to 0.8% by weight. The authors recommended not exceeding 0.8% polypropylene fibres by weight for CEB production and suggested that an ideal range was between 0.4% and 0.8%. The reason for the increased flexural capacity with the addition of the polypropylene fibres was attributed to the surface deformations of the fibres which enhanced the frictional bond development between the fibres and the matrix (Donkor and Obonyo 2016), something that the Phragmites fibres failed to do in this investigation.

3.3.8 Effect of Block Saturation on Flexural Strength

Flexural failure modes of CEBs tested in a saturated state were similar to those tested at the air-dry state (See Figure 3-16). It can be observed from the plot in Figure 3-14 that saturation by immersion in water reduced the average flexural strength of unreinforced CEBs and the reinforced coarse soil block by about 60%. The average flexural strength of the reinforced fine soil CEBs was reduced by 50% after saturation. The reduction in flexural strength of unreinforced blocks in the saturated state can be attributed to the liquefaction of unstabilized minerals, which deteriorate the bond between the components of the soil matrix, forming weak pockets and cavities causing a reduction in the internal friction of the CEB matrix. Figure 3-16 shows some of these cavities formed in the coarse soil block because of the removal of the gravel particles from their locations after saturation.

a) b)

Figure 3-16: Flexural failure modes of CEBs tested after saturation: a) with Phragmites, and b) without Phragmites

In addition to the erosion effect, water saturation weakened the bond between fibres and the soil matrix in the reinforced CEBs, causing the fibres to pull out and reducing the effectiveness of fibres in bridging the cracks (see Figure 3-16).

3.3.9 Relationship between Compressive and Flexural Tensile Strength

In concrete design, standards have been developed to relate flexural strength to compressive strength using empirical equations. For example, ACI 318-2014 (ACI 2014) and CSA A23.3-2014 (CSA 2014) codes estimate the flexural strength to be 60% of the square root of the compressive strength. Some researchers relate the concrete flexural strength to compressive strength through a (2/3) power model [(Mhaiskar and Naik 2012), (Ahmed, Mallick and Mohd 2016)]. To the best of the author's knowledge, currently no formula or equation exists to relate the compressive strength and flexural strength of CEBs.

An empirical relationship has been proposed based on the results of the current investigation as well as a collected database of 47 average test results which represent a total of 133 individual tests results from Villamizar et al., Sitton et al., Mostafa and Uddin, and Eko et al. [(Villamizar, et al. 2012), (Sitton, et al. 2018), (Mostafa and Uddin 2015), (Eko, Mpele, et al. 2006)]. The results in the database include CEBs produced with different soil compositions and stabilizers of up to 10%. All tests results and corresponding information used to compile that database can be found in a table in Appendix A. The dimensions of the CEBs in these studies varied, leading to compressive strengths that were measured with varying aspect (h/t) ratios from 0.54 to 1.4. To normalize the effect of varying aspect ratio, strengths were corrected by multiplying the measured unit strength by corrections factors from Equation 6. The corrected compressive strengths of CEBs included in the database range from 0.63 MPa to 7.5 MPa.

A regression analysis based on the least squares method was conducted with the flexural strength of CEBs (fr_{CEB}) considered to be the dependent variable and the compressive strength of CEBs corrected for h/t effects ($f_{CEB\ cor.}$) considered to be the independent variable. Since the flexural strength was measured using three-point bending in a similar fashion to tests conducted on concrete beams, both the square root and the power models were modelled to acquire the most representative formula. The regression analysis is shown in Figure 3-17 and Equation 7 provides the proposed equation to relate flexural and compressive strength of CEBs.

$$fr_{CEB} = 0.35(f_{CEB.cor.})^{0.8} \tag{7}$$

Figure 3-17 shows that Equation 7, based on the power model, achieved a coefficient of determination of 98%, an average *fr*$_{CEB}$ *(Exp) / fr*$_{CEB}$ *(Pred)* of 1.0, and a coefficient of variation of 16%. It can also be seen from Figure 3-17 that the squared model led to a formula with less representation of the database with a lower average *fr*$_{CEB}$ *(Exp) / fr*$_{CEB}$ *(Pred)* ratio and a higher coefficient of variation.

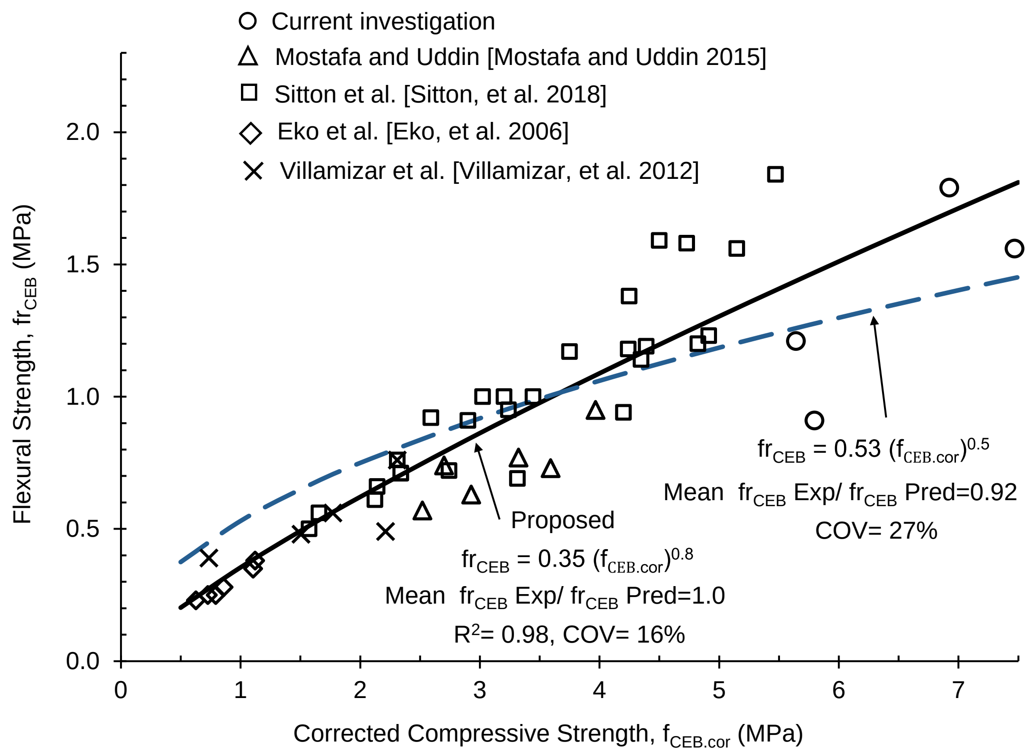

Figure 3-17: Regression analysis of database of test results to relate flexural and compressive strength of CEBs

It is important to note that the equation proposed from Figure 3-17 was developed using data from four investigations, however, there was substantially more data included in the figure from one investigation, (Sitton, et al. 2018), than for the other investigations. The Sitton study used prisms with a lower aspect ratio than those in the other studies, consequently resulting in lower correction factors. It is possible that these factors could be artificially driving the curve fitting, and so care should be taken when using this preliminary proposed equation. For example, the proposed equation does not predict the strengths from Mostafa and Uddin's (Mostafa and Uddin 2015) study conservatively, which is likely a result of the equation being driven by Sitton et al.'s data. In addition, it is noted from Figure 3-17 that the proposed equation is very close to a linear relationship, with the results from the current investigation likely causing the slight exponential curve. When looking at the proposed equation, a general guideline could also be suggested stating that the flexural tensile stress capacity of the CEBs is roughly one-third of the compressive strength of the CEBs, compared to a similar guideline for concrete of one-tenth of the compressive strength. This makes sense conceptually when considering that the compressive strength of concrete is generally greater than what is achieved from the CEBs.

3.4 Summary

Four CEB types were tested in unconfined compression and three-point bending to determine the effect of soil gradation and the addition of invasive Phragmites on the mechanical properties of the blocks at air-dry and saturated states. Based on this experimental study, the following conclusions can be made:

1. It is viable to manufacture compressed earth blocks with either fine or coarse soils. The compressive strength of CEBs produced from both types of soils used in this research were well above the International Building Code's minimum dry compressive strength requirement of 2.07 MPa (International Code Council 2006) and the minimum strength requirement of 2.0 MPa from Australia's Earth Building Handbook (Walker and Australia 2002). The presence of the gravel particles (larger than 4.75 mm and smaller than one-sixth of least block dimension) improved the compressive strength of the coarse soil CEB prisms by 23.5% to 28.8% compared to those of fine soil prisms. Less compression damage was noticed in coarse soil CEB prisms.

2. The compressive strength of unbonded CEB prisms reduced with increasing aspect ratio. Aspect ratio correction factors developed for compressed stabilized earth brick units and prisms Krefeld (Krefeld 1938), and Heathcote and Jankulovski (Heathcote and Jankulovski 1992) would seem equally suitable for on-site compressed earth blocks.
3. The corrected strengths of the unbonded coarse soil CEB prisms tested in the current investigation were close to the corrected strength of CEB prisms bonded with soil slurry tested in a previous investigation by Tattersall (Tattersall 2013). This finding needs to be further explored because it is important to determine the compressive strength of CEB masonry (made with low strength mortar) from unbonded prisms avoiding the complexities of handling bonded CEB prisms.
4. The use of coarse soil instead of fine soil increased the average flexural strength of CEBs by 15% in the unreinforced blocks and by 32% in blocks reinforced with Phragmites. However, variations associated with these increases likely make them statistically insignificant. Visual inspection of failure surfaces showed that the gravel particles provided an additional resistance mechanism (aggregate interlock) that helped in limiting the crack propagation and widening, leading to higher compressive and flexural strengths.
5. The addition of Phragmites fibres to CEBs improved flexural ductility by preventing sudden failure. No total separation of cracked pieces of fibre reinforced specimens was noticed during testing. A visual assessment of the crack zones of the fibre reinforced CEBs showed that the fibres bridged the cracks and held cracked sections together.
6. The addition of Phragmites fibres reduced the average flexural strengths by about 13% to 25% for the CEBs. The reduction in flexural capacity with the addition of Phragmites can be attributed to the size of the fibres, the inadequate bond between the fibres and the soil matrix,

and the formation of pre-cracks during the manufacturing phase. The results from this investigation are preliminary and future work should include further optimizing the use of Phragmites and other natural fibres in on-site CEB construction.

7. Saturation by immersion in water reduces unit compressive and flexural strength by 50% or more in comparison with corresponding air-dry state values. Strength reduction may be attributed to pore water pressures and liquefaction of unstabilized soil.
8. An empirical relationship relating the flexural and compressive strength of CEBs was proposed based on a collected database of test results from the literature and from the results of this investigation. The proposed equation accurately represents that data with an average $fr_{CEB}\,(Exp)\,/\,fr_{CEB}\,(Pred)$ ratio of 1.0 and a coefficient of variation of 16%.

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Chapter 4

The Mechanical Properties and Freeze-Thaw Durability of On-Site Manufactured Compressed Earth Blocks Reinforced with Natural Fibres

4.1 Introduction

Society's increased interest in sustainable building practices leads to increased demand for alternative materials that are more renewable and sustainable than conventional steel and concrete. Examples of sustainable materials considered for building are timber, straw, and earth. Traditionally, the concept of earth building stems from Mexican Pueblo housing designs, which use adobe bricks as the main building material (Wiersma and Wiersma 2018). Mud brick (adobe) houses have been discovered in Russian Turkestan dating from 8000 to 6000 BC, and rammed earth foundations have been discovered in Assyria dating from ca. 5000 BC (Minke 2006). A modern form of this building system is a compressed earth block (CEB) which is an unfired masonry unit comprised of compacted earth (Mak, MacDougall and Fam 2015). Much of the modern earth building practices predominantly exist in warm climate regions such as Africa, various European countries, and Mexico. However, CEBs are being considered for building in cold climate conditions due to their low thermal conductivity (Smigelski 2016) and capacity to balance air humidity in buildings (Loborel-Preneron, Aubert, et al., Plant Aggregates and Fibers in Earth Construction Materials: A Review 2016).

4.1.1 Objectives

Previous studies have shown that the addition of a cementitious chemical stabilizer, as well as a reinforcing fibre, can improve CEBs properties [(Loborel-Preneron, Aubert, et al. 2016), (Donkor and Obonyo 2016)], but these studies were conducted with laboratory manufactured samples. There is a lack of research regarding the mechanical characteristics of on-site manufactured CEBs. The method in which CEBs are manufactured (in the laboratory versus on-site) can greatly affect the performance of the blocks. The objectives of this project are to determine the effect of adding different natural fibre types (straw, switchgrass, and rice hulls) at varying quantities on the compressive and flexural strength of on-site manufactured CEBs and to assess the effect of these fibres on the freeze-thaw durability of the CEBs.

4.2 Experimental Method

An experimental investigation was conducted to determine the mechanical properties and the freeze-thaw durability of on-site manufactured CEBs constructed with varying types and quantities of natural fibre reinforcement. The following section outlines the materials and fabrication method used to construct the test specimens as well as the test setup used to perform the investigation.

4.2.1 Test Specimens

Eight different mix designs were considered in the test matrix. The CEBs were cast using a mixture of soil, cement, hydrated lime, and natural fibres. The block constituent material properties are discussed further in Section 4.2.2 and material quantities are listed along with other block properties in Table 4-1.

The dimensions of the block (length, width, and height) are presented in Table 4-1 as the average value of three measured blocks with associated standard deviations. The same three blocks were also weighed at ambient conditions and the bulk densities provided in Table 4-1 are also average of three repetitions with associated standard deviations. The moisture content was measured by weighing samples of the CEBs before and after oven drying. Only two samples for each mix were weighed, therefore only the average values of the two measurements are reported in Table 4-1.

Table 4-1: CEB composition and properties

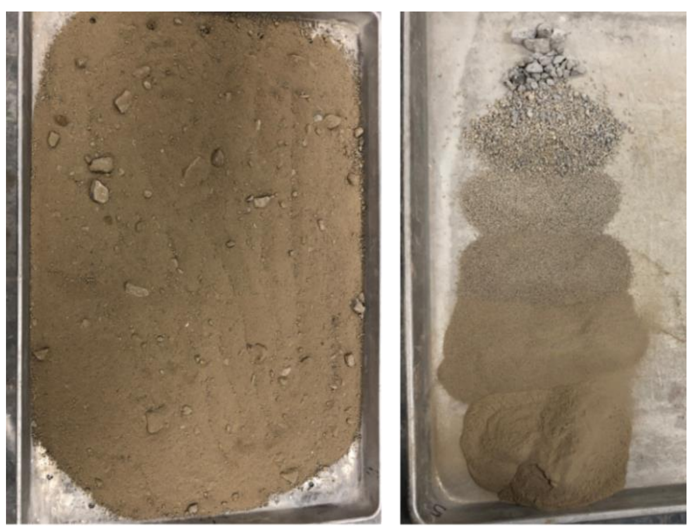
Ingredients			Dimensions (mm)			Physical Properties	
Fibre Type	Nominal Fibre Quantity (% by weight)	Actual Fibre Quantity (% by weight)	Length	Width	Height	Density (kg/m^3)	Moisture Content (%)
None	-	-	352.7±0.6	178.3±0.6	72.7±0.6	2203±28	2.57%
Switchgrass	0.25	0.24	353.3±0.6	177.3±1.2	74.7±0.6	2129±59	1.98%
Straw	0.125	0.12	352.7±0.6	178.7±0.6	74.4±0.6	2078±54	1.36%
	0.25	0.24	353.3±0.6	178.0±1.0	75.0±1.0	2165±41	1.57%
	0.75	0.73	355.0±1.0	177.7±1.2	77.7±0.6	1978±36	1.78%
Rice Hulls	0.25	0.26	353.7±0.6	178.3±0.6	75.7±1.2	2092±58	2.40%
	0.50	0.46	352.7±1.2	177.3±1.2	75.3±1.2	2086±6	2.29%
	0.75	0.67	353.7±0.6	178.7±0.6	75.0±1.0	2093±21	2.43%

The weight of fibres to be added to each mixture was calculated prior to arrival on-site on the day of block production. The nominal (desired) fibre quantities for each batch were determined as a percentage of total batch weight, and then the required weight of fibres was estimated per batch using the densities of the soil and fibres. The densities of the coarse soil and Phragmites fibres from the preliminary study in Chapter 3 were used to complete these calculations because no samples of the new soil and fibres were available. At the time of production, the exact weights of fibres added to each batch were measured and recorded. This weight was then used to calculate the actual quantity of fibres in each batch as a percentage of total batch weight. For the actual quantity calculations, the new soil and fibre densities were used because samples were collected on-site during production. Going forward, results will be reported using the nominal fibre quantity to differentiate the different block types.

The weight of cement-lime stabilizer added to each batch was kept consistent at 20 kg for all eight mixes and was measured by filling a five-gallon bucket with the stabilizer and weighing it on a scale. The weight of soil added to each batch was not measured as accurately as the fibres and stabilizer because it was added to the mixer using a front-end skid steer loader. The builder on-site had previously measured the capacity of the loader to hold fifteen - 60 lb buckets of soil, totalling about 408 kg of soil added to each batch.

4.2.2 Materials

Clay soil was used as the main ingredient in the CEBs. The manufacturer sourced clay locally and mixed in sand that was dug from the farm for on-site fabrication. Figure 4-1 shows a sample of the soil used in manufacturing the CEBs. The clay soil was processed using a 1-inch (25 mm) filter to screen out large rocks. The soil is typical of soils found in most parts of southern Ontario and contained 23.3% clay-sized particles by mass. The clay-sized particles were composed mostly of calcium carbonate (calcite), based on tests conducted by a commercial testing lab (Hamilton 2005), including X-ray diffraction and X-ray fluorescence analysis. No ball clay or kaolinite was detected. The bulk density of the soil was 1698.7 ± 20.5 kg/m^3 and was determined in the lab by measuring the weight of soil in a known volume cylinder.



a) b)

Figure 4-1: Sample of soil used in manufacturing the CEBs: a) before, and b) after sieving

A sieve analysis was completed on a sample of soil taken from the site following the standard test procedure outlined in ASTM D6913 (ASTM 2017) and the soil was classified as clayey sand as defined by ASTM D2487 (ASTM 2018). The soil sieve analysis was completed using sieve sizes ranging from No. 3/8" (9.5 mm) to No. 100 (150 μm), as shown in Figure 4-2. The soil was composed of gravel, sand, silt, and clay particles with about 95% of the soil particles passing through the No. 4 sieve (4.75 mm) and about 28% of the soil particles passing the No. 100 sieve (150 μm).

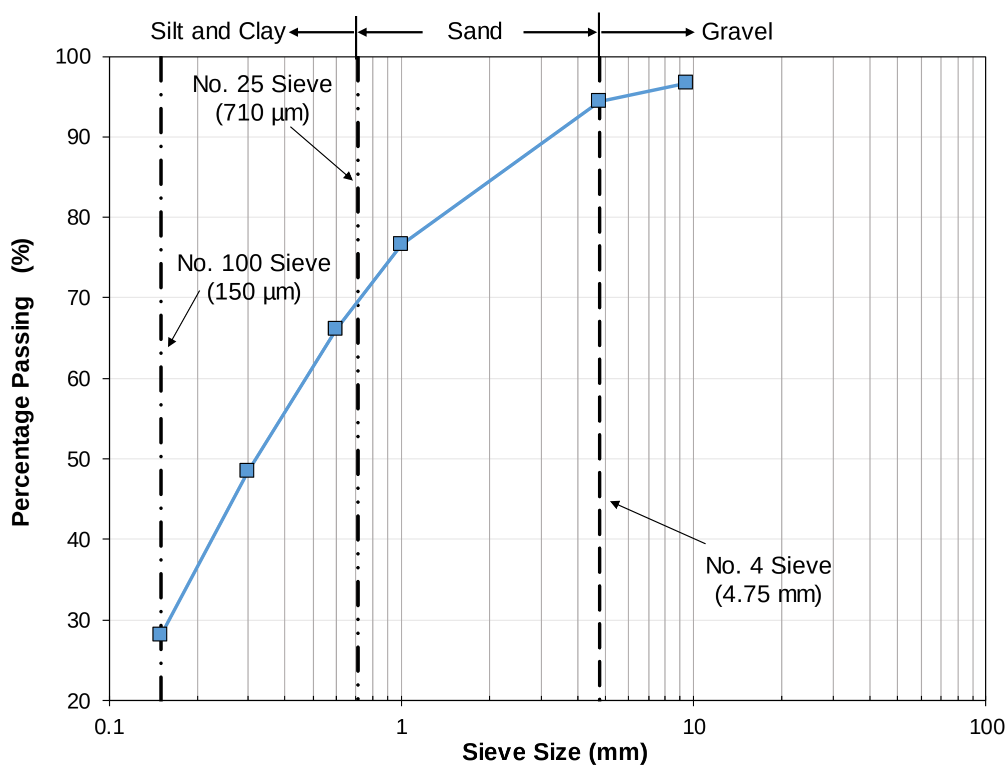


Figure 4-2: Results from soil sieve analysis

From a combination of previous literature [(Mak, MacDougall and Fam 2015), (Hallal, Sadek and Najjar 2018), (Nagaraj, Rajesh and Sravan 2016), (Bahar, Benazzoug and Kenai 2004)] and local expertise (Wiersma and Wiersma 2018) it was determined that adding a 1:1 cement: lime chemical stabilizer at 5% by weight (2.5% Type 1 Portland cement and 2.5% hydrated dolomite lime) was enough to stabilize the clay soil and prevent the blocks from eroding during adverse weather conditions. The cement-lime stabilizer was added in the same quantity to all block mixes. Straw fibres (see Figure 4-3a) were added at 0.125%, 0.25% and 0.75% by weight, switchgrass fibres (see Figure 4-3b) were added at 0.25% by weight, and rice hulls (see Figure 4-3c) were added at 0.25%, 0.50%, and 0.75% by weight.

