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MECHANICAL PROPERTIES OF ON-SITE MANUFACTURED COMPRESSED EARTH BLOCKS

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Abstract: Compressed earth blocks (CEBs) use ancient building techniques to provide a sustainable building solution to substitute industrial building materials. The CEBs used in this project were manufactured on-site by an experienced builder in Coburg, Ontario, Canada using two soil types: coarse and fine, with and without the addition of a natural fibres (*Phragmites australis*). Four block mixes were tested: coarse soil with and without *Phragmites*, and fine soil with and without *Phragmites*. The CEBs were tested in compression and in flexure, at air-dry state. The compressive strength of the blocks was observed to increase when *Phragmites* were added, however this increase is likely statistically insignificant. The *Phragmites* had no significant effect on the flexural strength of the blocks, but the type of soil used in the block (coarse or fine) was observed to have a larger effect on structural performance. By comparing the compressive strengths achieved in this project with the required strength from the Australian Earth Building Handbook and the International Building Code, strengths were deemed adequate. It was concluded that the *Phragmites* fibres likely decreased the flexural strength of the fine soil blocks due to inadequate bond capabilities and a naturally in-flexible nature. The *Phragmites* had marginal effects on the flexural capacity of the course soil blocks. More consideration should be given to soil type in addition to fibre type for improvement of structural performance. If optimum performance can be obtained from the CEBs, they can be a useful building material for remote Indigenous communities where access to conventional building materials is limited.

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 comprised 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, et al. 2016), thus creating a sustainable building solution.

2 BACKGROUND AND OBJECTIVES

2.1 Literature Review

Earth construction is a relatively new concept and no generalized testing procedure has been developed. A procedure for quality control strength testing of compressed earth blocks has been adopted in many national standards and codes of practice that is similar to that used for fired clay and concrete blocks. However, the RILEM Technical Committee 164 (Morel, Pkla and Walker 2007) has proposed a test method that is radically different from traditional concrete block testing methods. Morel, Pkla and Walker (2007) suggest testing the blocks stacked together with a mortar joint in a prism formation.

Blocks constructed from plain soil are referred to as un-stabilized blocks, and often have poor tensile, compressive, and shearing strengths in both wet and dry conditions (Smigelski 2016). Morel, Pkla, and Walker (2007) found that the compressive strength of saturated un-stabilized compressed earth blocks is zero. For this reason, chemical additives referred to as binders or stabilizers are added to the CEB mixtures. Typical binders can 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. Mak, MacDougall, and Fam (2015) looked at the effect of adding a commercial silane/siloxane water-repellent admixture (Plasticure), to the CEBs. The study found that the addition of Plasticure had no significant impact on the dry strengths of the CEBs. The wet strength was significantly stronger with the inclusion of Plasticure than without. Typical values of compressive strength of manually pressed CEBs are in a range of 2-3 MPa, which restricts their use to only one-storey buildings (Morel, Pkla and Walker 2007), (Mostafa and Uddin 2015).

Soil blocks reinforced with fibres show an improved performance in resisting cracks and crack propagation and increase in tensile strength (Donkor and Obonyo 2016). Fibres can also decrease the compressive strength of the earth block depending on the fibre and matrix properties (Loborel-Preneron, et al. 2016). Visual assessments of crack zones of fibre-reinforced beams in Donkor and Obonyo's (2016) study show many of the fibres bridging the crack and holding the cracked sections together. Usually very low percentages of fibres are needed to achieve optimal performance of fibre-reinforced soil blocks, with an optimum fibre content found to be between 0.4% and 0.8% by weight. Natural fibres are the most economical fibres to use to produce CEBs, 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).