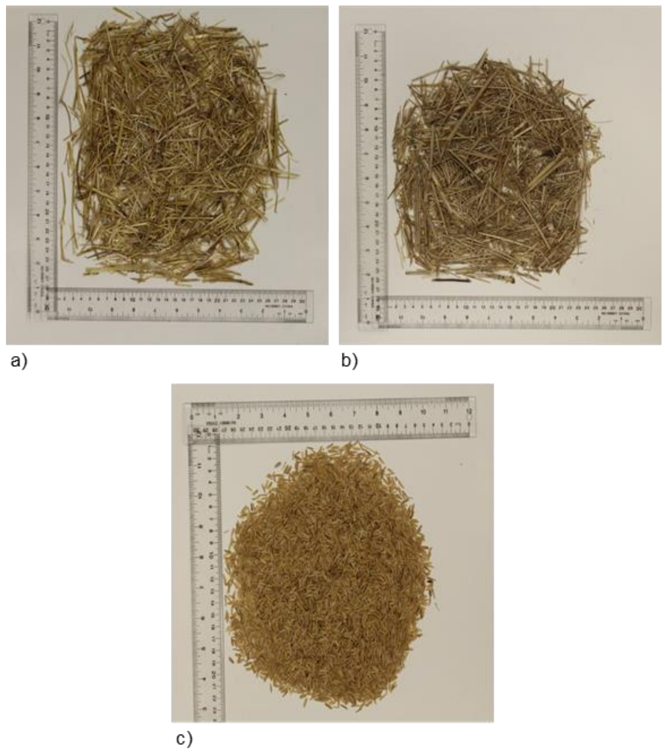


Figure 4-3: Samples of fibres used in CEB fabrication: a) straw, b) switchgrass, and c) rice hulls

Fibres were either sourced locally near the fabrication site, or in the case of the rice hulls, delivered from a source near Toronto, Ontario, Canada. The switchgrass and straw fibres were cut into smaller sizes using a weed trimmer on site. The fibres were then screened to ensure a consistent and even distribution of fibre size before being added to the soil. The rice hulls were uniform in size and shape when delivered and therefore were not modified before being added to the soil mixture. The bulk densities of the fibres were determined in the lab by measuring the weight of fibres in a known volume cylinder. Bulk densities of the straw, switchgrass, and rice hulls were calculated using the average of three repetitions and were found to be 49.2 ± 1.9 kg/m^3, 48.0 ± 0.7 kg/m^3, and 126.5 ± 4.6 kg/m^3, respectively.

4.2.3 Fabrication of Earth Blocks

All blocks were manufactured on-site by an experienced builder in Cobourg, Ontario, Canada. The soil, cement, lime, and fibres were combined using a mechanical one-yard mixer (see Figure 4-4a) and water was added via a garden hose until the desired consistency was reached. The moisture content was determined by inserting the prongs of a moisture sensor into the mix and taking readings from the sensor. The optimum moisture content was found to be around 6.5% and was checked by hand (Figure 4-4b) using a standard drop test. A drop test is a good first approximation of the optimum moisture content of a soil mixture, especially when working on site where more refined methods of determining optimum moisture content are not available (Maniatidis and Walker 2003). To complete the drop test, a handful of soil was compressed by hand and dropped onto the ground from a height of approximately 1.5 m. If the soil is too dry, the handful will break into many pieces. If the soil breaks into only a few pieces, then it is very close to its optimum moisture content. If the soil completely retains its shape upon being dropped then the mixture is too wet. Because water was gradually added until the desired moisture content was obtained, the third outcome did not occur.

The blocks were mechanically compressed using an AECT 3500 Compressed Earth Block Machine (see Figure 4-4c). The pressure was read and recorded from the pressure gauge on the earth block machine in pounds per square inch (psi) and reported in megapascals (MPa). The average compressive pressure and associated standard deviation for the eight batches was 11.5 ± 1.2 MPa. Blocks were cross stacked in single stacks on pallets and were left outside covered for one to two days prior to transportation inside the barn, where they were stored for up to two months until transportation to the lab.

Figure 4-4: On-site manufacturing of the compressed earth blocks at Fifth Wind Farm: a) adding soil, lime, cement, and fibres to mixer, b) adding water to mixture until desired consistency reached, c) production of the CEBs

Because of manufacturing constraints, there was a slight variance of the height of the blocks ranging from 70 mm to 80 mm. The difference in height was attributed to various factors including quantity of fibres, pressure, and moisture content. CEBs that were manufactured without any fibres had a thickness around 70 mm and were able to be compressed at a more consistent pressure. Blocks with high fibre quantities, such as the 0.75% straw, had the largest thickness of around 80 mm and the pressure at which the blocks were compressed was more difficult to maintain. To circumvent this inconsistency in block height in future work or applications, the soil mixture should be weighed prior to compression to ensure the same amount of soil is being used in each block. Also, the pressure and duration of compression should remain consistent for the entire batch. Something to consider when manufacturing on-site CEBs is the practicality of using higher fibre quantities. At first glance it may seem that using higher quantities of fibres will result in an increase in performance, however, since the higher fibre quantity blocks resulted in less consistent compression pressure, it can reduce the strength and overall performance of the blocks. Therefore, finding an optimum fibre quantity is important in manufacturing on-site CEBs.

After the blocks were removed from the hydraulic press they were transported by hand to where they were stacked and dried. More than 94% of the blocks were manufactured intact without missing parts. However, because the blocks were still wet during this process, small parts of the blocks (especially at the corners) crumbled away resulting in loss of surface area in some of the CEBs (less than 6%). Also, pre-cracks formed in some of the fibre reinforced CEBs during the process of transporting and stacking.

4.2.4 Test Setup

A combination of compression and flexure tests were performed on the CEBs in the air-dry state and after being exposed to six and twelve freeze-thaw conditioning cycles, as shown in Table 4-2. Approximately 160 CEBs were tested in this investigation.

Table 4-2: CEB test repetitions and arrangements

Block Type	2-Block Prism Compression			Flexure			No. Blocks Tested
	No. Freeze Thaw Cycles			No. Freeze Thaw Cycles			
	Zero (0)	Six (6)	Twelve (12)	Zero (0)	Six (6)	Twelve (12)	
R	3	3	3	3	3	3	27
G-0.25	3	3	3	3	3	3	27
S-0.125	3	-	-	3	-	-	9
S-0.25	3	-	-	3	-	-	9
S-0.75	3	-	-	3	-	-	9
RH-0.25	3	3	3	3	3	3	27
RH-0.50	3	3	3	3	3	3	27
RH-0.75	3	3	3	3	3	3	27
No. Blocks Tested	48	30	30	24	15	15	162

In Table 4-2, the block type is described using "R" for the reference block with no fibre, "G" for the blocks containing switchgrass, "S" for the blocks containing straw, and "RH" for the blocks containing rice hulls.

4.2.5 Unconfined Compression

CEBs are commonly tested with the same standards as concrete and fired-clay brick masonry (Mak, MacDougall and Fam 2015). A Forney Testing Machine with a capacity of 2224 kN, shown in Figure 4-5, was used to test the CEBs in uniaxial compression. The CEBs were stacked unbonded, in prisms of two, and tested under uniaxial compression in accordance with ASTM C140 (ASTM 2018) and ASTM C1314 (ASTM 2012). The prisms were capped with 3 mm thick sheets of plywood.

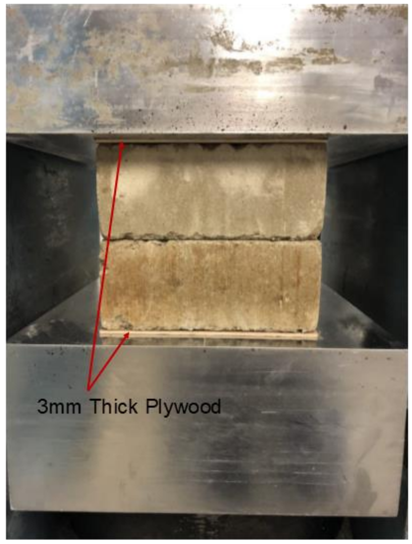


Figure 4-5: Uniaxial compression test set up

Pressure was applied at a rate of 0.25 MPa/s until failure as determined in a previous study using similar on-site manufactured CEBs (Mak, MacDougall and Fam 2015). The compressive strength, f_{CEB}, of the prism was calculated using Equation 1.

$$f_{CEB} = \frac{P_{failure}}{A} \tag{1}$$

where f_{CEB} is the ultimate compressive strength of the prism (MPa), $P_{failure}$ is the peak load at failure (N), and A is the original surface area to which the load was applied (mm^2).

4.2.6 Flexure

The tests were conducted according to ASTM C67-07 (ASTM 2007) with a modification from loading the block at third points to loading the block at the midpoint. The block was loaded in three-point bending, as shown in Figure 4-6. The load was applied through a steel plate and a 30 mm diameter roller that were placed on the block at midpoint. The CEBs rested on two steel plates and rollers positioned 25 mm from each end of the blocks resulting in an unsupported span of 305 mm. The dimensions of each block were measured and recorded before each test, and lines were drawn at the centre of each dimension to ensure symmetrical loading. The blocks were loaded at a constant displacement rate of 0.25 mm/min until failure, and the peak applied load for each test was recorded in kilonewtons.

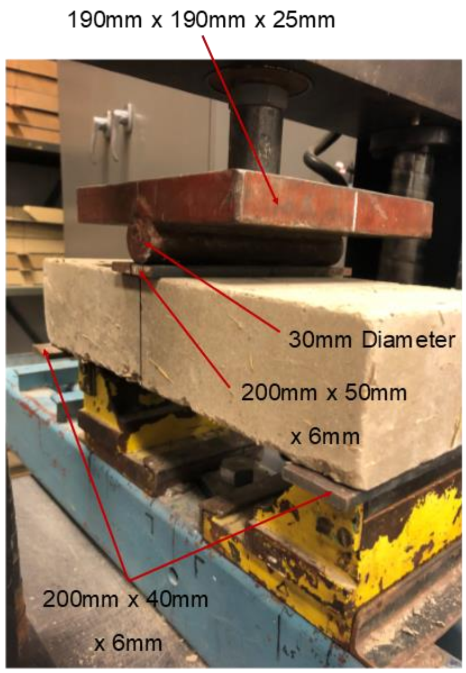


Figure 4-6: Three-point bending test set up

The flexural strength of the blocks, fr_{CEB}, was calculated using Equation 2. The moment induced at the mid-span (M) of the block was calculated given the peak applied force using Equation 3, and the moment of inertia ($I_{N/A}$) of each block was calculated given the measured width and height of the CEBs using Equation 4.

$$fr_{CEB} = \frac{M*C}{I_{N/A}} \tag{2}$$

where,

$$M = \frac{P_{failure}*L}{4} \tag{3}$$

$$I_{N/A} = \frac{bh^3}{12} \tag{4}$$

and C is the distance from the neutral axis to the extreme fibre in tension (half the block thickness).

4.2.7 Freeze-Thaw Conditioning

The CEBs were subjected to freezing and thawing in an environmental chamber in accordance with a previous study (Mak, MacDougall and Fam 2016) and ASTM D560 (ASTM 1996). The blocks were placed inside the environmental chamber on a support system that was fabricated inside a tub with dimensions five feet wide, twelve feet long, and two feet deep (see Figure 4-7). The support system was constructed from sheets of plywood for the base, vapour barrier, and strapping around the edges to create a tray. Felt sheets were placed on top of the vapour barrier, and the CEBs were placed on top of the felt sheets such that the entire base of the CEBs were covered by felt. A constant supply of water was manually added to the trays via a garden hose such that the water level was enough to fully saturate the felt sheets, however, the water level did not exceed the height of the felt pads. This ensured water absorption via capillary action.

Figure 4-7: Freeze-thaw conditioning test set up: a) and b) CEBs in plywood trays, and c) drying

CEBs were exposed to six and twelve 48-hour freeze-thaw cycles, consisting of a 23-hour thaw period at a temperature of +23°C, a 24-hour freeze period at a temperature of -30°C, and 1 hour of transition. Mass was recorded prior to and after the six and twelve cycling periods. The environmental chamber and freeze-thaw conditioning setup was the same as that used as the study conducted by Mak, MacDougall and Fam (2016), as well as CEBs constructed using similar soil from the same location and manufacturer. Figure 4-8 from Mak, MacDougall and Fam (2016) shows the ASTM freeze-thaw requirements, recorded room temperatures, and internal temperatures of the blocks. Because of time constraints caused by various factors outside of the author's control, thermocouple measurements for internal CEB temperature were not included. Since the environmental chamber was programmed to run at the same time intervals and temperatures as the previous study (Mak, MacDougall and Fam, Freeze-Thaw Performance of On-Site Manufactured Compressed Earth Blocks: Effect of Water Repellent and Other Additives 2016), it was assumed that CEB internal temperature measurements would be comparable.

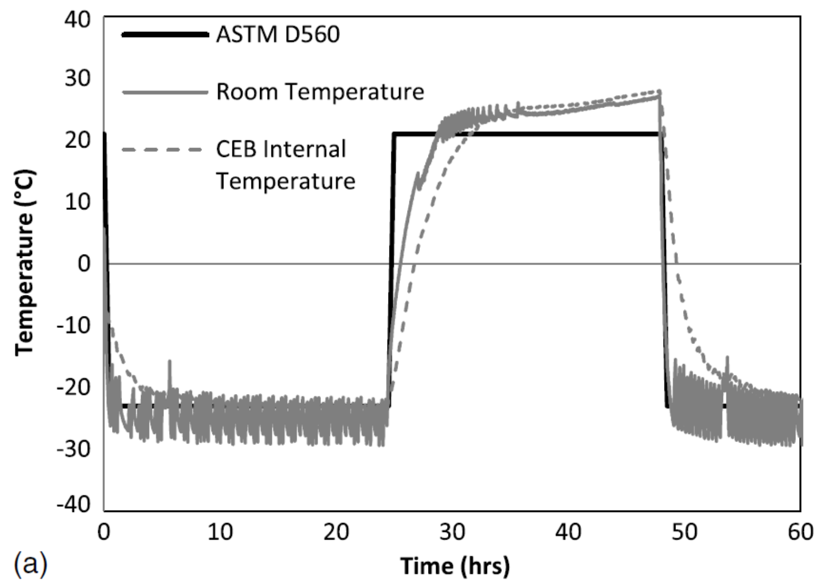


Figure 4-8: Freeze-thaw cycle temperature conditions (Mak, MacDougall and Fam, Freeze-Thaw Performance of On-Site Manufactured Compressed Earth Blocks: Effect of Water Repellent and Other Additives 2016)

ASTM D560 (ASTM 1996) requires flipping of the blocks at the beginning of each freeze cycle. As with Mak, MacDougall, and Fam's (2016) study, it was impractical to flip and restack all blocks in between cycles because of the nature of the test setup. Additionally, Mak, MacDougall, and Fam's (2016) study found that the difference in strength of flipped and non-flipped specimens that did not include a water repelling admixture (Plasticure) was not statistically significant at the 95% confidence level. Only the flipped specimens containing Plasticure had a statistically significant higher strength retention than their non-flipped counterparts (Mak, MacDougall and Fam 2016). Finally, when considering the configuration of CEBs in practical building applications, once the CEBs are cast into a wall system they are not flipped in between every freeze-thaw cycle occurring naturally in the environment. Therefore, the CEBs were not flipped between the freeze-thaw cycles.

After the freeze-thaw cycles were complete, the CEBs were removed from the environmental chamber and placed on pallets to dry (see Figure 4-7c). Blocks were placed at a minimum of 50 mm apart, and two fans were used to circulate airflow between specimens. Specimens were dried in the lab using this configuration for 21-30 days, after which the blocks were considered at ambient conditions and were tested in compression and in flexure using the same procedures as Sections 4.2.5 and 4.2.6. In this case, "ambient conditions" refers to a moisture content of around 2%, which was the moisture content observed in samples of the blocks prior to freeze-thaw cycling reported in Table 4-1.

4.3 Experimental Results and Discussion

Multiple samples were tested for each type of block used in this investigation. The strength results of each test have been reported as average values with the associated standard deviation, indicated by the "±" symbol following the average value. Appendix B presents the complete database of test results from all test conducted in this investigation.

Freeze-thaw conditioning was applied only to the reference (no fibre) blocks, 0.25% switchgrass blocks, and the 0.25%, 0.50% and 0.75% rice hull blocks. Many of the straw blocks were damaged prior to arrival at the lab. Enough blocks were intact to use for the un-conditioned tests, however, there were not enough intact straw blocks to use in the freeze-thaw conditioning component of this thesis. Only the results from the five previously mentioned block mixes will be presented and discussed in terms of freeze-thaw durability.

4.3.1 Analysis of Variance (ANOVA) of Block Properties

The length, width, and height showed low variability between blocks in the same batch because the blocks were compressed in a mould (Table 4-1). A one-way analysis of variance (ANOVA) was used to assess the statistical significance of batch to batch variability of the length, width, height, and density measurements. The results are presented in Table 4-3. The null hypothesis was that the results from difference groups were from the same statistical population.

Table 4-3: Analysis of variance of CEB properties

Parameter	X	SSW	SSB	MSW	MSB	DF (W,B)	F	$F_{critical}$ (F0.05)	Result	Conclusion
Height	75.10	12.00	39.83	0.75	5.69	(16,7)	7.59	2.66	Reject	Significant
Length	353.38	8.67	12.96	0.54	1.85	(16,7)	3.42	2.66	Reject	Significant
Width	178.04	12.67	6.29	0.79	0.90	(16,7)	1.14	2.66	Accept	Not
Density	2102.87	28000.25	93998.13	1750.02	13428.30	(16,7)	7.67	2.66	Reject	Significant

In Table 4-3, X represents the mean of all specimens, SSW is the sum of squares within the group, SSB is the sum of squares between groups, MSW is the mean sum of squares within the group, MSB is the mean sum of squares between groups, DF is degree of freedom, F is f ratio, and $F_{critical}$ is the critical value of F taken at the 95% confidence level. The null hypothesis was rejected when F was greater than $F_{critical}$ indicating a significant difference in the results.

The ANOVA showed that the batch to batch variability of the length, height, and density was statistically significant. The addition of fibres had a significant impact on the height and density of the blocks. CEBs produced with fibres, and especially greater quantities of fibres, had significantly lower densities then the blocks produced with no-fibres. The blocks produced with 0.75% straw fibres had significantly larger block heights than the no-fibre and lower quantities of fibre blocks. Block length was also significantly affected by the addition of fibres; blocks produced with larger quantities of fibres had significantly larger lengths than blocks produced with no fibres or lower quantities of fibres.

It is important to note that this analysis of variance is based on the results of three specimens for each block type and not on every block tested in the investigation. In future work, more measurements should be included to potentially obtain more accurate variability.

4.3.2 Aspect Ratio Correction Factors for Compressive Strength

As the aspect ratio (h/t) of CEB prisms increase, the measured compressive strength will decrease. To obtain strength values that are representative of in-situ CEB masonry, an aspect ratio correction factor is used. Correction factors reduce the measured strength of CEB prisms with aspect ratios less than five and convert the strengths to an equivalent prism size with an aspect ratio greater than five. There are two methods of determining correction factors based on aspect ratio; Krefeld (Krefeld 1938) brick masonry prisms and Heathcote and Jankulovski (Heathcote and Jankulovski 1992) for soilcrete block prisms. Although both methods are based on nonlinear relationships between the correction factor and the aspect ratio, it is important to note that Krefeld correction factors are given for specific aspect ratio values. Other Krefeld correction factors can be linearly interpolated between these values as follows:

$$K_a = \begin{cases} 0 - 0.5 \; for \; 0 \leq A_r \leq 0.4 \\ 0.5 - 0.6 \; for \; 0.4 \leq A_r \leq 0.7 \\ 0.6 - 0.7 \; for \; 0.7 \leq A_r \leq 1.0 \\ 0.7 - 0.85 \; for \; 1.0 \leq A_r \leq 3.0 \\ 0.85 - 1.0 \; for \; 3.0 \leq A_r \leq 5.0 \\ 1.0 \; for \; A_r > 5.0 \end{cases} \tag{5}$$

where, K_a denotes the calculated correction factor and A_r denotes the aspect ratio.

The Heathcote and Jankulovski correction factors can be calculated using the following equation:

$$K_a = 10.1\left(8.9 + \frac{8.0}{A_r^{1.2} - 0.061}\right)^{-1} \tag{6}$$

Table 4-4 provides aspect ratios for the varying block types based on block height and corresponding correction factors for both the linearly interpolated Krefeld method and the Heathcote and Jankulovski equation. The aspect ratio was calculated using the height of the prism (two times the block height) divided by the width of the blocks.

Table 4-4: Aspect ratio and Krefeld (1938) and Heathcote and Jankulovski (1992) correction factors with uncorrected and corrected strength values for 0, 6, and 12 freeze-thaw cycles

No. Cycles	Block Type	Uncorrected Strength (MPa)		Aspect Ratio	Heathcote & Jankulovski's Method			Krefeld's Method		
					Correction Factor	Corrected Strength (MPa)		Correction Factor	Corrected Strength (MPa)	
		Average	SD			Average	SD		Average	SD
0	No Fibre	8.22	0.13	0.78	0.51	4.22	0.07	0.63	5.15	0.08
	0.25% Switchgrass	8.27	0.77	0.83	0.54	4.45	0.42	0.64	5.33	0.50
	0.125% Straw	8.96	0.71	0.83	0.54	4.81	0.38	0.64	5.77	0.45
	0.25% Straw	8.84	0.60	0.83	0.54	4.75	0.33	0.64	5.70	0.39
	0.75% Straw	6.98	0.19	0.89	0.56	3.90	0.11	0.66	4.62	0.13
	0.25% Rice Hulls	7.95	0.24	0.83	0.54	4.27	0.13	0.64	5.12	0.15
	0.50% Rice Hulls	8.06	0.28	0.83	0.54	4.33	0.15	0.64	5.20	0.18
	0.75% Rice Hulls	7.18	0.32	0.83	0.54	3.86	0.17	0.64	4.63	0.20
6	No Fibre	11.09	1.38	0.78	0.51	5.70	0.71	0.63	6.94	0.86
	0.25% Switchgrass	8.98	0.94	0.83	0.54	4.83	0.50	0.64	5.79	0.61
	0.25% Rice Hulls	10.09	0.76	0.83	0.54	5.42	0.41	0.64	6.50	0.49
	0.50% Rice Hulls	10.05	0.44	0.83	0.54	5.40	0.24	0.64	6.48	0.28
	0.75% Rice Hulls	8.53	0.64	0.83	0.54	4.58	0.34	0.64	5.50	0.41
12	No Fibre	10.02	0.82	0.78	0.51	5.15	0.42	0.63	6.27	0.51
	0.25% Switchgrass	9.28	0.56	0.83	0.54	4.99	0.30	0.64	5.98	0.36
	0.25% Rice Hulls	9.63	0.30	0.83	0.54	5.17	0.16	0.64	6.21	0.20
	0.50% Rice Hulls	9.21	0.72	0.83	0.54	4.95	0.39	0.64	5.93	0.46
	0.75% Rice Hulls	7.80	0.61	0.83	0.54	4.19	0.33	0.64	5.03	0.40

4.3.3 Effect of Fibre Type and Quantity on Compressive Strength

This section presents and discusses the results of the unconfined compressive test, outlined in Section 4.2.5, performed on all eight block mixes not subjected to any freeze-thaw conditioning (0 cycles). Three test repetitions were performed for each of the block mixes and the results are presented in Table 4-4 as average values with the associated standard deviation of all test repetitions with and without aspect ratio correction factors.

Figure 4-9 presents the average compressive strength obtained by each of the eight block mixes not subjected to freeze-thaw. The figure provides the results as uncorrected values (the measured strength of the prism) and with the two methods of determining corrected strengths as discussed in Section 4.3.2.

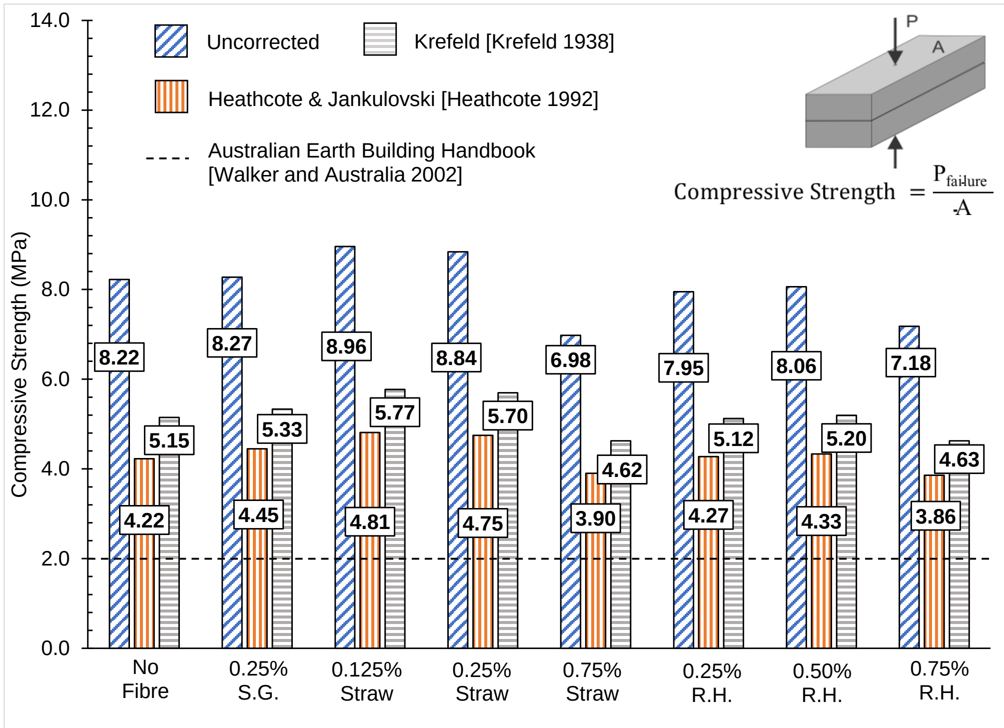


Figure 4-9: Results of unconfined compression tests showing uncorrected strength values, and corrected with Heathcote & Jankulovski (1992) and Krefeld (1938) correction factors for 0 freeze-thaw cycles

The two block mixes corresponding to the highest uncorrected compressive strengths were found to be the 0.125% and 0.25% straw mixes with average strength values of 8.96 MPa and 8.84 MPa, respectively. This represented an increase in strength ranging from 8-9% from the reference block mix containing the same quantity of cement-lime stabilizer without any fibres, with an average strength of 8.22 MPa. The blocks from the 0.75% straw mix, which had an uncorrected average strength of 6.98 MPa, were approximately 21-22% lower in strength than the blocks from the other straw mixes, and 15% less than the strength of the reference block. This large decrease in strength can be attributed to the average density of the block, which was less than all other average block densities. From Table 4-

1, the 0.75% straw mix blocks had a density of 1978 ± 36 kg/m^3, whereas the 0.125% and 0.25% straw mixes had average densities of 2078 ± 54 kg/m^3 and 2165 ± 41 kg/m^3, respectively. This represented up to an 8.6% decrease in density between the three straw mixes and a 10.2% decrease in density from the reference block that had the highest density at 2203 ± 28 kg/m^3. Because of the large quantity of straw fibres added to the mixture, the machine was not able to compress the blocks as consistently or to as high of a pressure as the other mixes. The lower pressure achieved during block production resulted in lower compressive strength achieved in the laboratory, which was observed by the measured strength of the 0.75% straw mix blocks. The same fibre type (straw), when added in varying quantities obtained the most widely varying results, achieving both the highest and lowest strengths of all the blocks tested in the investigation.

The next lowest strength of 7.18 MPa was obtained with the 0.75% rice hull mix, having an average block density of 2093 kg/m^3. It is interesting to note that this is the largest density of the three rice hull mixes, with the 0.25% and 0.50% rice hull mixes having average block densities of 2092 kg/m^3 and 2086 kg/m^3, respectively. The range of average densities of blocks produced with rice hulls showed less variation than the range of average densities of blocks produced with straw fibres. There was less than 0.4% difference between the highest and lowest density values of the blocks produced with rice hulls. In this case, the fact that the rice hull fibres were much smaller and more uniform than the straw fibres allowed the 0.75% rice hull mix to be compressed consistently and with adequate pressure, giving more consistent average block densities than found for the straw fibre blocks.

The block mix containing 0.25% switchgrass had an average compressive strength of 8.27 MPa, which represented a decrease in strength of 6.4% when compared with the same quantity of straw and a decrease in strength of 7.7% when compared with the highest average compressive strength achieved by the 0.125% straw mix. However, the 0.25% switchgrass blocks had higher strength values than the

0.25% rice hull blocks by about 4%, and the reference block by 0.6%. These findings were consistent with what was expected given the results of the straw fibres. Since the switchgrass fibres had higher flexural stiffness than the straw fibres, it was reasonable that the corresponding compressive strength was slightly less. The less stiff nature of the straw allowed some deflection and deformation of the fibre during loading whereas the switchgrass fibres did not. The result was fibre pull-out or fracture at an earlier applied load than what might have been achieved with the straw fibres.

In general, the block types with larger fibres (straw and switchgrass) showed more variation in results than the reference block and those made with rice hulls. Figure 4-10 shows each of the three test repetitions along with the average uncorrected strength and the standard deviation bars for each of the eight block types.

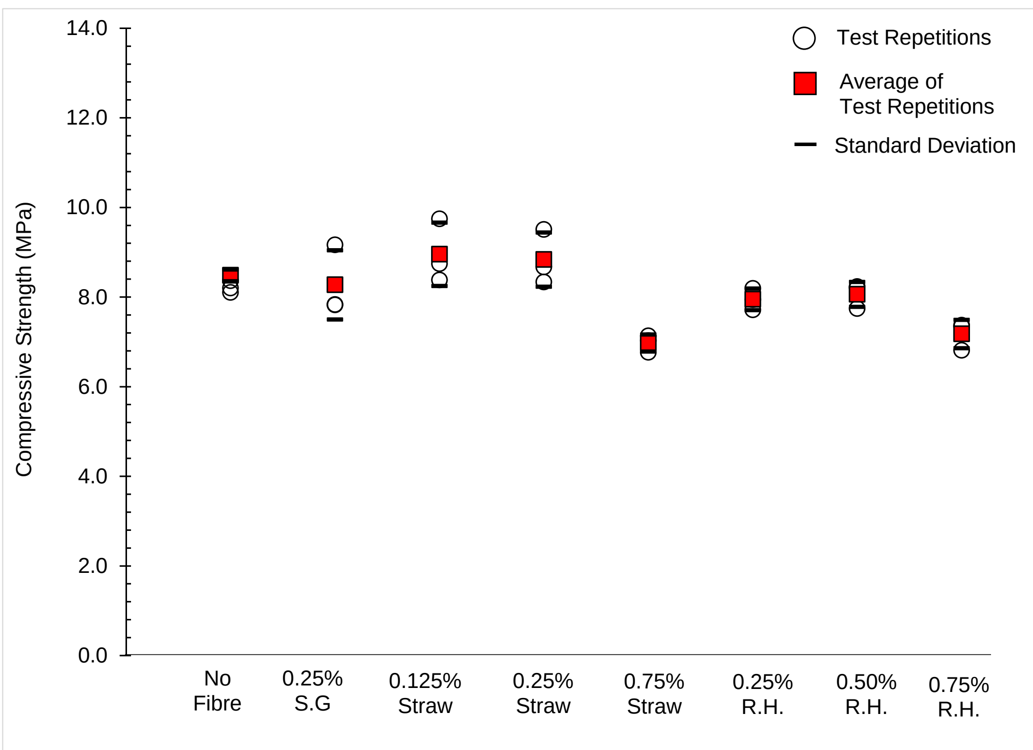


Figure 4-10: Individual test repetitions and average strength values with standard deviation bars for uncorrected compressive strength at 0 freeze-thaw cycles

Blocks that contained 0.25% switchgrass, 0.125% straw, and 0.25% straw showed the most variation in results despite obtaining some of the largest average compressive strengths of all the blocks tested. When considering standard deviations and the associated strength ranges of the switchgrass and straw blocks, the performance of the 0.25% and 0.50% rice hull blocks were found to be considered comparable to that of the switchgrass and straw blocks. The blocks with the rice hulls displayed much more consistent strengths than the blocks with the other two types of fibres. The reason for the lower variability in the no-fibre and rice hull blocks was again be attributed to the production phase and the machine's ability to compress the blocks at a constant pressure, increasing the likelihood of producing uniform CEBs. The rice hull fibres were small and relatively uniform when compared to straw and switchgrass fibres (Figure 4-3) therefore the machine was able to apply constant and consistent pressure to the mix when compressing the blocks, similar to producing the block mix with no fibres. With the addition of larger and stiffer fibres, the pressure at which the blocks were compressed became more varied, which resulted in more variation in measured strength values. It is interesting to note however, that the 0.75% straw blocks also showed low variability between the three test repetitions. While this seems to contradict the previous statement as to why straw and switchgrass blocks have larger variability between test repetitions, it is important to note that in addition to having low variability this block mix achieved consistently lower strengths than the other seven block mixes. There are a few reasons why the variability was low. Firstly, since the blocks were manufactured on-site many variables are difficult to control as opposed to producing blocks in a laboratory setting. For example, during the production of this block mix it is possible that the pressure was consistent over the six blocks produced and used in this test (out of a total of about 30 blocks produced for this mix type) but due to the large volume of fibres the pressure was consistently lower than the pressure used to compress other block mixes. This would result in consistently lower strengths achieved in comparison to the other block mixes, as is the case in Figure 4-10. Another reason for this low variability could be the amount of test repetitions. Because only three test repetitions were completed for each block mix, it is likely that increasing the amount of test repetitions would affect the measured variability of results achieved. Increasing the amount of test repetitions to include a larger bank of data is something that could be examined further in future work.

The blocks generally had a conical failure mode, as shown in Figure 4-11. The corners and edges of the blocks began to show visible cracking at around 200-300 kN of applied load, which was roughly 50% of the load obtained at final block failure.

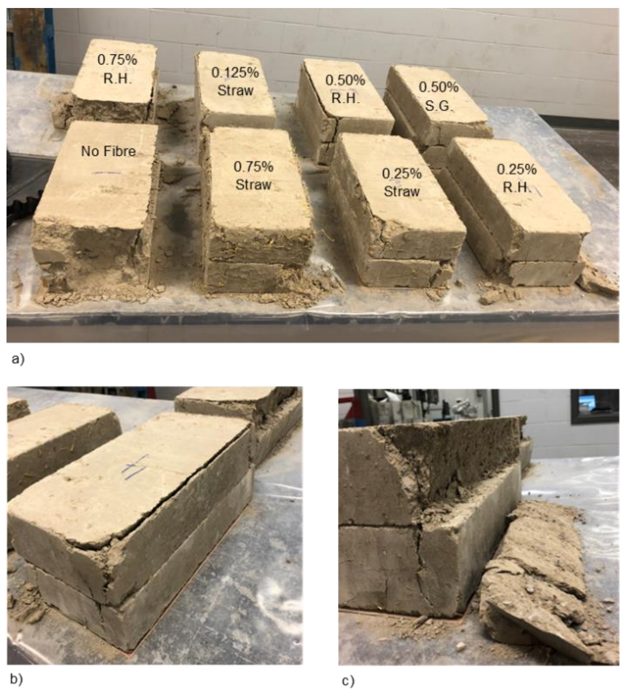


Figure 4-11: Failure modes in compression of block mixes not subjected to freeze-thaw: a) all block types, b) and c) edge of block failure for 0.25% rice hull mix

At failure, many cracks were observed around the corners and edges of the blocks with usually one or two larger cracks that appeared to have caused the failure. Often entire sides of blocks separated from the prism as shown in Figure 4-11. More visible damage was observed in the reference blocks and the blocks produced with rice hull fibres. This damage was attributed to the fact that the longer fibres such as straw and switchgrass helped to hold the block together by bridging cracks as they developed and propagated. The rice hull fibres were shorter than the straw and switchgrass fibres so the ability of the rice hulls to control cracking was limited to smaller cracks that were less likely to be the cause of failure. Figure 4-12 shows a lone fibre bridging a crack as it widened, until the fibre pulled out from the block matrix. This crack bridging phenomenon can improve compressive strength of the prisms, as observed by the results of the 0.125% and 0.25% straw mixes, however, having a fibre quantity that is too high can actually cause a loss in strength, which was also observed by the data.

Figure 4-12: Fibre bridging crack during widening of crack during loading

It is important to note that blocks with more visible damage, such as the no-fibre block, did not necessarily have lower strength. From Figure 4-11, the 0.75% straw block had less visible damage than the reference block with no fibre, however, as was previously discussed the reference block had a higher uncorrected compressive strength than the 0.75% straw block by about 22%.

In addition to uncorrected (actual) strengths, Figure 4-9 also presents strengths obtained using the Krefeld (1938) and Heathcote and Jankulovski (1992) aspect ratio correction factors. As previously discussed, the correction factors were used to find equivalent prism strengths for prisms with larger aspect ratios. Therefore, the corrected results provide more realistic strength values to what would be expected in a wall, as opposed to strength values which are measured from prisms of two in a laboratory. A decrease in strength of 35-37% from the measured strength was observed when Krefeld correction values were used, and a decrease in strength of 44-49% was observed when Heathcote and Jankulovski correction factors were used. In addition to being a more conservative design, Heathcote and Jankulovski used an equation to estimate a correction factor, as opposed to Krefeld's method that linearly interpolates between correction factors for given aspect ratios. Both methods however, resulted in compressive strength values that exceeded the acceptable limit of 2.0 MPa given in the Australian Earth Building standards by a safety factor of at least 1.93 (Walker and Australia 2002) and the limit of 2.07 MPa given in the International Building Code by a safety factor of at least 1.86 (International Code Council 2006).

4.3.4 Statistical Significance of Fibres on Compressive Strength

A one-way analysis of variance (ANOVA) was used to assess the statistical significance of the effect of adding fibres on the compressive strength of the CEBs. The null hypothesis was that the results from difference groups were from the same statistical population. Table 4-5 summarizes only the results that were found to be statistically significant, and a complete summary table with all ANOVA results is provided in Appendix B.

Table 4-5: Statistically significant results using ANOVA for effect of fibres on compressive strength

Sample Groups	X	SSW	SSB	MSW	MSB	DF	F	$F_{critical}$ ($F_{0.05}$)	Result	Conclusion
(0, 0.75 S)	7.60	0.11	2.33	0.03	2.33	(4,1)	86.61	7.71	Reject	Significant
(0, 0.75 RH)	7.70	0.24	1.63	0.06	1.63	(4,1)	27.64	7.71	Reject	Significant
(0.25 RH, 0.75 RH)	7.56	0.32	0.89	0.08	0.89	(4,1)	11.22	7.71	Reject	Significant
(0.50 RH, 0.75 RH)	7.62	0.36	1.18	0.09	1.18	(4,1)	13.13	7.71	Reject	Significant
(0.125 S, 0.75 S)	7.97	1.06	5.90	0.27	5.90	(4,1)	22.22	7.71	Reject	Significant
(0.25 S, 0.75 S)	7.91	0.81	5.21	0.20	5.21	(4,1)	25.68	7.71	Reject	Significant

In Table 4-5, X represents the mean of all specimens of the sample groups, SSW is the sum of squares within the group, SSB is the sum of squares between groups, MSW is the mean sum of squares within the group, MSB is the mean sum of squares between groups, DF is degree of freedom, F is f ratio, and $F_{critical}$ is the critical value of F taken at the 95% confidence level. The null hypothesis was rejected when F was greater than $F_{critical}$ indicating a significant difference in the results.

The results of the ANOVA show that the decrease in strength observed with both the 0.75% rice hull and 0.75% straw blocks was statistically significant when compared with the no-fibre blocks. There was no significant difference in strength between the no-fibre blocks and blocks produced with the two lower quantities of straw and rice hulls, and the CEBs produced with switchgrass. There was also no significant difference between the 0.125% and 0.25% straw, the 0.25% and 0.50% rice hulls, or the 0.25% straw, 0.25% switchgrass, and 0.25% rice hulls, which suggested that regardless of the physical attributes of the fibre (size, shape, density, stiffness, etc.), the quantity of fibres added had a greater impact on the compressive strength of the CEBs. This suggests that adding fibres in quantities up to 0.25% for larger and stiffer fibres such as straw and switchgrass and up to 0.50% for smaller and more uniform fibres such as the rice hulls is the most efficient way to improve compressive strength.

4.3.5 Effect of Fibre Type and Quantity on Flexural Strength

This section presents and discusses the results of the three-point bending test, as outlined in Section 4.2.6, performed on all eight block mixes not subjected to any freeze-thaw conditioning (0 cycles). Three test repetitions were performed for each of the block mixes. Figure 4-13 shows each of the three test repetitions along with the average flexural strength and standard deviation bars obtained for each of the eight block mixes tested in this investigation.