Other fibre types such as banana fibres and plant aggregates are being considered for use in CEB design. Banana fibres are widely available worldwide as agricultural waste from banana cultivation; they are also environmentally friendly and present important attributes such as low density, light weight, low cost, high tensile strength, and water and fire resistance. The highest flexural and compressive strength values for the utilization of banana fibres were recorded at reinforcement with 50mm fibres and 0.35% fibre content by weight (Mostafa and Uddin 2015). Plant aggregates have a similar effect on the tensile and flexural strengths of the CEBs as other natural fibres. The main advantage of adding plant aggregates or fibres to earth materials over other options is to improve their thermal insulation (to save energy). The thermal conductivity is directly linked with the density of the material, which is decreased as the aggregate or fibre content increases (Loborel-Preneron, et al. 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.

Nagaraj, Rajesh, and Sravan (2016) argue that soils available in nature are not suitable to prepare stabilized CEBs. The paper suggests reconstituting of the soil such that sand, silt and clay are in certain proportions. For blocks that are manufactured on-site this may not be a viable option, thus, other alternatives should be considered. The same study found that using cement alone as a stabilizer will yield satisfactory results only when there is a lower clay content in the block (around 13%), and that higher proportions of clay in soil can still be favorably used in the preparation of stabilized CEBs by using lime in combination with cement (Nagaraj, Rajesh and Sravan 2016). Most of the literature focuses 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 the CEBs, in terms of coarse-grained particles versus fine-grained particles.

2.2 Objectives

Some concerns exist with the mechanical properties of compressed earth blocks. Previous studies have shown that the addition of a cementitious stabilizer as well as a type of reinforcing fibre can improve its properties (Morel, Pkla and Walker 2007), (Donkor and Obonyo 2016).

The goal of this project was to determine the effect of the soil gradation and invasive *Phragmites* on the compressive and flexural strength of the CEBs. The project goal was achieved by performing various tests and was defined by two main objectives, which are as follows:

- Determining the effect of soil gradation on the mechanical properties of the CEBs at air-dry state;
- Determine the effect of *Phragmites* on the mechanical properties of the CEBs at air-dry state.

3 METHOD

Four block types were tested throughout the duration of this project: coarse soil with no fibre, fine soil with no fibre, coarse soil with *Phragmites*, and fine soil with *Phragmites*. From January 2018 to April 2018, thirty-seven CEBs were tested, in compression and flexure at air-dry state. Table 1 outlines the block types and test matrix.

Table 1: Description of CEB types and associated test matrix.

Type	Soil Type	Description	Code	Tests
No Reinforcement	Coarse	Coarse clay soil, cement, and lime	0	3 Compression 4 Flexure
	Fine	Fine clay soil, cement, and lime	1	3 Compression 3 Flexure
Phragmites Reinforcement	Coarse	Coarse clay soil, cement, lime, and *Phragmites*	0F	3 Compression 3 Flexure
	Fine	Fine clay soil, cement, lime, and *Phragmites*	1F	4 Compression 4 Flexure

3.1 CEB Preparation

The CEBs were constructed by an experienced builder at Fifth Wind Farm in Coburg, Ontario, Canada using local earth found on the property. This material is a clay soil found in most parts of southern Ontario. The soil composition in the CEBs is the same as the soil used in an investigation conducted by Mak, MacDougall, and Fam (2015), containing 23.3% clay-sized particles by mass. The soil was dug from the farm at the same time creating a pond on site. After the soil was excavated, it was processed using a filter to screen out large rocks and a hammer mill to break up the rest of the soil into a finer mixture. The processed soil was then mixed using a one-yard concrete mixer. During mixing, cement-lime stabilizer was added along with the invasive form of *Phragmites (*where applicable). Trial-and-error has found that adding 2.5% Type 1 Portland cement and 2.5% hydrated dolomite lime in combination is enough to stabilize the clay soil in the CEBs and prevent the blocks from eroding during adverse weather conditions. The blocks were mechanically compressed using an AECT 3,500 Compressed Earth Block Machine with an average compressive pressure of 10.7 MPa. Table 2 outlines the ingredient composition of each of the four types of CEBs tested.