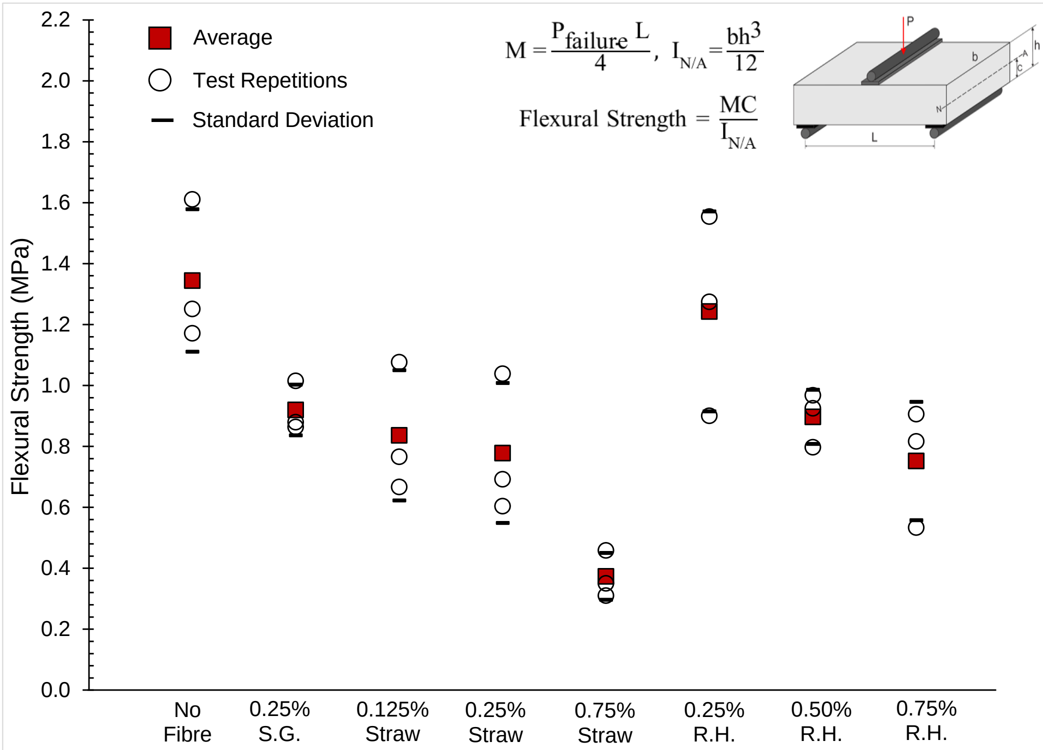
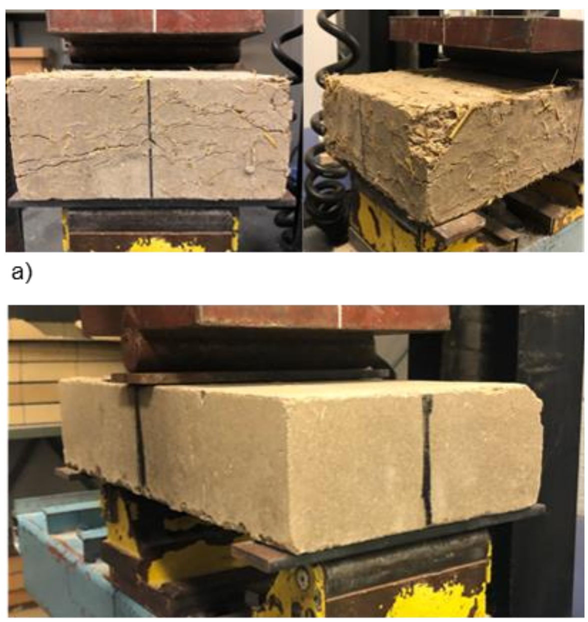


Figure 4-13: Results of three-point bending test on CEBs not subjected to freeze-thaw with each of the three test repetitions, average, and standard deviation bars

The block mix with the highest strength was the no-fibre mix, which had an average flexural strength of 1.34 MPa. The 0.25% rice hull mix had an average flexural strength of 1.24 MPa and was the second-best performing block with a 7.5% decrease in strength from the no-fibre mix. The remaining six block types obtained strengths that were at least 26% less than the 0.25% rice hull mix, which indicates that the larger fibres, as well as larger fibre quantities, may have had a negative effect on the flexural strength of the blocks, as opposed to the positive effect observed on compressive strength.

The block mix that obtained the lowest strength was the 0.75% straw mixture, which had an average flexural strength of 0.37 MPa. This represented a decrease in strength of 72% from the no-fibre block and a decrease in strength of 53-56% from the other two straw mixes which had average flexural strengths of 0.84 MPa and 0.78 MPa for the 0.125% and 0.25% straw mixes, respectively. This large decrease in strength was attributed to pre-cracks and other imperfections that occurred during production of the blocks. Pre-cracks, shown in Figure 4-14a, developed because of the high quantity of fibres added to the mixture during production. As previously discussed, with this quantity of fibre the machine was unable to apply adequate pressure to the mixture and upon transferring the blocks to the pallet, the wet soil in the block allowed the fibres to shift causing the bond to weaken and cracks to develop before the block began to cure. This weakened the ability of the blocks to resist loading in three-point bending, thus large decreases in strength were observed when compared to the blocks with lower or no fibres added. Figure 4-14 compares the physical appearance of the 0.75% straw block mix with the no-fibre block mix prior to applying load in three-point bending.



a)

b)

Figure 4-14: Visual assessment of CEBs prior to applying load showing: a) Blocks produced with 0.75% straw with many pre-cracks, and b) Blocks produced with no-fibres with no pre-cracks

The blocks constructed with no fibres had virtually no pre-cracks prior to applying any load, even though there were some slight imperfections around the corners and edges. The loose and missing material around the corners and edges of the blocks did not have as large of an impact on the flexural capacity of the blocks as the presence of pre-cracks, which was observed from the strength results in Figure 4-13.

When comparing the average flexural strengths of the 0.75% straw with the 0.75% rice hulls, which had a strength of 0.75 MPa, the straw mix obtained 51% less strength than that of the same quantity of rice hulls. Similar to the results observed in compression, the flexural strengths of the 0.75% straw blocks were consistently lower than the other seven block mixes, with a lower variability in results as well. It was also noted, in Figure 4-13, that all eight block mixes had higher variabilities than those observed from the compression tests and there appeared to be no specific fibre type or quantity that resulted in a lower variability of results, apart from the 0.25% switchgrass, 0.75% straw, and 0.50% rice hulls which did show slightly less variation between results than the other mixes.

Once the blocks reached failure they were removed from the machine and separated by hand to visually inspect the interior failure surfaces of the CEBs. Consistent with the findings in Chapter 3, the larger aggregate particles in the blocks had a greater effect on the capacity of the blocks when compared with the fibres. This is due to better bond achieved from the aggregate to soil particles than with the fibre to soil particles. Figure 4-15 shows the interior of a block containing 0.25% rice hulls after failure, where a larger aggregate particle was fractured most likely resulting in block failure.

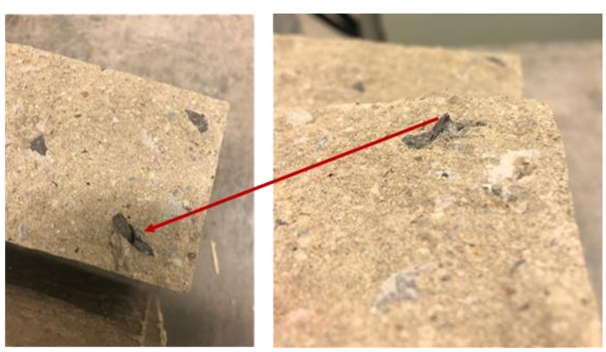


Figure 4-15: CEB with 0.25% rice hull fibres with larger aggregate particle rupture

Using smaller fibre sizes and lower fibre quantities resulted in more of the block volume composed of soil and cement than blocks with higher quantities of fibres or larger fibre sizes. This was observed visually, because the failure surfaces of the blocks with only 0.125% of straw looked more comparable to that of a concrete block than the failure surface of the blocks containing 0.75% straw fibres (Figure 4-16). From visual inspection, it appeared that the lower quantities of straw blocks, 0.125% and 0.25%, were able to cure more effectively than the 0.75% straw blocks which contained more loose soil on the interior than the other two block types.

a) b) c)

Figure 4-16: Visual assessment of failure surface for CEBs with a) 0.125% straw, b) 0.25% straw, and c) 0.75% straw

When the CEBs were loaded in three-point bending, the failure mode was generally a large flexural crack slightly off centre from the midspan of the block, as shown in Figure 4-17. Depending on the location, severity, and number of pre-cracks in the blocks before loading it was also possible to observe some shear cracks while load was being applied. Although shear cracks did develop simultaneously with the flexural cracks, it was usually the flexural crack that caused failure.

Figure 4-17: Typical failure mechanism for CEBs with fibres in three-point bending

Blocks produced with fibres, such as those shown in Figure 4-17, remained whole after the failure load was reached. In these cases, the blocks continued to deflect at midspan without supporting any additional load. Blocks constructed without fibres broke once the failure load was reached such that no additional deflection occurred, as shown in Figure 4-18. Thus, the fibres introduced some deformability into the failure modes of the specimens.

Figure 4-18: Typical failure mechanism for CEBs without fibres in three-point bending

While it is clear from Figure 4-18 that the block had failed and no longer supported any additional loads or deflections, most of the blocks that contained some quantity of fibre continued to deflect after failure load was reached. This behaviour should be further examined by using linear potentiometers (LPs) to measure the deflection of the CEBs at midspan and comparing it with the applied load using a load versus deflection curve. The load versus deflection curve should then be compared to similar investigations completed on other building materials such as masonry and concrete to compare similarities and differences between the performance of the different materials.

4.3.6 Statistical Significance of Fibres on Flexural Strength

A one-way analysis of variance (ANOVA) was used to assess the statistical significance of the effect of adding fibres on the flexural strength of the CEBs. The null hypothesis was that the results from difference groups were from the same statistical population. Table 4-6 summarizes only the results that were found to be statistically significant, and a complete summary table with all ANOVA results is provided in Appendix B.

Table 4-6: Statistically significant results using ANOVA for effect of fibres on flexural strength

Sample Groups	X	SSW	SSB	MSW	MSB	DF	F	$F_{critical}$ ($F_{0.05}$)	Result	Conclusion
(0, 0.25 SG)	1.13	0.12	0.27	0.03	0.27	(4,1)	8.76	7.71	Reject	Significant
(0, 0.25 S)	1.06	0.22	0.48	0.05	0.48	(4,1)	8.94	7.71	Reject	Significant
(0, 0.75 S)	0.86	0.12	1.42	0.03	1.42	(4,1)	46.49	7.71	Reject	Significant
(0, 0.50 RH)	1.12	0.13	0.30	0.03	0.30	(4,1)	9.57	7.71	Reject	Significant
(0, 0.75 RH)	1.05	0.19	0.53	0.05	0.53	(4,1)	11.37	7.71	Reject	Significant
(0.75 S, 0.75 RH)	0.56	0.09	0.22	0.02	0.22	(4,1)	9.88	7.71	Reject	Significant
(0.125 S, 0.75 S)	0.60	0.10	0.32	0.03	0.32	(4,1)	12.45	7.71	Reject	Significant
(0.25 S, 0.75 S)	0.58	0.12	0.25	0.03	0.25	(4,1)	8.40	7.71	Reject	Significant

The decrease in flexural strength observed between the no-fibre block and the 0.25% switchgrass, 0.25% and 0.75% straw, and 0.5% and 0.75% rice hull blocks were found to be statistically significant at the 95% confidence level. It is interesting to note that the lowest quantity of blocks with both straw and rice hull fibres obtained strength values that were considered to be within the same statistical population (not statistically significant) as the blocks with no fibres, despite the fact that the 0.125%

straw had an average flexural strength that was less than the 0.25% switchgrass. From Figure 4-13, the variation within the group for the 0.25% switchgrass was less than the variation within the group for the 0.125% straw, which overlapped with the variation within the no-fibre block group. This is likely why the difference in strength between the no-fibre and 0.125% straw blocks was not statistically significant and the difference between no-fibre and 0.25% switchgrass was significant. Further tests should be conducted on more blocks with 0.125% to see if larger sample sizes would change the statistical conclusions. Also, ANOVA assumes that all groups have the same variability and thus the results need to be interpreted with caution in cases where the variability for one group is appreciably different from that of other groups.

The 50% decrease in strength from the 0.75% rice hull blocks to the 0.75% straw blocks was statistically significant at the 95% confidence level, but the difference in strength between the 0.25% straw, 0.25% switchgrass, and 0.25% rice hull blocks was not statistically significant. This suggests that unlike the findings of the effect of fibre on compressive strength, the physical attributes of the fibres might have influenced the flexural strength of the blocks when added in large quantities. This was observed by the statistically insignificant difference between the strengths observed in the three block types produced with different fibre types at the same quantity for the compressive strength results. The ANOVA also suggested that, similar to the trends observed with the compressive strength, the flexural strength of the blocks generally reduced as fibre quantity increased.

4.3.7 Mass Retention after Freeze-Thaw Cycles

This section presents and discusses the percentage of water absorbed during, and mass retained after subjecting five types of CEBs to six and twelve freeze-thaw cycles. Each CEB was weighed prior to being placed in the environmental chamber (at ambient conditions prior to freeze-thaw), immediately after being removed from the environmental chamber (wet), and 21-30 days after being removed from the environmental chamber (at ambient conditions after freeze-thaw). The mass retention and water absorbed during the six and twelve freeze-thaw cycles are summarized in Table 4-7 as average values with associated standard deviations.

Table 4-7: Mass retention and percent water absorbed after subjecting CEBs to six and twelve freeze-thaw cycles

Block Type	No. Freeze-Thaw Cycles	Mass Retention (%)		Water Absorbed during Freeze-Thaw Conditioning (%)	
		Average	SD	Average	SD
No Fibre	0	-	-	-	-
	6	97.3%	6.5%	7.49%	0.72%
	12	99.8%	0.7%	7.08%	0.85%
0.25% Switchgrass	0	-	-	-	-
	6	99.7%	1.7%	8.24%	1.08%
	12	99.9%	0.5%	8.50%	1.02%
0.25% Rice Hulls	0	-	-	-	-
	6	98.9%	0.3%	7.22%	0.44%
	12	100%	0.1%	8.45%	0.69%
0.50% Rice Hulls	0	-	-	-	-
	6	98.9%	0.8%	6.44%	0.63%
	12	99.3%	0.9%	8.08%	1.00%
0.75% Rice Hulls	0	-	-	-	-
	6	92.6%	8.2%	4.25%	1.68%
	12	98.0%	0.9%	7.09%	0.45%

For both the six and twelve cycles, nine specimens were placed in the chamber for each of the five mixes. The mass retention was calculated using the weights of the CEBs at ambient conditions before freeze-thaw and the weights of the CEBs at ambient conditions after freeze-thaw. The change in weight was divided by the initial weight for each of the nine blocks and the mass retention is provided in Table 4-7 as average values with associated standard deviations. The water absorbed during freeze-thaw was calculated using the weights of the CEBs at ambient conditions before freeze-thaw and the weights of the CEBs immediately after removal from the environmental chamber (while wet). The change in weight was divided by the initial weight for each of the nine blocks and the results are provided in Table 4-7 as average values with associated standard deviations.

For both six and twelve freeze-thaw cycles all block types retained greater than 90% of their original mass, with most of the block types retained greater than 97% of their original mass. It was also noted that while the blocks subjected to six freeze-thaw cycles had marginally higher mass retention, the standard deviations associated with those average values was generally higher than the blocks subjected to twelve cycles. This was explained by the amount of water that was manually added to the set up during freeze-thaw cycles. It was noticed during the first few cycles that the support system for the blocks was slightly uneven and water was pooling in some areas while other areas were completely dry. This imbalance mainly affected the no-fibre and 0.75% rice hull blocks that absorbed both more and less water across the nine specimens for each block type than the other types. Blocks that absorbed more water during the cycling process showed more visible damage and mass loss than those that did not (Figure 4-19).

a) b)

Figure 4-19: a) Visible damage and colour difference of 0.75% rice hull blocks, and b) Visible damage and deterioration around edges and corners of a block with no fibre

The same block type, 0.75% rice hulls, had varying levels of deterioration (Figure 4-19a). The darker colour of blocks 8-1 and 8-2 showed that those blocks absorbed more water during the six freeze-thaw cycles than the other blocks shown. Figure 4-19b shows a different type of block (without fibres) that had also absorbed more water than most of the other blocks and showed a large amount of visible mass loss around the corners and edges of the block. In general, the blocks showed the most deterioration at the base of the block where the water was absorbed from the felt sheets into the blocks via capillary action (Figure 4-20).

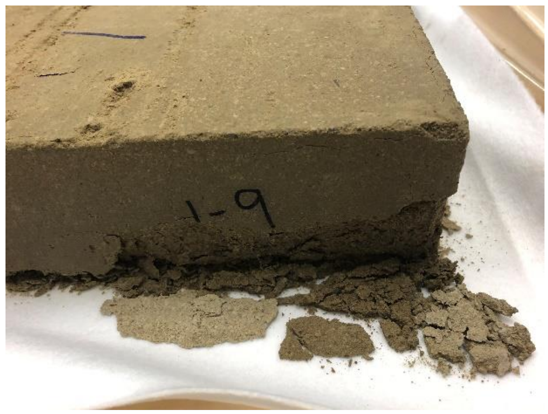


Figure 4-20: Block damage on base of no fibre block after exposure to six freeze-thaw cycles

On most of the CEBs some degree of mass loss was observed around the upper edges and corners of the blocks due to the moisture in the block expanding when freezing temperatures were reached. The expansion of water and moisture particles caused spalling of the soil to occur, shown in Figure 4-20. Because the imbalance of the support system, less water was added during the twelve cycles to avoid having uneven block damage as occurred during the six cycles. This resulted in the CEBs retaining more of their original mass even after more cycles. Based on the difference in water quantity that was added during the six and twelve freeze-thaw cycles, it is clear that the amount of water the blocks absorbed during the cycles had a large impact on the amount of mass retention.

4.3.8 Compressive Strength Retention after Freeze-Thaw Cycles

This section presents and discusses the results of the unconfined compressive test, outlined in Section 4.2.5, performed on the five block mixes subjected to six and twelve freeze-thaw cycles. Three test repetitions were performed for each of the block mixes and the results are presented in Table 4-4 as average values with the associated standard deviation of all test repetitions with and without aspect ratio correction factors. Figure 4-21 shows a graphical representation of the uncorrected compressive strength of the five block types that were subjected to the six and twelve freeze-thaw cycles, as well as the strengths from the same block types not subjected to freeze-thaw.

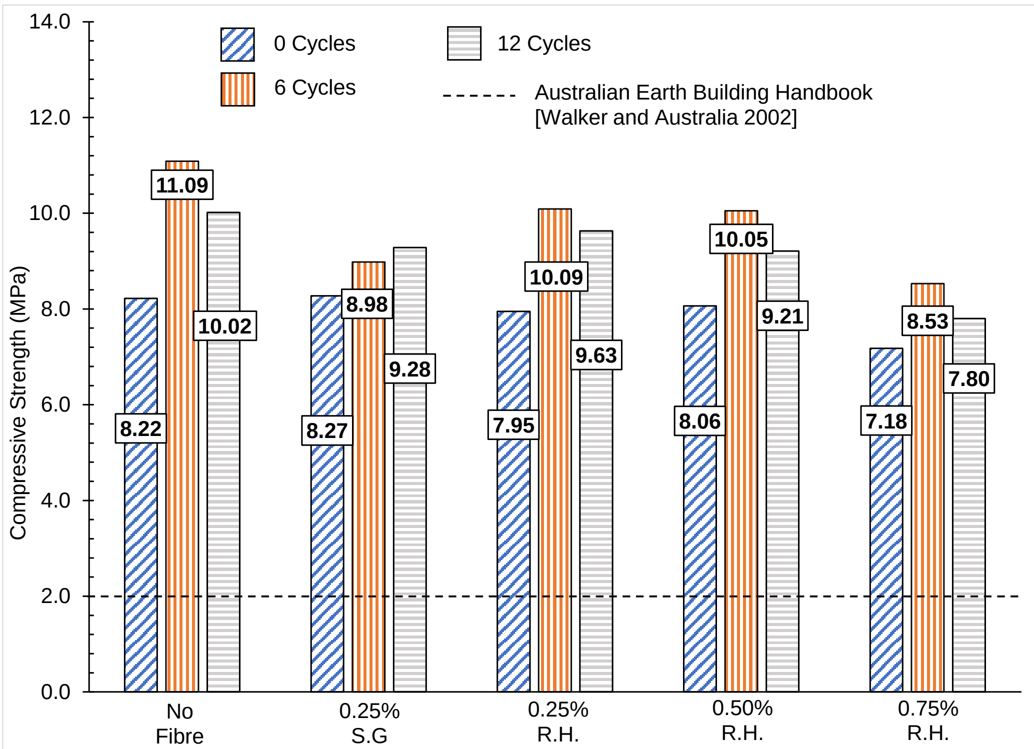


Figure 4-21: Uncorrected compressive strengths of five block types subjected to 0, 6, and 12 freeze-thaw cycles

The results from Figure 4-21 show that after being subjected to both six and twelve freeze-thaw cycles, the average compressive strength of all CEB types increased. The blocks containing no fibre had the highest average uncorrected strength of 11.09 MPa after six cycles, which was about 10% greater than the next highest strength of 10.09 MPa from the 0.25% rice hull mix also after six cycles. The blocks with no fibre also displayed the largest difference in strength between the blocks subjected to six freeze-thaw cycles and the blocks not subjected to freeze-thaw cycles. The average strength of the no fibre block after six freeze-thaw cycles was 35% greater than the average strength of the blocks not subjected to freeze-thaw. The average strength of the no fibre block after twelve freeze-thaw cycles was 22% greater than the average strength of the blocks not subjected to freeze-thaw. A full table showing compressive strength retention of the CEBs is provided in Appendix B.

The increase in strength after freeze-thaw could be attributed to the age of the blocks when tested. The blocks not subjected to any freeze-thaw cycles were tested about three months before the blocks subjected to six freeze-thaw cycles, and about four months before the blocks subjected to twelve freeze-thaw cycles. In future work, some room temperature specimens should be kept for testing at different times to compare any differences in strength observed. It is possible that the additional time between tests allowed the CEBs to develop more strength, however, similar results were also observed in a previous study by Mak, MacDougall, and Fam. This study observed strength retention values of up to 130% in blocks subjected to between three and twelve freeze-thaw cycles (Mak, MacDougall and Fam 2016). In the study, the authors suggested that the increased strength was attributed to the additional water which was added to the blocks during the freeze-thaw process that resulted in additional curing of the blocks. To further examine this theory, future research should include performing the tests outlined in Section 4.2.5 and Section 4.2.6 after the CEBs have been fully submerged in water for about twenty-four hours and then allowed to dry completely.

4.3.9 Flexural Strength Retention after Freeze-Thaw Cycles

This section presents and discusses the results of the three-point bending test, outlined in Section 4.2.6, performed on the five block mixes subjected to six and twelve freeze-thaw cycles. Two test repetitions were performed for each block type subjected to freeze-thaw cycles and three test repetitions were performed for each block type not subjected to freeze-thaw cycles (from Section 4.3.5). The results are presented graphically in Figure 4-22.

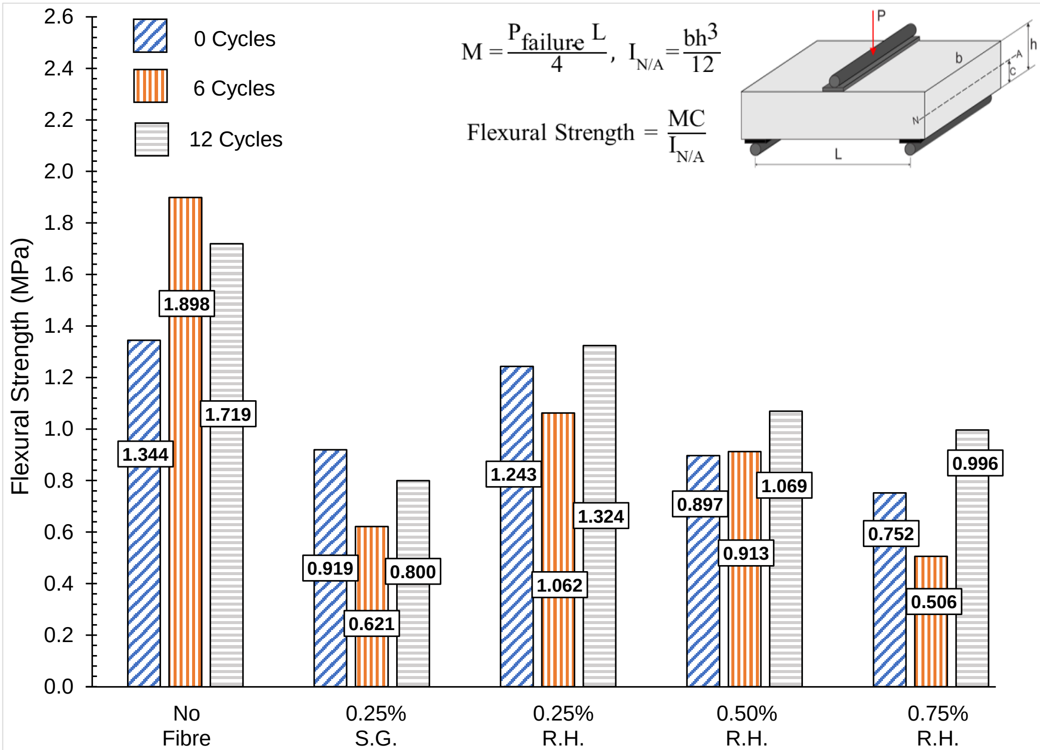


Figure 4-22: Average flexural strength from three-point bending test for CEBs subjected to 0, 6, and 12 freeze-thaw cycles

The average flexural strengths of the blocks were observed to both increase and decrease between the number of freeze-thaw cycles the CEBs experienced for each block type. The no-fibre blocks showed an increase in strength of 41% when subjected to six cycles and 30% when subjected to twelve cycles. The no-fibre block type was the only block type observed to have a six-cycle strength that was greater than the twelve-cycle strength. The remaining four block types, which all include fibres, had higher strength after twelve cycles than after six cycles. All rice hull blocks obtained twelve-cycle strengths that were also greater than the zero-cycle strengths, while the 0.25% switchgrass obtained twelve-cycle strengths that were less than the zero-cycle strengths. It is interesting to note that the average flexural strengths of the five CEBs tested in this part of the investigation followed a similar trend, which can be observed in Figure 4-22, but is better visualized in Figure 4-23.

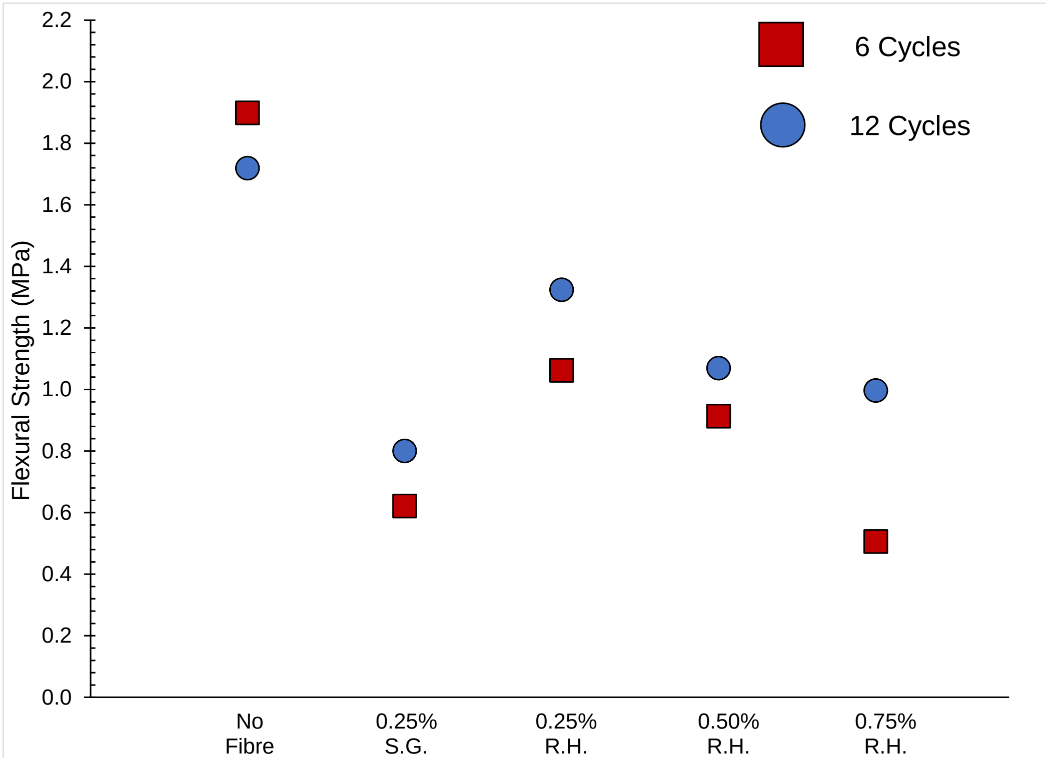


Figure 4-23: Average flexural strength from three-point bending for CEBs subjected to 6 and 12 freeze-thaw cycles

The addition of fibres decreased the flexural strength of the CEBs after freeze-thaw cycles. Varying levels of deterioration in the CEBs because of uneven water distribution may have resulted in the blocks with fibres having higher flexural strengths after twelve cycles than after six cycles. The twelve-cycles CEBs generally absorbed less water than the six-cycles, therefore slightly less damage was visually observed. The degree of damage of the CEBs prior to loading in three-point bending influenced the flexural capacity of the block. The decrease in strength of the CEBs with fibres after freeze-thaw cycling was attributed to additional voids in the blocks that were created when the fibres were added. Any additional water that entered the blocks could cause more cracking and damage to the blocks and potentially on the interior of the block when the water expanded at low temperatures. Interior cracking would not have been visible prior to loading but it could have a drastic effect on the flexural capacity of the block. Future work should consider SEM images of the blocks to try and observe such voids and damage.

4.3.10 Statistical Significance of Freeze-Thaw Cycles on Strength Retention

A one-way analysis of variance (ANOVA) was used to assess the statistical significance of the effect of subjecting CEBs to six and twelve freeze-thaw cycles on the compressive strength retention. The null hypothesis was that the results from difference groups were from the same statistical population. Table 4-8 summarizes only the results that were found to be statistically significant, and a complete summary table with all ANOVA results is provided in Appendix B. Because only two test repetitions were performed for the six and twelve freeze-thaw cycles in three-point bending, an ANOVA was not completed for flexural strength retention.

Table 4-8: Statistically significant results using ANOVA for effect of freeze-thaw on strength

Sample Groups	X	SSW	SSB	MSW	MSB	DF	F	$F_{critical}$ ($F_{0.05}$)	Result	Conclusion
(0-0, 0-6)	9.65	3.83	12.30	0.96	12.30	(4,1)	12.84	7.71	Reject	Significant
(0-0, 0-12)	9.12	1.39	4.84	0.35	4.84	(4,1)	13.95	7.71	Reject	Significant
(0.25 RH-0, 0.25 RH-6)	9.02	1.29	6.86	0.32	6.86	(4,1)	21.36	7.71	Reject	Significant
(0.25 RH-0, 0.25 RH-12)	8.79	0.30	4.23	0.08	4.23	(4,1)	56.38	7.71	Reject	Significant
(0.50 RH-0, 0.50 RH-6)	9.06	0.54	5.94	0.14	5.94	(4,1)	43.85	7.71	Reject	Significant
(0.75 RH-0, 0.75 RH-6)	7.85	1.02	2.75	0.26	2.75	(4,1)	10.73	7.71	Reject	Significant

The increase in compressive strength observed after no-fibre CEBs had been subjected to six and twelve freeze-thaw cycles was determined by the ANOVA to be statistically significant at the 95% confidence level. The increase in compressive strength observed after the 0.25% rice hull blocks were subjected to six and twelve freeze-thaw cycles was also determined to be statistically significant. Only the 0.5% and 0.75% rice hull blocks subjected to six cycles had significant increases in strength when compared with the same block type not subjected to any freeze-thaw cycles. The changes in compressive strength between the six and twelve cycles was not found to be significant in any of the block types. This suggests that the additional water absorbed by the blocks during the freeze-thaw cycles allowed additional curing of the CEBs resulting in increased strength. Additional studies should be conducted to consider this finding further.

It is also important to consider that the laboratory freeze-thaw cycles conducted in this thesis do not accurately replicate how freeze-thaw would occur in a practical application. Over the lifespan of a building, CEBs will be exposed to more than six or twelve freeze-thaw cycles, but also, will likely not absorb as much water as was shown in this investigation. In order to most accurately determine the effect of freeze-thaw on the CEBs, there is a need for a long-term test setup in which the blocks are constructed into a home and the effects of freeze-thaw over a longer time period are observed.

4.4 Summary

This chapter presented a series of tests completed on eight different CEB mixes produced with varying quantities of straw, switchgrass, and rice hulls. The CEBs were tested in both unconfined compression and three-point bending at ambient conditions and after having been subjected to six and twelve freeze-thaw cycles. Only the results of the no-fibre, 0.25% switchgrass, and 0.25%, 0.50%, and 0.75% rice hull mixes were presented in terms of freeze-thaw durability and mass retention due to damage that occurred to the pallets of straw blocks prior to arriving at the lab.

To summarize the conclusions of this chapter:

1. The quantity of fibre had a greater affect on the compressive and flexural strength of the CEBs than the fibre type when considering physical attributes of fibres (size, density, etc.). Having

too high of fibre quantity significantly reduced both the compressive and flexural strength of the CEBs as well as the ease and ability to produce them.

2. The optimum fibre content for fibres that were larger in size and had a greater flexural stiffness (straw and switchgrass) was in the range of 0% to 0.25% while the optimum fibre content for smaller and more uniform fibres (rice hulls) was in the range of 0% to 0.5%.
3. When water was absorbed by the CEBs during freeze-thaw cycles, significant increases in compressive and flexural strengths were observed, especially for CEBs containing no or low quantities of fibres.
4. The flexural strength observed in CEBs containing fibres appeared to generally decrease after being subjected to freeze-thaw cycles.
5. The amount of water absorbed by the CEBs seemed to have a large influence on amount of visible damage observed after freeze-thaw cycles. The degree of visible damage did not necessarily correlate with lower strengths, however, there was more of a correlation with visible damage and lower observed flexural strengths than there was with the compressive strengths.
6. Analysis of variance (ANOVA) was used to assess whether changes in compressive and flexural strengths were statistically significant when varying fibre type and quantities and subjecting blocks to freeze-thaw cycles. The results of the ANOVA were used to support the assumptions made from the data as to whether results were part of the same statistical population. The results should be interpreted with caution in cases where the variability for one group was appreciably different from that of the groups because ANOVA assumes all groups have the same variability.

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Chapter 5

Discussion, Conclusions, and Recommendations

5.1 Discussion of Practical Building with CEBs

Ideally, CEBs should be used for interior walls and floors, and other interior building components because of the substantial decrease in strength of the CEBs when saturated. Even with the addition of a water repelling admixture (Mak, MacDougall and Fam 2015), the saturated strengths were much lower than the strengths of the CEBs in the air-dry state. In this context, the term "interior" refers to the interior of the building envelope. In other words, the CEBs may be used as structural members in the exterior wall of a building, however, the CEBs should be placed such that they are inside the building envelope and consequently not exposed to exterior elements like rain and snow.

An interesting point to consider, however, is that the blocks did obtain compressive strength results when fully saturated that were considered acceptable according to Australia's Earth Building Handbook (Walker and Australia 2002). There are many other things to consider when determining whether CEBs are adequate for use outside of the building envelope, especially considering that testing the blocks fully saturated was quite a severe condition. It is likely that in the lifespan of a building, blocks will never reach this same fully saturated state, even when exposed to rain, snow, and humidity. However, erosion of blocks must also be considered. From Chapter 4, it was seen that increasing the water absorbed by the blocks during freeze-thaw also increased the amount of damage and mass loss, and this was only over a period of twelve to twenty-four days. More erosion and mass loss will occur over longer period if the blocks are continued to be subjected to water absorption, even if they are not reaching a fully saturated state.

This erosion and mass loss can be seen in a practical application on-site. At Fifth Wind Farm in Cobourg, Ontario, Canada, the owner of the farm has experimented with using CEBs as exterior walkway paving stones. The blocks were produced with 20% cement by weight as stabilizer as opposed to the 2.5% cement and 2.5% lime that was used to construct the CEBs in this thesis. After about five years in place the CEBs showed deterioration (Figure 5-1) due to exposure to the elements (rain, snow, wind, freeze-thaw, etc.). The walkway still functions for its purpose and does not appear to be a safety concern from a structural viewpoint, however, the erosion of the CEBs results in an aesthetically displeasing view. This may be something considered to be unacceptable by a client or homeowner if they paid money to have this walkway installed. This suggests further that CEBs are not suitable for this type of application where there is direct exposure to the elements.

Figure 5-1: CEBs used as exterior paving stones for earth block home at Fifth Wind Farm

It should also be noted that the owner was cautious to avoid de-icing salts in the winter, as that would likely cause substantially more deterioration in a shorter time.

5.2 Conclusions

This thesis presents and discusses the results of two field studies that investigated the suitability of using on-site manufactured compressed earth blocks for building in northern and remote regions. This chapter summarizes the results of the investigations and provides recommendations for future research.

5.2.1 Chapter 3 Conclusions

Four CEB types were tested in unconfined compression and three-point bending to determine the effect of soil gradation and the addition of invasive Phragmites on the mechanical properties of the CEBs at air-dry and saturated states.

The investigation found that, although the CEBs constructed with both coarse and fine soil gradations achieved adequate strengths according to the Australian Earth Building Handbook (Walker and Australia 2002) and the International Building Code (International Code Council 2006), the gravel particles in the coarse soil resulted in increased compressive and flexural performance. This suggests that for CEB construction in other regions, such as Northern Ontario where soil composition may vary, the addition of gravel particles to the in-situ soil (if the soil lacks larger aggregates) may improve block performance. Also, in regions where soil contains higher contents of clay, adding in sand to the in-situ soil can also improve CEB performance.

Finally, the addition of the Phragmites fibres showed potential to increase both compressive and flexural strength of the CEBs. However, because the fibres were relatively large and had a high flexural stiffness, adequate fibre to soil bond was not achieved and the fibres reduced the flexural capacity of the blocks. This was considered when preparing the fibres for the investigation in Chapter 4 where more focus was placed on the effect of adding natural fibres on the compressive and flexural strength of the earth blocks.

5.2.2 Chapter 4 Conclusions

Based on the conclusions from Chapter 3, eight new block mixes were designed, produced, and tested in unconfined compression and three-point bending at ambient conditions and after being subjected to six and twelve freeze-thaw cycles.

The investigation found that the quantity of natural fibres added to the CEBs had a greater influence on the compressive and flexural strength of the CEBs than the physical attributes of the fibre type itself. This suggests that similar results may be obtained by adding different fibre types with similar properties (flexural stiffness, length, width, etc.) as the straw, switchgrass, and rice hulls. This is applicable when considering how the same process of manufacturing CEBs can be applied in other regions in Canada using different materials based on what is available locally. Adding grass or straw fibres with similar properties to those tested in this investigation at fibre contents ranging from 0% to 0.5% by weight may produce similar improvements in the compressive and flexural strengths of the CEBs. For blocks subjected to freeze-thaw cycles, it appeared that the additional water absorbed by the blocks during the cycling process increased both the compressive and flexural strength of the CEBs by up to 140%.

5.3 Recommendations for Future Work

Based on the results of the investigations presented in Chapter 3 and Chapter 4, the following recommendations for future research are suggested:

1. Conduct additional tests on bonded and unbonded CEB prisms to determine the adequacy of estimating bonded CEB masonry strength from unbonded CEB prisms to avoid the complexities of working with mortared prisms.
2. Examine the flexural deformability of CEBs with fibres by using linear potentiometers (LPs) to measure deflection at midspan during loading in three-point bending. Developing a load

versus deflection curve may provide more insight as to how the fibres affect the deformability of the CEBs because it is clear that blocks constructed with no fibres are much less deformable (shown from the complete separation of no-fibre blocks at failure).

3. Conduct additional tests in unconfined compression after blocks have been fully submerged in water for at least 24 hours and then dried to ambient conditions, and compare these results with CEBs that have been tested in unconfined compression, at ambient conditions, without having been submerged in water at all to determine the strength retention.
4. Conduct additional tests in both unconfined compression and in three-point bending with varying numbers of test repetitions to determine how the variation in results changes and potentially determine an optimum number of test repetitions to form a design standard for on-site construction.
5. Conduct additional tests on the effect of curing time on the compressive and flexural strength of the CEBs to determine the duration of curing required for the CEBs to achieve full strength.
6. Conduct additional research on the effect of living in a CEB home on the wellness of its inhabitants. This recommendation has less to do with the mechanical properties and strength performance of the blocks, but instead focuses on the holistic benefits to using compressed earth as a building material. For many Indigenous communities, the holistic benefits and spiritual meaning of living under the protection of Mother Earth is equally important as the physical adequacy of the material.

5.4 References

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Appendix A

Test Result Database (Chapter 3)

A.1 Compressive Strength Results

A.1.1 One-Block Prisms (Dry)

Coarse Soil with No Fibre (Dry)					
Sample	Length (mm)	Width (mm)	Thickness (mm)	Load (kN)	f_{CEB} (MPa)
1	359	180	80	1329.00	20.57
2	359	180	80	1196	18.51
				Average	**19.5**
				Standard Deviation	**-**

Coarse Soil with 0.5% Phragmites (Dry)					
Sample	Length (mm)	Width (mm)	Thickness (mm)	Load (kN)	f_{CEB} (MPa)
1	356	180	82	1649.85	25.75
2	355	180	81	1502.50	23.51
				Average	**24.6**
				Standard Deviation	**-**

Fine Soil with No Fibre (Dry)					
Sample	Length (mm)	Width (mm)	Thickness (mm)	Load (kN)	f_{CEB} (MPa)
1	356	179	79	1259.70	19.77
2	357	179	79	1150.80	18.01
				Average	**18.9**
				Standard Deviation	**-**

Fine Soil with 0.5% Phragmites (Dry)					
Sample	Length (mm)	Width (mm)	Thickness (mm)	Load (kN)	f_{CEB} (MPa)
1	356	177	78	1208.70	19.18
2	356	180	80	1241.70	19.38
				Average	**19.3**
				Standard Deviation	**-**

A.1.2 Two-Block Prisms (Dry)

Coarse Soil with No Fibre (Dry)					
Sample	Length (mm)	Width (mm)	Thickness (mm)	Load (kN)	f_{CEB} (MPa)
1	355	180	79x2	782.55	12.2
2	355	180	78x2	834.85	13.1
3	355	180	78x2	887.10	13.9
				Average	**13.1**
				Standard Deviation	**0.82**

Coarse Soil with 0.5% Phragmites (Dry)					
Sample	Length (mm)	Width (mm)	Thickness (mm)	Load (kN)	f_{CEB} (MPa)
1	355	180	78x2	917.90	14.4
2	355	180	78x2	852.95	13.3
3	355	180	78x2	930.80	14.6
				Average	**14.1**
				Standard Deviation	**0.65**

Fine Soil with No Fibre (Dry)					
Sample	Length (mm)	Width (mm)	Thickness (mm)	Load (kN)	f_{CEB} (MPa)
1	355	180	78x2	649.80	10.2
2	355	180	78x2	658.90	10.3
3	355	180	78x2	731.95	11.5
				Average	**10.6**
				Standard Deviation	**0.70**

Coarse Soil with 0.5% Phragmites (Dry)					
Sample	Length (mm)	Width (mm)	Thickness (mm)	Load (kN)	f_{CEB} (MPa)
1	355	180	78x2	744.00	11.6
2	354	180	79x2	720.70	11.3
4	355	180	78x2	630.00	9.9
				Average	**10.9**
				Standard Deviation	**0.95**

A.1.3 Two-Block Prisms (Wet)

Coarse Soil with No Fibre (Wet)					
Sample	Length (mm)	Width (mm)	Thickness (mm)	Load (kN)	f_{CEB} (MPa)
1	355	180	79x2	491.95	7.70
2	355	180	78x2	354.80	5.6
3	355	180	78x2	429.40	6.7
				Average	**6.7**
				Standard Deviation	**1.07**

Coarse Soil with 0.5% Phragmites (Wet)					
Sample	Length (mm)	Width (mm)	Thickness (mm)	Load (kN)	f_{CEB} (MPa)
1	355	180	78x2	438.00	6.9
2	355	180	79x2	458.80	7.2
3	355	180	78x2	375.15	5.9
				Average	**6.6**
				Standard Deviation	**0.68**

Fine Soil with No Fibre (Wet)					
Sample	Length (mm)	Width (mm)	Thickness (mm)	Load (kN)	f_{CEB} (MPa)
1	355	180	78x2	373.60	5.8
2	355	180	78x2	406.95	6.4
3	355	180	78x2	391.10	6.1
				Average	**6.1**
				Standard Deviation	**0.26**

Fine Soil with 0.5% Phragmites (Wet)					
Sample	Length (mm)	Width (mm)	Thickness (mm)	Load (kN)	f_{CEB} (MPa)
1	355	180	78x2	325.40	5.1
2	355	180	78x2	370.90	5.8
3	355	180	78x2	354.65	5.6
				Average	**5.5**
				Standard Deviation	**0.36**

5.4.1 Four-Block Prisms (Dry)

Coarse Soil with No Fibre (Dry)					
Sample	Length (mm)	Width (mm)	Thickness (mm)	Load (kN)	f_{CEB} (MPa)
1	355	180	80x4	460.00	7.20
2	355	180	80x4	478.00	7.48
				Average	**7.34**
				Standard Deviation	**-**

Coarse Soil with 0.5% Phragmites (Dry)					
Sample	Length (mm)	Width (mm)	Thickness (mm)	Load (kN)	f_{CEB} (MPa)
1	360	182	80x4	494.95	7.55
2	359	180	80x4	513.60	7.95
				Average	**7.75**
				Standard Deviation	**-**

Fine Soil with No Fibre (Dry)					
Sample	Length (mm)	Width (mm)	Thickness (mm)	Load (kN)	f_{CEB} (MPa)
1	356	180	79x4	423.60	6.61
2	355	180	79x4	494.20	7.73
				Average	**7.17**
				Standard Deviation	**-**

Fine Soil with 0.5% Phragmites (Dry)					
Sample	Length (mm)	Width (mm)	Thickness (mm)	Load (kN)	f_{CEB} (MPa)
1	357	179	79x4	525.95	8.23
2	355	179	80x4	437.35	6.88
				Average	**7.56**
				Standard Deviation	**-**

A.2 Corrected Compressive Strength

A.2.1 Correction Factors

Aspect Ratio (h/t)	0.43	0.87	1.73
Krefeld's Correction Factor (Linear Interpolation from Equation 5)	0.51	0.67	0.76
Heathcote & Jankulovski's (Equation 6)	0.29	0.53	0.77

A.2.2 Corrected Compressive Strengths

<table>
<tr><th rowspan="2">Prism Configuration</th><th rowspan="2">Block Type</th><th rowspan="2">Uncorrected Strength (MPa)</th><th rowspan="2">Aspect Ratio</th><th colspan="2">Heathcote & Jankulovski's Method</th><th colspan="2">Krefeld's Method</th></tr>
<tr><th>Correction Factors</th><th>Corrected Strength (MPa)</th><th>Correction Factors</th><th>Corrected Strength (MPa)</th></tr>
<tr><td rowspan="4">One-Block Prims</td><td>Coarse Soil with no Fibre</td><td>19.54</td><td>0.43</td><td>0.29</td><td>5.67</td><td>0.5</td><td>9.77</td></tr>
<tr><td>Coarse Soil with 0.5% Phragmites</td><td>24.60</td><td>0.43</td><td>0.29</td><td>7.13</td><td>0.5</td><td>12.30</td></tr>
<tr><td>Fine Soil with no Fibre</td><td>18.89</td><td>0.43</td><td>0.29</td><td>5.48</td><td>0.5</td><td>9.45</td></tr>
<tr><td>Fine Soil with 0.5% Phragmites</td><td>19.28</td><td>0.43</td><td>0.29</td><td>5.59</td><td>0.5</td><td>9.64</td></tr>
<tr><td rowspan="4">Two-Block Prims</td><td>Coarse Soil with no Fibre</td><td>13.06</td><td>0.87</td><td>0.53</td><td>6.92</td><td>0.67</td><td>8.75</td></tr>
<tr><td>Coarse Soil with 0.5% Phragmites</td><td>14.09</td><td>0.87</td><td>0.53</td><td>7.47</td><td>0.67</td><td>9.44</td></tr>
<tr><td>Fine Soil with no Fibre</td><td>10.65</td><td>0.87</td><td>0.53</td><td>5.64</td><td>0.67</td><td>7.13</td></tr>
<tr><td>Fine Soil with 0.5% Phragmites</td><td>10.94</td><td>0.87</td><td>0.53</td><td>5.80</td><td>0.67</td><td>7.33</td></tr>
<tr><td rowspan="4">Four-Block Prims</td><td>Coarse Soil with no Fibre</td><td>7.34</td><td>1.73</td><td>0.77</td><td>5.65</td><td>0.76</td><td>5.58</td></tr>
<tr><td>Coarse Soil with 0.5% Phragmites</td><td>7.75</td><td>1.73</td><td>0.77</td><td>5.97</td><td>0.76</td><td>5.89</td></tr>
<tr><td>Fine Soil with no Fibre</td><td>7.17</td><td>1.73</td><td>0.77</td><td>5.52</td><td>0.76</td><td>5.45</td></tr>
<tr><td>Fine Soil with 0.5% Phragmites</td><td>7.56</td><td>1.73</td><td>0.77</td><td>5.82</td><td>0.76</td><td>5.74</td></tr>
<tr><td>Tattersall (Tattersall 2013)] 3 bonded prisms</td><td>Coarse Soil with no Fibre</td><td>8.20</td><td>1.6</td><td>0.74</td><td>6.08</td><td>0.78</td><td>6.40</td></tr>
</table>

A.3 Flexural Strength Results

A.3.1 Flexural Strength (Dry)

Coarse Soil with No Fibre (Dry)								
Sample	Length (mm)	Clear Span (mm)	Width (mm)	Thickness (mm)	I (mm^4)	Load (kN)	Moment (Nmm)	fr_{CEB} (MPa)
1	355	305	178	77	6771906.2	4.58	349225	1.99
2	355	305	178	78	7039188.0	3.20	244000	1.35
3	355	305	178	75	6257812.5	3.56	271450	1.63
4	355	305	178	75	6257812.5	4.50	343125	2.06
						Average		**1.76**
						Standard Deviation		**0.33**

Coarse Soil with 0.5% Phragmites (Dry)								
Sample	Length (mm)	Clear Span (mm)	Width (mm)	Thickness (mm)	I (mm^4)	Load (kN)	Moment (Nmm)	fr_{CEB} (MPa)
1	355	305	178	77	6771906.2	4.70	358375	2.04
2	355	305	178	77	6771906.2	2.68	204350	1.16
3	355	305	178	77	6771906.2	3.45	263062.5	1.50
4	355	305	180	75	6328125.0	3.40	259250	1.54
						Average		**1.56**
						Standard Deviation		**0.36**

Fine Soil with No Fibre (Dry)								
Sample	Length (mm)	Clear Span (mm)	Width (mm)	Thickness (mm)	I (mm^4)	Load (kN)	Moment (Nmm)	fr_{CEB} (MPa)
1	355	305	180	79	7395585	4.20	320250	1.71
2	355	305	180	78	7118280	2.09	159363	0.87
3	355	305	180	78	7118280	2.40	183000	1.00
4	355	305	180	78	7118280	3.00	228750	1.25
						Average		**1.21**
						Standard Deviation		**0.37**

Fine Soil with 0.5% Phragmites (Dry)								
Sample	Length (mm)	Clear Span (mm)	Width (mm)	Thicknes s (mm)	I (mm^4)	Load (kN)	Moment (Nmm)	fr_{CEB} (MPa)
1	355	305	180	79.5	7536898.13	2.35	179188	0.95
2	355	305	180	77	6847995	2.38	181475	1.02
3	355	305	180	77	6847995	1.79	136488	0.77
4	355	305	180	80	7680000	2.3	175375	0.91
						Average		**0.91**
						Standard Deviation		**0.11**

A.3.2 Flexural Strength (Wet)

Coarse Soil with No Fibre (Wet)								
Sample	Length (mm)	Clear Span (mm)	Width (mm)	Thickness (mm)	I (mm^4)	Load (kN)	Moment (Nmm)	fr_{CEB} (MPa)
1	355	305	180	78	7118280.0	1.2	91500	0.50
2	355	305	180	78	7118280.0	2.23	170037.5	0.93
3	355	305	180	78	7118280.0	1.81	138012.5	0.76
						Average		**0.73**
						Standard Deviation		**0.22**

Coarse Soil with 0.5% Phragmites (Wet)								
Sample	Length (mm)	Clear Span (mm)	Width (mm)	Thickness (mm)	I (mm^4)	Load (kN)	Moment (Nmm)	fr_{CEB} (MPa)
1	355	305	180	78	7118280.0	1.4	106750	0.58
2	355	305	180	78	7118280.0	2.2	167750	0.92
3	355	305	180	78	7118280.0	1.3	99125	0.54
						Average		**0.68**
						Standard Deviation		**0.21**

Fine Soil with No Fibre (Wet)								
Sample	Length (mm)	Clear Span (mm)	Width (mm)	Thicknes s (mm)	I (mm^4)	Load (kN)	Moment (Nmm)	fr_{CEB} (MPa)
1	355	305	178	77	6771906.17	1.33	101413	0.58
2	355	305	178	77	6771906.17	0.86	65575	0.37
3	355	305	178	77	6771906.17	1.30	99125	0.56
						Average		**0.50**
						Standard Deviation		**0.11**

Fine Soil with 0.5% Phragmites (Wet)								
Sample	Length (mm)	Clear Span (mm)	Width (mm)	Thicknes s (mm)	I (mm^4)	Load (kN)	Moment (Nmm)	fr_{CEB} (MPa)
1	355	305	178	77	6771906.17	1.11	84638	0.48
2	355	305	178	77	6771906.17	1.12	85400	0.49
3	355	305	178	77	6771906.17	0.96	73200	0.42
						Average		**0.46**
						Standard Deviation		**0.04**

A.4 Database of Flexural Tensile Strength of Stabilized CEBs

No.	Reference	CEB Materials					Compressive strength (MPa)				Flexural strength (MPa)		
		CEB ID	No of tests	CEB Dimensions	Soil Composition	Stabilizer Type and (%)	Reported f_{CEB}	h/t in the test configuration	Correction factor	Corrected $f_{CEB\ cor.}$	Experimental fr_{CEB}	Predicted fr_{CEB}	$fr_{CEBExp.}$ / $fr_{CEBPred.}$
1	Current Study	0	3	355x180x75	G=20%,S=30 %, Sil=27%, C=23%	Cement/ Lime 2.5%/2.5%	6.92	0.88	0.53	6.92	1.79	1.68	1.07
2		0Ph	3				7.47	0.88	0.53	7.47	1.56	1.78	0.88
3		1	3		G=0%,S=25 %, Sil=48%, C=27%		5.64	0.88	0.53	5.64	1.21	1.42	0.85
4		1Ph	3				5.80	0.88	0.53	5.80	0.91	1.45	0.63
5	Sitton et al. (Sitton, Zeinali, et al., Effect of Mix Design on Compressed Earth Block Strength 2018)	01-7D	2	355x180x75	80%(S+Sil+C)+20%S	Cement 5.5%	6.42	0.54	0.36	2.31	0.76	0.69	1.10
6		02-7D	2		80%(S+Sil+C)+20%S	Cement 9.1%	9.57	0.54	0.36	3.45	1.00	0.96	1.05
7		03-7D	2		78%(S+Sil+C)+22%S	Cement 10.9%	9	0.54	0.36	3.24	0.95	0.91	1.04
8		04-7D	2		78%(S+Sil+C)+22%S	Cement 5.5%	12.2	0.54	0.36	4.39	1.19	1.16	1.02
9		05-7D	2		77%(S+Sil+C)+23%S	Cement 9.1%	13.65	0.54	0.36	4.91	1.23	1.27	0.97
10		06-7D	2		77%(S+Sil+C)+23%S	Cement 10.9%	13.4	0.54	0.36	4.82	1.20	1.25	0.96
11		07-7D	2		(S+Sil+C)	Cement 3.6%	5.95	0.54	0.36	2.14	0.66	0.65	1.01
12		08-7D	2		(S+Sil+C)	Cement 3.6%	4.37	0.54	0.36	1.57	0.50	0.51	0.98
13		09-7D	2		72%(S+Sil+C)+28%S	Cement 3.6%	6.5	0.54	0.36	2.34	0.71	0.70	1.01
14		10-7D	2		72%(S+Sil+C)+28%S	Cement 3.6%	4.6	0.54	0.36	1.66	0.56	0.53	1.05
15		11-7D	2		(S+Sil+C)	Cement 9.1%	8.4	0.54	0.36	3.02	1.00	0.86	1.16
16		12-7D	2		(S+Sil+C)	Cement 9.1%	5.9	0.54	0.36	2.12	0.61	0.65	0.94
17		13-7D	2		69%(S+Sil+C)+31%S	Cement 9.1%	11.8	0.54	0.36	4.25	1.38	1.13	1.22
18		14-7D	2		69%(S+Sil+C)+31%S	Cement 9.1%	8.9	0.54	0.36	3.20	1.00	0.90	1.11
19		01-28D	2		79%(S+Sil+C)+21%S	Cement 5.5%	8.06	0.54	0.36	2.90	0.91	0.83	1.09
20		02-28D	2		79%(S+Sil+C)+21%S	Cement 9.1%	12.08	0.54	0.36	4.35	1.14	1.15	0.99
21		03-28D	2		78%(S+Sil+C)+22%S	Cement 10.9%	11.78	0.54	0.36	4.24	1.18	1.13	1.04
22		04-28D	2		78%(S+Sil+C)+22%S	Cement 5.5%	12.5	0.54	0.36	4.50	1.59	1.19	1.34
23		05-28D	2		77%(S+Sil+C)+23%S	Cement 9.1%	13.14	0.54	0.36	4.73	1.58	1.23	1.28
24		06-28D	2		77%(S+Sil+C)+23%S	Cement 10.9%	15.2	0.54	0.36	5.47	1.84	1.39	1.33
25		07-28D	2		(S+Sil+C)	Cement 3.6%	7.62	0.54	0.36	2.74	0.72	0.80	0.90
26		09-28D	2		72%(S+Sil+C)+28%S	Cement 3.6%	7.2	0.54	0.36	2.59	0.92	0.76	1.21

27		10-28D	2		72%(S+Sil+C)+28%S	Cement 3.6%	6.5	0.54	0.36	2.34	0.71	0.70	1.01
28		11-28D	2		(S+Sil+C)	Cement 9.1%	11.67	0.54	0.36	4.20	0.94	1.12	0.84
29		12-28D	2		(S+Sil+C)	Cement 9.1%	9.21	0.54	0.36	3.32	0.69	0.93	0.74
30		13-28D	2		69%(S+Sil+C)+31%S	Cement 9.1%	14.3	0.54	0.36	5.15	1.56	1.32	1.18
31		14-28D	2		69%(S+Sil+C)+31%S	Cement 9.1%	10.42	0.54	0.36	3.75	1.17	1.02	1.14
32	Villamizar et al. (Villamizar, et al. 2012)	T2	5	320x80x150	clay-rich Soil	Coal Ash 5%	3.3	1.4	0.7	2.31	0.76	0.69	1.10
33		T3	5				2.15	1.4	0.7	1.51	0.48	0.49	0.98
34		T4	5			Coal Ash 7.5%	2.53	1.4	0.7	1.77	0.56	0.56	1.00
35		T5	5			Coal Ash 10%	1.05	1.4	0.7	0.74	0.39	0.28	1.41
36	Mostafa &Uddin (Mostafa and Uddin, Effect of Banana Fibers on the Compressive and Flexural Strength of Compressed Earth Blocks 2015)	#1	5	120x120x90	G(>5mm)=30% S=30% C=30%	Cement 7%	3.3	1.3	0.67	2.21	0.49	0.67	0.73
37		#2	5				4.37	1.3	0.67	2.93	0.63	0.84	0.75
38		#3	5				4.96	1.3	0.67	3.32	0.77	0.93	0.83
39		#4	5				3.76	1.3	0.67	2.52	0.57	0.74	0.77
40		#5	5				4.03	1.3	0.67	2.70	0.74	0.79	0.94

Appendix B

Test Result Database (Chapter 4)

B.1 Compressive Strength Data

B.1.1 Zero Freeze-Thaw Cycles

Batch 1 - No Fibre					
Sample	Length (mm)	Width (mm)	Thickness (mm)	Load (kN)	f_{ceb} (MPa)
1	355	180	70	523.95	8.20
2	355	180	70	517.80	8.10
4	355	180	70	534.40	8.36
				Average	**8.22**
				SD	**0.13**

Batch 5 - 0.25% Switchgrass					
Sample	Length (mm)	Width (mm)	Thickness (mm)	Load (kN)	f_{ceb} (MPa)
1	355	180	75	499.95	7.82
2	355	180	75	500.50	7.83
3	355	180	75	585.70	9.17
				Average	**8.27**
				SD	**0.77**

Batch 3 - 0.125% Straw					
Sample	Length (mm)	Width (mm)	Thickness (mm)	Load (kN)	f_{ceb} (MPa)
1	355	180	75	535.50	8.38
2	355	180	75	622.65	9.74
3	355	180	75	558.85	8.75
				Average	**8.96**
				SD	**0.71**

Batch 7 - 0.25% Straw					
Sample	Length (mm)	Width (mm)	Thickness (mm)	Load (kN)	f_{ceb} (MPa)
1	354	178	75	525.20	8.33
2	353	179	75	548.00	8.67
3	356	179	75	606.00	9.51
				Average	**8.84**
				SD	**0.60**

Batch 2 - 0.75% Straw					
Sample	Length (mm)	Width (mm)	Thickness (mm)	Load (kN)	f_{ceb} (MPa)
1	360	180	80	438.35	6.76
2	357	180	80	458.40	7.13
3	355	180	80	449.22	7.03
				Average	**6.98**
				SD	**0.19**

Batch 4 - 0.25% Rice Hulls					
Sample	Length (mm)	Width (mm)	Thickness (mm)	Load (kN)	f_{ceb} (MPa)
1	356	179	75	491.55	7.71
2	356	178	75	519.25	8.19
3	356	178	75	503.40	7.94
				Average	**7.95**
				SD	**0.24**

Batch 6 - 0.5% Rice Hulls					
Sample	Length (mm)	Width (mm)	Thickness (mm)	Load (kN)	f_{ceb} (MPa)
1	355	180	75	494.75	7.74
2	356	179	75	524.80	8.24
3	356	179	75	523.10	8.21
				Average	**8.06**
				SD	**0.28**

Batch 8 - 0.75% Rice Hulls					
Sample	Length (mm)	Width (mm)	Thickness (mm)	Load (kN)	f_{ceb} (MPa)
1	356	180	75	436.60	6.81
2	357	179	75	469.65	7.35
3	355	179	75	468.45	7.37
				Average	**7.18**
				SD	**0.32**

B.1.2 Six Freeze-Thaw Cycles

Batch 1 - No Fibre					
Sample	Length (mm)	Width (mm)	Thickness (mm)	Load (kN)	f_{ceb} (MPa)
1	355	180	70	809.50	12.67
2	355	180	70	666.50	10.43
3	355	180	70	649.00	10.16
				Average	**11.09**
				SD	**1.38**

Batch 5 - 0.25% Switchgrass					
Sample	Length (mm)	Width (mm)	Thickness (mm)	Load (kN)	f_{ceb} (MPa)
1	355	180	75	639.45	10.01
2	355	180	75	560.30	8.77
3	355	180	75	521.75	8.17
				Average	**8.98**
				SD	**0.94**

Batch 4 - 0.25% Rice Hulls					
Sample	Length (mm)	Width (mm)	Thickness (mm)	Load (kN)	f_{ceb} (MPa)
1	355	180	75	596.00	9.33
2	355	180	75	644.45	10.09
3	355	180	75	693.75	10.86
				Average	**10.09**
				SD	**0.76**

Batch 6 - 0.5% Rice Hulls					
Sample	Length (mm)	Width (mm)	Thickness (mm)	Load (kN)	f_{ceb} (MPa)
1	355	180	75	652.80	10.22
2	355	180	75	610.45	9.55
3	355	180	75	663.75	10.39
				Average	**10.05**
				SD	**0.44**

Batch 8 - 0.75% Rice Hulls					
Sample	Length (mm)	Width (mm)	Thickness (mm)	Load (kN)	f_{ceb} (MPa)
1	355	180	75	592.25	9.27
2	355	180	75	526.00	8.23
3	355	180	75	517.25	8.09
				Average	**8.53**
				SD	**0.64**

B.1.3 Twelve Freeze-Thaw Cycles

Batch 1 - No Fibre					
Sample	Length (mm)	Width (mm)	Thickness (mm)	Load (kN)	f_{ceb} (MPa)
1	355	180	70	572.20	9.07
2	355	180	70	670.20	10.49
3	355	180	70	670.70	10.50
				Average	**10.02**
				SD	**0.82**

Batch 5 - 0.25% Switchgrass					
Sample	Length (mm)	Width (mm)	Thickness (mm)	Load (kN)	f_{ceb} (MPa)
1	353	177	75	607.30	9.75
2	354	178	75	544.60	8.66
3	353	176	75	583.30	9.43
				Average	**9.28**
				SD	**0.56**

Batch 4 - 0.25% Rice Hulls					
Sample	Length (mm)	Width (mm)	Thickness (mm)	Load (kN)	f_{ceb} (MPa)
1	355	180	75	631.45	9.94
2	355	180	75	594.50	9.33
3	355	180	75	614.55	9.62
				Average	**9.63**
				SD	**0.30**

Batch 6 - 0.5% Rice Hulls					
Sample	Length (mm)	Width (mm)	Thickness (mm)	Load (kN)	f_{ceb} (MPa)
1	353	173	75	536.60	8.79
2	353	174	75	608.50	10.04
3	353	173	75	530.16	8.80
				Average	**9.21**
				SD	**0.72**

Batch 8 - 0.75% Rice Hulls					
Sample	Length (mm)	Width (mm)	Thickness (mm)	Load (kN)	f_{ceb} (MPa)
1	352	172	75	428.25	7.12
2	352	172	75	496.30	8.30
3	353	170	75	475.80	7.99
				Average	**7.80**
				SD	**0.61**

B.2 Aspect Ratios and Correction Factors

Aspect Ratio	0	0.4	0.7	1	3	>5
Krefeld's Correction Factor Use Linear Interpolation	0	0.5	0.6	0.7	0.85	1

Individual Block Thickness	70mm	75mm	80mm
Aspect Ratio (h/t)	0.78	0.83	0.89
Krefeld's Correction Factor (Linear Interpolation from Equation 5)	0.63	0.64	0.66
Heathcote & Jankulovski's Correction Factor (Equation 6)	0.51	0.54	0.56

B.3 Flexural Strength Data

B.3.1 Zero Freeze-Thaw Cycles

No Fibre								
Sample	Length (mm)	Clear Span (mm)	Width (mm)	Thickness (mm)	I (mm^4)	Load (kN)	Moment (Nmm)	fr_{ceb} (MPa)
1	355	305	180	70	5145000	3.105	236756.25	1.611
2	355	305	180	70	5145000	2.412	183915	1.251
3	355	305	180	70	5145000	2.258	172172.5	1.171
							Average	**1.344**
							SD	**0.234**

0.25% Switchgrass								
Sample	Length (mm)	Clear Span (mm)	Width (mm)	Thickness (mm)	I (mm^4)	Load (kN)	Moment (Nmm)	fr_{ceb} (MPa)
1	355	305	180	75	6328125	1.912	145790	0.864
2	355	305	180	75	6328125	1.946	148382.5	0.879
3	355	305	180	75	6328125	2.246	171257.5	1.015
							Average	**0.919**
							SD	**0.083**

0.125% Straw								
Sample	Length (mm)	Clear Span (mm)	Width (mm)	Thickness (mm)	I (mm^4)	Load (kN)	Moment (Nmm)	fr_{ceb} (MPa)
1	355	305	180	75	6328125	1.475	112468.75	0.666
2	355	305	180	75	6328125	1.695	129243.75	0.766
3	355	305	180	75	6328125	2.382	181627.5	1.076
							Average	**0.836**
							SD	**0.214**

0.25% Straw								
Sample	Length (mm)	Clear Span (mm)	Width (mm)	Thickness (mm)	I (mm^4)	Load (kN)	Moment (Nmm)	fr_{ceb} (MPa)
1	355	305	180	75	6328125	2.298	175222.5	1.038
2	355	305	180	75	6328125	1.336	101870	0.604
3	355	305	180	75	6328125	1.532	116815	0.692
							Average	**0.778**
							SD	**0.230**

0.75% Straw								
Sample	Length (mm)	Clear Span (mm)	Width (mm)	Thickness (mm)	I (mm^4)	Load (kN)	Moment (Nmm)	fr_{ceb} (MPa)
1	355	305	180	80	7680000	0.781	59551.25	0.310
2	355	305	180	80	7680000	1.155	88068.75	0.459
3	355	305	180	80	7680000	0.882	67252.5	0.350
							Average	**0.373**
							SD	**0.077**

0.25% Rice Hulls								
Sample	Length (mm)	Clear Span (mm)	Width (mm)	Thickness (mm)	I (mm^4)	Load (kN)	Moment (Nmm)	fr_{ceb} (MPa)
1	355	305	180	75	6328125	3.440	262300	1.554
2	355	305	180	75	6328125	1.992	151890	0.900
3	355	305	180	75	6328125	2.82	215025	1.274
							Average	**1.243**
							SD	**0.328**

0.5% Rice Hulls								
Sample	Length (mm)	Clear Span (mm)	Width (mm)	Thickness (mm)	I (mm^4)	Load (kN)	Moment (Nmm)	fr_{ceb} (MPa)
1	355	305	180	75	6328125	2.047	156083.75	0.925
2	355	305	180	75	6328125	2.142	163327.5	0.968
3	355	305	180	75	6328125	1.764	134505	0.797

							Average	0.897
							SD	0.089

0.75% Rice Hulls								
Sample	Length (mm)	Clear Span (mm)	Width (mm)	Thickness (mm)	I (mm^4)	Load (kN)	Moment (Nmm)	fr_{ceb} (MPa)
1	355	305	180	75	6328125	1.181	90051.25	0.534
2	355	305	180	75	6328125	1.806	137707.5	0.816
3	355	305	180	75	6328125	2.004	152805	0.906
							Average	**0.752**
							SD	**0.194**

B.3.2 Six Freeze-Thaw Cycles

No Fibre								
Sample	Length (mm)	Clear Span (mm)	Width (mm)	Thickness (mm)	I (mm^4)	Load (kN)	Moment (Nmm)	fr_{ceb} (MPa)
1	355	305	180	70	5145000	3.56	271450	1.847
2	355	305	180	70	5145000	3.76	286700	1.950
							Average	**1.898**
							SD	**-**

0.25% Switchgrass								
Sample	Length (mm)	Clear Span (mm)	Width (mm)	Thickness (mm)	I (mm^4)	Load (kN)	Moment (Nmm)	fr_{ceb} (MPa)
1	355	305	180	75	6328125	1.52	115900	0.687
2	355	305	180	75	6328125	1.23	93787.5	0.556
							Average	**0.621**
							SD	**-**

0.25% Rice Hulls								
Sample	Length (mm)	Clear Span (mm)	Width (mm)	Thickness (mm)	I (mm^4)	Load (kN)	Moment (Nmm)	fr_{ceb} (MPa)

1	355	305	180	75	6328125	1.610	122762.5	0.727
2	355	305	180	75	6328125	3.09	235612.5	1.396
							Average	**1.062**
							SD	**-**

0.5% Rice Hulls								
Sample	Length (mm)	Clear Span (mm)	Width (mm)	Thickness (mm)	I (mm^4)	Load (kN)	Moment (Nmm)	fr_{ceb} (MPa)
1	355	305	180	75	6328125	1.27	96837.5	0.574
2	355	305	180	75	6328125	2.77	211212.5	1.252
							Average	**0.913**
							SD	**-**

0.75% Rice Hulls								
Sample	Length (mm)	Clear Span (mm)	Width (mm)	Thickness (mm)	I (mm^4)	Load (kN)	Moment (Nmm)	fr_{ceb} (MPa)
1	355	305	180	75	6328125	1.156	88145	0.522
2	355	305	180	75	6328125	1.083	82578.75	0.489
							Average	**0.506**
							SD	**-**

B.3.3 Twelve Freeze-Thaw Cycles

No Fibre								
Sample	Length (mm)	Clear Span (mm)	Width (mm)	Thickness (mm)	I (mm^4)	Load (kN)	Moment (Nmm)	fr_{ceb} (MPa)
1	355	305	180	74	6078360	3.963	302178.75	1.839
2	355	305	180	75	6328125	3.538	269772.5	1.599
							Average	**1.719**
							SD	**-**

0.25% Switchgrass								
Sample	Length (mm)	Clear Span (mm)	Width (mm)	Thickness (mm)	I (mm^4)	Load (kN)	Moment (Nmm)	fr_{ceb} (MPa)

1	355	305	180	78	7118280	1.834	139842.5	0.766
2	355	305	180	76	6584640	1.894	144417.5	0.833
							Average	**0.800**
							SD	**-**

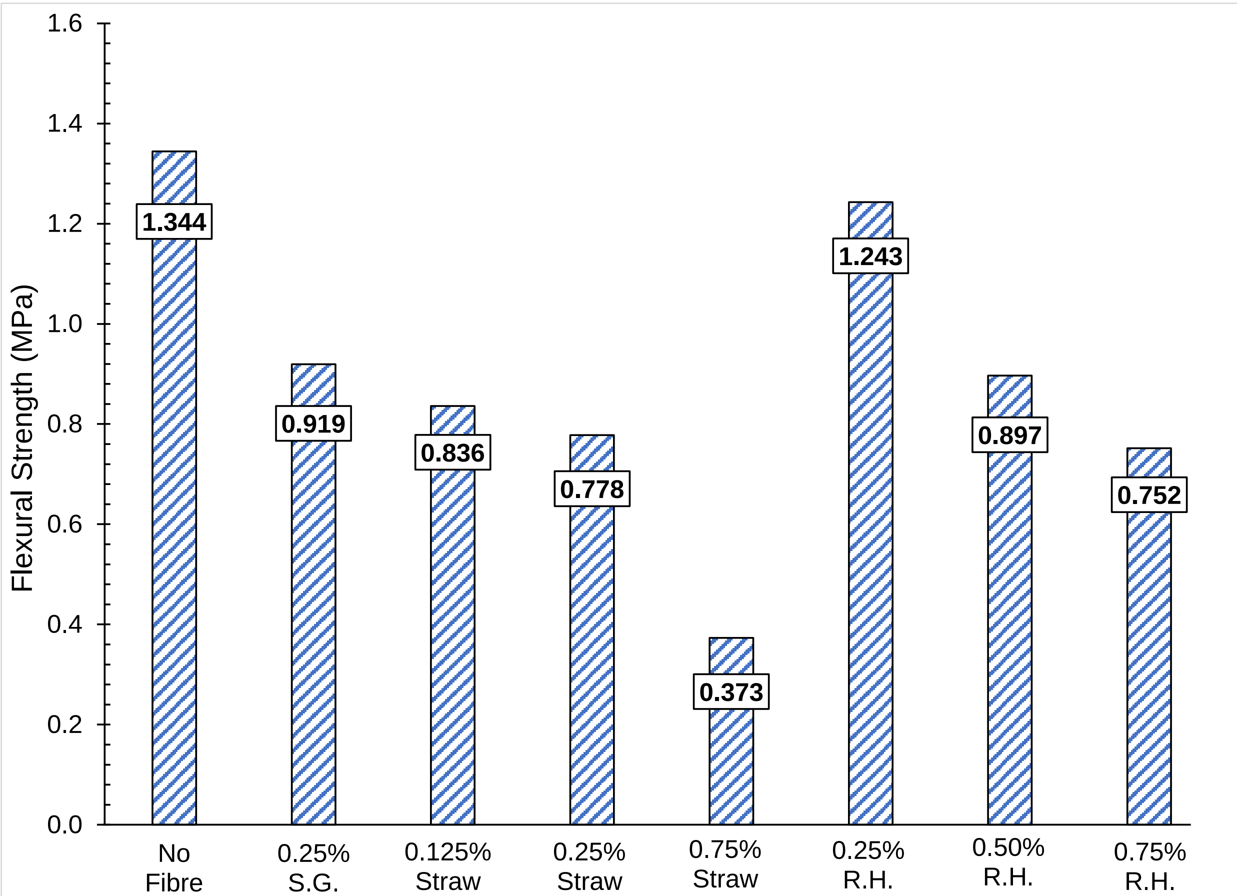
0.25% Rice Hulls								
Sample	Length (mm)	Clear Span (mm)	Width (mm)	Thickness (mm)	I (mm^4)	Load (kN)	Moment (Nmm)	fr_{ceb} (MPa)
1	355	305	180	77	6847995	2.414	184067.5	1.035
2	355	305	180	75	6328125	3.569	272136.25	1.613
							Average	**1.324**
							SD	**-**

0.5% Rice Hulls								
Sample	Length (mm)	Clear Span (mm)	Width (mm)	Thickness (mm)	I (mm^4)	Load (kN)	Moment (Nmm)	fr_{ceb} (MPa)
1	355	305	180	79	7395585	2.308	175985	0.940
2	355	305	180	76	6584640	2.724	207705	1.199
							Average	**1.069**
							SD	**-**

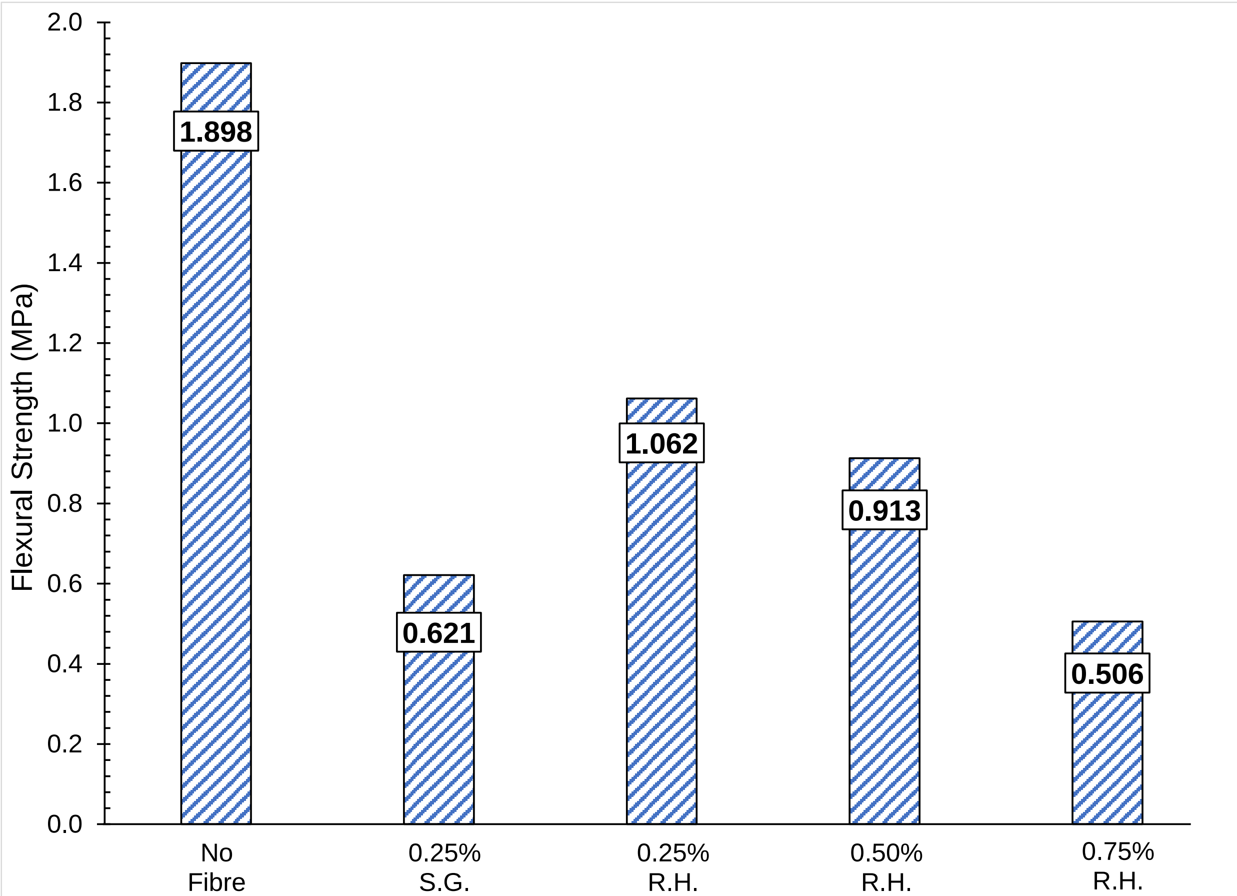
0.75% Rice Hulls								
Sample	Length (mm)	Clear Span (mm)	Width (mm)	Thickness (mm)	I (mm^4)	Load (kN)	Moment (Nmm)	fr_{ceb} (MPa)
1	355	305	180	76	6584640	1.941	148001.25	0.854
2	355	305	180	76	6584640	2.587	197258.75	1.138
							Average	**0.996**
							SD	**-**

B.4 Flexural Strength Graphs

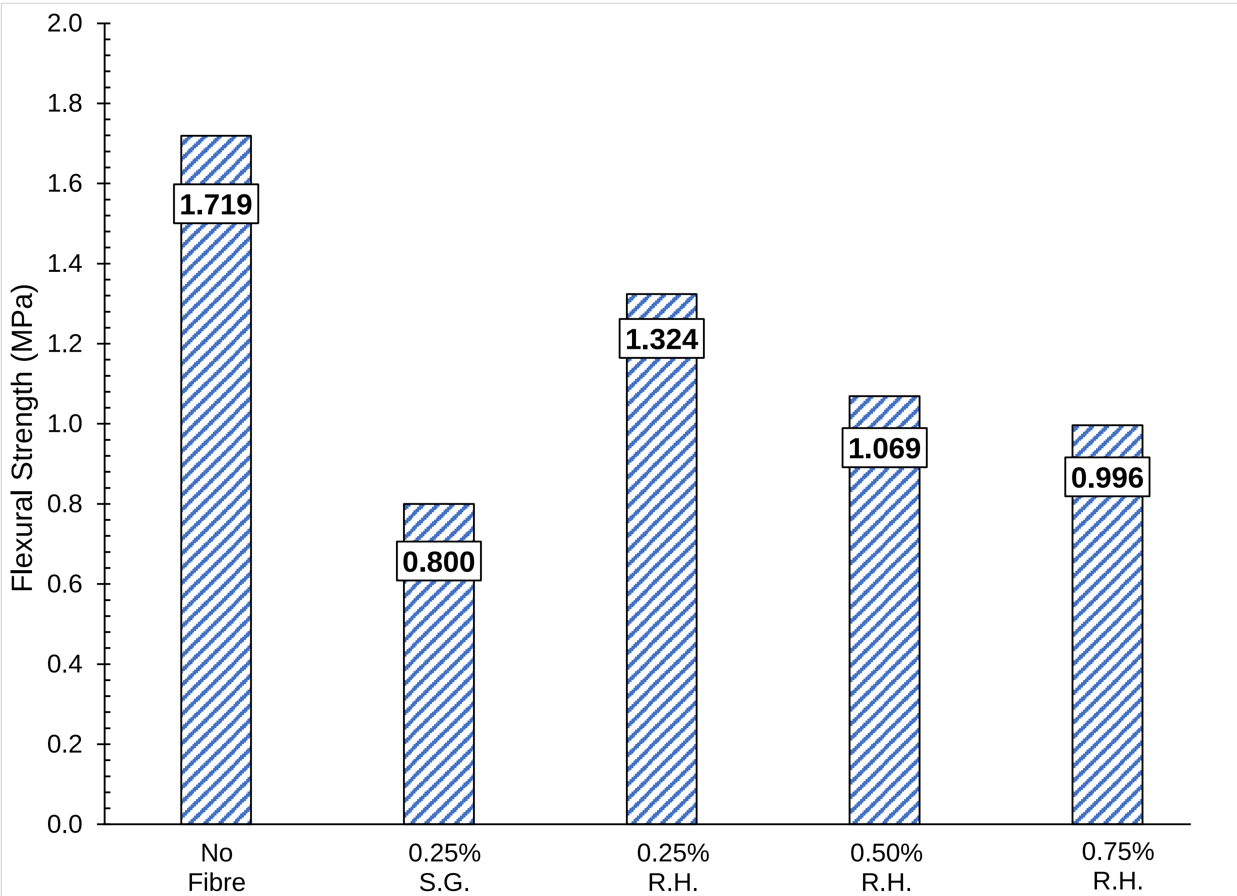
B.4.1 Zero Freeze-Thaw Cycles



B.4.2 Six Freeze-Thaw Cycles



B.4.3 Twelve Freeze-Thaw Cycles



B.5 Water Absorption and Mass Retention

B.5.1 Six Cycles

Block Type	Block No.	Weight Before (kg)	Weight After (kg)		Water Absorption (%)	Mass Loss (%)	Retention (%)
			Wet	Dry			
		11-May-20	23-May-20	15-Jun-20			
No Fibre	1	9.603	10.291	9.520	7.16%	-0.86%	99.1%
	2	9.900	10.510	9.863	6.16%	-0.37%	99.6%
	3	9.774	10.493	9.739	7.36%	-0.36%	99.6%
	4	9.692	10.395	9.592	7.25%	-1.03%	99.0%
	5	9.735	10.467	9.672	7.52%	-0.65%	99.4%
	6	9.700	10.489	9.666	8.13%	-0.35%	99.6%
	7	9.589	10.411	9.540	8.57%	-0.51%	99.5%
	8	9.855	10.617	9.801	7.73%	-0.55%	99.5%
	9	9.870	8.600	7.892	-12.87%	-20.04%	80.0%
0.25% RH	1	9.712	10.397	9.543	7.05%	-1.74%	98.3%
	2	9.964	10.715	9.897	7.54%	-0.67%	99.3%
	3	10.15	10.862	9.999	7.01%	-1.49%	98.5%
	4	10.002	10.781	9.921	7.79%	-0.81%	99.2%
	5	9.906	10.685	9.799	7.86%	-1.08%	98.9%
	6	9.843	10.564	9.713	7.33%	-1.32%	98.7%
	7	9.871	10.52	9.783	6.57%	-0.89%	99.1%
	8	9.715	10.379	9.600	6.83%	-1.18%	98.8%
	9	9.679	10.357	9.590	7.00%	-0.92%	99.1%
0.25% SG	1	9.321	10.042	9.257	7.74%	-0.69%	99.3%
	2	9.519	10.227	9.448	7.44%	-0.75%	99.3%
	3	9.587	10.387	9.552	8.34%	-0.37%	99.6%
	4	9.603	10.261	9.302	6.85%	-3.13%	96.9%
	5	9.397	10.196	9.630	8.50%	2.48%	102.5%
	6	9.75	10.488	9.969	7.57%	2.25%	102.2%
	7	9.468	10.303	9.390	8.82%	-0.82%	99.2%
	8	10.069	10.904	9.969	8.29%	-0.99%	99.0%
	9	9.352	10.343	9.277	10.60%	-0.80%	99.2%
0.5% RH	1	9.976	10.647	9.756	6.73%	-2.21%	97.8%
	2	9.957	10.641	9.879	6.87%	-0.78%	99.2%
	3	9.944	10.617	9.714	6.77%	-2.31%	97.7%

	4	9.992	10.698	9.875	7.07%	-1.17%	98.8%
	5	10.111	10.798	10.023	6.79%	-0.87%	99.1%
	6	10.000	10.646	9.846	6.46%	-1.54%	98.5%
	7	9.764	10.339	9.738	5.89%	-0.27%	99.7%
	8	10.099	10.607	10.083	5.03%	-0.16%	99.8%
	9	9.898	10.527	9.832	6.35%	-0.67%	99.3%
0.75% RH	1	9.660	9.465	7.360	-2.02%	-23.81%	76.2%
	2	10.124	10.084	8.590	-0.40%	-15.15%	84.8%
	3	10.035	10.797	8.611	7.59%	-14.19%	85.8%
	4	9.676	9.918	9.411	2.50%	-2.74%	97.3%
	5	9.936	10.286	9.724	3.52%	-2.13%	97.9%
	6	10.243	10.537	10.087	2.87%	-1.52%	98.5%
	7	10.11	10.580	10.002	4.65%	-1.07%	98.9%
	8	10.135	10.574	9.964	4.33%	-1.69%	98.3%
	9	9.989	10.414	9.516	4.25%	-4.74%	95.3%

Block Type	Average Water Absorption (%)	SD	Average Mass Loss (%)	SD	Average Mass Retention (%)	SD
No Fibre	7.49%	0.72%	-2.75%	6.49%	97.3%	6.5%
0.25% RH	7.22%	0.44%	-1.12%	0.35%	98.9%	0.3%
0.25% SG	8.24%	1.08%	-0.31%	1.72%	99.7%	1.7%
0.5% RH	6.44%	0.63%	-1.11%	0.78%	98.9%	0.8%
0.75% RH	4.25%	1.68%	-7.45%	8.21%	92.6%	8.2%

B.5.2 Twelve Cycles

Block Type	Block No.	Weight Before (kg)	Weight After (kg)		Water Absorption (%)	Mass Loss (%)	Retention (%)
			Wet	Dry			
		25-May-20	19-Jun-20	20-Jul-20			
No Fibre	1	9.809	10.551	9.686	7.56%	-1.25%	98.7%
	2	9.913	10.665	9.882	7.59%	-0.31%	99.7%
	3	9.807	10.576	9.712	7.84%	-0.97%	99.0%
	4	9.700	10.297	9.741	6.15%	0.42%	100.4%
	5	9.714	10.370	9.739	6.75%	0.26%	100.3%
	6	10.022	10.565	10.065	5.42%	0.43%	100.4%
	7	9.866	10.558	9.766	7.01%	-1.01%	99.0%
	8	9.651	10.370	9.709	7.45%	0.60%	100.6%
	9	9.576	10.340	9.612	7.98%	0.38%	100.4%
0.25% RH	1	9.885	10.820	9.9	9.46%	0.15%	100.2%
	2	9.936	10.854	9.972	9.24%	0.36%	100.4%
	3	10.013	10.880	10.036	8.66%	0.23%	100.2%
	4	9.699	10.459	9.724	7.84%	0.26%	100.3%
	5	10.148	10.901	10.161	7.42%	0.13%	100.1%
	6	10.103	10.893	10.112	7.82%	0.09%	100.1%
	7	9.876	10.760	9.926	8.95%	0.51%	100.5%
	8	9.72	10.535	9.752	8.38%	0.33%	100.3%
	9	9.965	10.786	9.972	8.24%	0.07%	100.1%
0.25% SG	1	9.965	10.733	9.861	7.71%	-1.04%	99.0%
	2	9.722	10.606	9.74	9.09%	0.19%	100.2%
	3	9.426	10.322	9.35	9.51%	-0.81%	99.2%
	4	9.714	10.605	9.705	9.17%	-0.09%	99.9%
	5	9.633	10.505	9.647	9.05%	0.15%	100.1%
	6	9.920	10.670	9.901	7.56%	-0.19%	99.8%
	7	9.365	10.282	9.388	9.79%	0.25%	100.2%
	8	9.768	10.521	9.768	7.71%	0.00%	100.0%
	9	10.094	10.794	10.12	6.93%	0.26%	100.3%
0.5% RH	1	9.972	10.727	9.953	7.57%	-0.19%	99.8%
	2	10.128	10.907	10.125	7.69%	-0.03%	100.0%
	3	9.597	10.544	9.329	9.87%	-2.79%	97.2%
	4	10.129	10.918	10.03	7.79%	-0.98%	99.0%
	5	9.861	10.79	9.783	9.42%	-0.79%	99.2%

	6	10.042	10.773	9.917	7.28%	-1.24%	98.8%
	7	9.735	10.576	9.731	8.64%	-0.04%	100.0%
	8	9.962	10.688	9.91	7.29%	-0.52%	99.5%
	9	10.313	11.049	10.309	7.14%	-0.04%	100.0%
0.75% RH	1	10.095	10.841	10.009	7.39%	-0.85%	99.1%
	2	9.991	10.753	9.925	7.63%	-0.66%	99.3%
	3	9.889	10.560	9.697	6.79%	-1.94%	98.1%
	4	9.671	10.343	9.388	6.95%	-2.93%	97.1%
	5	9.889	10.565	9.686	6.84%	-2.05%	97.9%
	6	9.904	10.541	9.628	6.43%	-2.79%	97.2%
	7	9.836	10.599	9.587	7.76%	-2.53%	97.5%
	8	10.040	10.775	9.923	7.32%	-1.17%	98.8%
	9	9.910	10.576	9.608	6.72%	-3.05%	97.0%

Block Type	Average Water Absorption (%)	SD	Average Mass Loss (%)	SD	Average Mass Retention (%)	SD
No Fibre	7.08%	0.85%	-0.16%	0.74%	99.8%	0.7%
0.25% RH	8.45%	0.69%	0.24%	0.14%	100.2%	0.1%
0.25% SG	8.50%	1.02%	-0.14%	0.47%	99.9%	0.5%
0.5% RH	8.08%	1.00%	-0.74%	0.89%	99.3%	0.9%
0.75% RH	7.09%	0.45%	-2.00%	0.91%	98.0%	0.9%

B.6 Compressive and Flexural Strength Retention

Block Type	No. Freeze-Thaw Cycles	Mass Retention (%)		Dry Compressive Strength (MPa)			Dry Flexural Strength (MPa)		
		Average	SD	Average	SD	Retention (%)	Average	SD	Retention (%)
No Fibre	0	-	-	8.22	0.13	-	1.344	0.234	-
	6	97.3%	6.5%	11.09	1.38	135%	1.898	-	141%
	12	99.8%	0.7%	10.02	0.82	122%	1.719	-	128%
0.25% Switchgrass	0	-	-	8.27	0.77	-	0.919	0.083	-
	6	99.7%	1.7%	8.98	0.94	109%	0.621	-	68%
	12	99.9%	0.5%	9.28	0.56	112%	0.800	-	87%
0.125% Straw	0	-	-	8.96	0.71	-	0.836	0.214	-
	6	-	-	-	-	-	-	-	-
	12	-	-	-	-	-	-	-	-
0.25% Straw	0	-	-	8.84	0.60	-	0.778	0.230	-
	6	-	-	-	-	-	-	-	-
	12	-	-	-	-	-	-	-	-
0.75% Straw	0	-	-	6.98	0.19	-	0.373	0.077	-
	6	-	-	-	-	-	-	-	-
	12	-	-	-	-	-	-	-	-
0.25% Rice Hull	0	-	-	7.95	0.24	-	1.243	0.328	-
	6	98.9%	0.3%	10.09	0.76	127%	1.062	-	85%
	12	100.2%	0.1%	9.63	0.30	121%	1.324	-	107%
0.5% Rice Hull	0	-	-	8.06	0.28	-	0.897	0.089	-
	6	98.9%	0.8%	10.05	0.44	125%	0.913	-	102%
	12	99.3%	0.9%	9.21	0.72	114%	1.069	-	119%
0.75% Rice Hull	0	-	-	7.18	0.32	-	0.752	0.194	-
	6	92.6%	8.2%	8.53	0.64	119%	0.506	-	67%
	12	98.0%	0.9%	7.80	0.61	109%	0.996	-	132%

B.7 ANOVA of the Effect of Fibre Type and Quantity on CEB Strength

B.7.1 Compressive Strength

Sample Groups	X	SSW	SSB	MSW	MSB	DF	F	$F_{critical}$ ($F_{0.05}$)	Result	Conclusion
(0, 0.25 SG)	8.25	1.24	<0.01	0.31	<0.01	(4,1)	0.01	7.71	Accept	Not
(0, 0.125 S)	8.59	1.02	0.81	0.26	0.81	(4,1)	3.18	7.71	Accept	Not
(0, 0.25 S)	8.53	0.77	0.57	0.19	0.57	(4,1)	2.95	7.71	Accept	Not
(0, 0.75 S)	7.60	0.11	2.33	0.03	2.33	(4,1)	86.61	7.71	Reject	Significant
(0, 0.25 RH)	8.08	0.15	0.11	0.04	0.11	(4,1)	3.00	7.71	Accept	Not
(0, 0.50 RH)	8.14	0.19	0.04	0.05	0.04	(4,1)	0.77	7.71	Accept	Not
(0, 0.75 RH)	7.70	0.24	1.63	0.06	1.63	(4,1)	27.64	7.71	Reject	Significant
(0.25 SG, 0.25 S)	8.56	1.94	0.48	0.49	0.48	(4,1)	0.98	7.71	Accept	Not
(0.25 S, 0.25 RH)	8.39	0.85	1.19	0.21	1.19	(4,1)	5.57	7.71	Accept	Not
(0.25 SG, 0.25 RH)	8.11	1.32	0.16	0.33	0.16	(4,1)	0.48	7.71	Accept	Not
(0.75 S, 0.75 RH)	7.08	0.28	0.06	0.07	0.06	(4,1)	0.90	7.71	Accept	Not
(0.25 RH, 0.50 RH)	8.01	0.27	0.02	0.07	0.02	(4,1)	0.30	7.71	Accept	Not
(0.25 RH, 0.75 RH)	7.56	0.32	0.89	0.08	0.89	(4,1)	11.22	7.71	Reject	Significant
(0.50 RH, 0.75 RH)	7.62	0.36	1.18	0.09	1.18	(4,1)	13.13	7.71	Reject	Significant
(0.125 S, 0.25 S)	8.90	1.73	0.02	0.43	0.02	(4,1)	0.05	7.71	Accept	Not
(0.125 S, 0.75 S)	7.97	1.06	5.90	0.27	5.90	(4,1)	22.22	7.71	Reject	Significant
(0.25 S, 0.75 S)	7.91	0.81	5.21	0.20	5.21	(4,1)	25.68	7.71	Reject	Significant
(0.125 S, 0.25 SG)	8.62	2.19	0.70	0.55	0.70	(4,1)	1.28	7.71	Accept	Not

B.7.2 Flexural Strength

Sample Groups	X	SSW	SSB	MSW	MSB	DF	F	$F_{critical}$ ($F_{0.05}$)	Result	Conclusion
(0, 0.25 SG)	1.13	0.12	0.27	0.03	0.27	(4,1)	8.76	7.71	Reject	Significant
(0, 0.125 S)	1.09	0.20	0.39	0.05	0.39	(4,1)	7.70	7.71	Accept	Not
(0, 0.25 S)	1.06	0.22	0.48	0.05	0.48	(4,1)	8.94	7.71	Reject	Significant
(0, 0.75 S)	0.86	0.12	1.42	0.03	1.42	(4,1)	46.49	7.71	Reject	Significant
(0, 0.25 RH)	1.29	0.33	0.02	0.08	0.02	(4,1)	0.19	7.71	Accept	Not
(0, 0.50 RH)	1.12	0.13	0.30	0.03	0.30	(4,1)	9.57	7.71	Reject	Significant
(0, 0.75 RH)	1.05	0.19	0.53	0.05	0.53	(4,1)	11.37	7.71	Reject	Significant
(0.75 S, 0.75 RH)	0.56	0.087	0.215	0.022	0.215	(4,1)	9.88	7.71	Reject	Significant
(0.25 SG, 0.25 S)	0.85	0.119	0.03	0.03	0.03	(4,1)	1.01	7.71	Accept	Not
(0.25 S, 0.25 RH)	1.01	0.321	0.324	0.08	0.324	(4,1)	4.04	7.71	Accept	Not
(0.25 SG, 0.25 RH)	1.08	0.229	0.157	0.057	0.157	(4,1)	2.74	7.71	Accept	Not
(0.25 RH, 0.50 RH)	1.07	0.23	0.18	0.06	0.18	(4,1)	3.11	7.71	Accept	Not
(0.25 RH, 0.75 RH)	1.00	0.29	0.36	0.07	0.36	(4,1)	4.97	7.71	Accept	Not
(0.50 RH, 0.75 RH)	0.82	0.09	0.03	0.02	0.03	(4,1)	1.38	7.71	Accept	Not
(0.125 S, 0.25 S)	0.81	0.20	0.01	0.05	0.01	(4,1)	0.10	7.71	Accept	Not
(0.125 S, 0.75 S)	0.60	0.10	0.32	0.03	0.32	(4,1)	12.45	7.71	Reject	Significant
(0.25 S, 0.75 S)	0.58	0.12	0.25	0.03	0.25	(4,1)	8.40	7.71	Reject	Significant
(0.125 S, 0.25 SG)	0.88	0.11	0.01	0.03	0.01	(4,1)	0.40	7.71	Accept	Not

B.8 ANOVA of the Effect of Freeze-Thaw Cycles on CEB Strength

B.8.1 Compressive Strength

Sample Groups	X	SSW	SSB	MSW	MSB	DF	F	$F_{critical}$ ($F_{0.05}$)	Result	Conclusion
(0-0, 0-6)	9.65	3.83	12.30	0.96	12.30	(4,1)	12.84	7.71	Reject	Significant
(0-0, 0-12)	9.12	1.39	4.84	0.35	4.84	(4,1)	13.95	7.71	Reject	Significant
(0-6, 0-12)	10.55	5.15	1.71	1.29	1.71	(4,1)	1.33	7.71	Accept	Not
(0.25 SG-0, 0.25 SG-6)	8.63	2.96	0.75	0.74	0.75	(4,1)	1.01	7.71	Accept	Not
(0.25 SG-0, 0.25 SG-12)	8.78	1.83	1.52	0.46	1.52	(4,1)	3.33	7.71	Accept	Not
(0.25 SG-6, 0.25 SG-12)	9.13	2.40	0.14	0.60	0.14	(4,1)	0.23	7.71	Accept	Not
(0.25 RH-0, 0.25 RH-6)	9.02	1.29	6.86	0.32	6.86	(4,1)	21.36	7.71	Reject	Significant
(0.25 RH-0, 0.25 RH-12)	8.79	0.30	4.23	0.08	4.23	(4,1)	56.38	7.71	Reject	Significant
(0.25 RH-6, 0.25 RH-12)	9.86	1.35	0.32	0.34	0.32	(4,1)	0.94	7.71	Accept	Not
(0.50 RH-0, 0.50 RH-6)	9.06	0.54	5.94	0.14	5.94	(4,1)	43.85	7.71	Reject	Significant
(0.50 RH-0, 0.50 RH-12)	8.64	1.18	1.97	0.30	1.97	(4,1)	6.68	7.71	Accept	Not
(0.50 RH-6, 0.50 RH-12)	9.63	1.42	1.07	0.35	1.07	(4,1)	3.01	7.71	Accept	Not
(0.75 RH-0, 0.75 RH-6)	7.85	1.02	2.75	0.26	2.75	(4,1)	10.73	7.71	Reject	Significant
(0.75 RH-0, 0.75 RH-12)	7.49	0.95	0.58	0.24	0.58	(4,1)	2.45	7.71	Accept	Not
(0.75 RH-6, 0.75 RH-12)	8.17	1.58	0.80	0.39	0.80	(4,1)	2.03	7.71	Accept	Not