Table 2: Block composition of each type of CEB.

Code	Cement (% by mass)	Lime (% by mass)	*Phragmites* (% by volume)
0	2.50%	2.50%	-
0F	2.50%	2.50%	-
1	2.50%	2.50%	0.50%
1F	2.50%	2.50%	0.50%

3.2 Testing Apparatus and Procedure

3.2.1 Compression

The Forney Testing Machine is shown in Figure 1a) and was used to test the CEBs in uniaxial compression.

(a) Forney testing machine (b) Compression test set-up

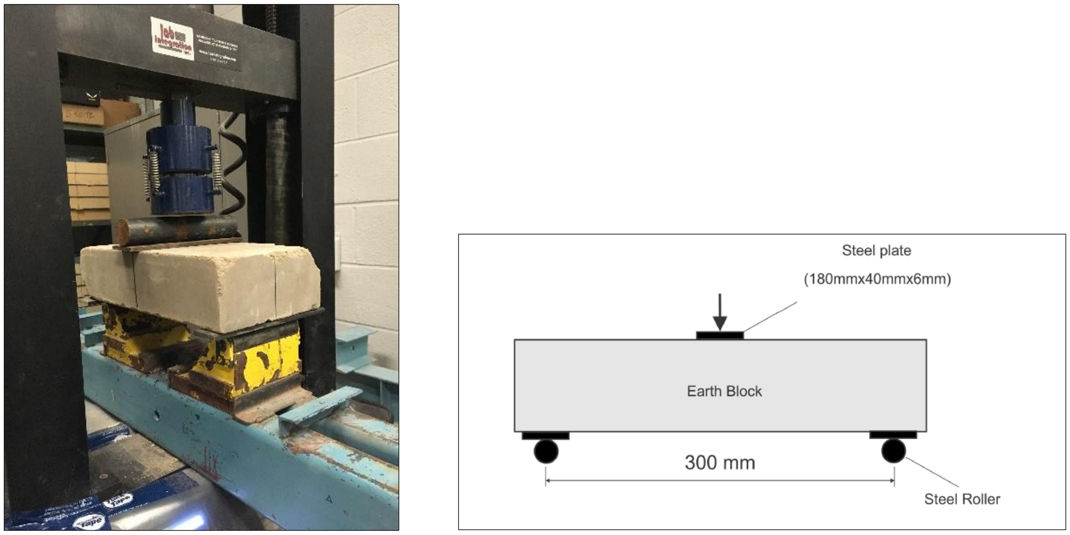
Figure 1: Unconfined compression test.

The method used for testing the CEBs in compression is adapted from the RILEM Technical Committee 164, which has proposed an alternative method for determining the unconfined compressive strength of compressed earth blocks. With the RILEM testing method, the CEBs are halved and stacked bonded using an earth mortar bed joint and then capped with a layer of neoprene to enable even transfer of stress between platens and blocks. A sheet of Teflon is placed between the platen and block at each end to minimize friction (Morel, Pkla and Walker 2007). The purpose of this test configuration is to replicate the performance of the CEBs as they would act in construction.

For the purpose of this investigation, the unconfined compressive strength of the prisms was found using a modified form of the RILEM testing method which is shown in Figure 1b). Two blocks were stacked un-bonded and were capped using two 3mm plywood sheets. Compressive force was applied at a rate of 0.25 MPa/s until failure. The peak load was used to calculate the compressive strength of the two-block prism given the surface area to which the load was applied.

3.2.2 Flexure

The Unit-O-Matic Testing Machine shown in Figure 2a) was used to test the flexural strength of the CEBs. The tests were conducted according to ASTM C67-07 (ASTM 2007) with the modification from loading the block at third-points to loading the block at the midpoint.



(a) Unit-O-Matric testing machine (b) Flexural strength test set-up

Figure 2: Flexural test set-up and Unite-O-Matic testing apparatus.

The block was loaded in three-point bending, as shown in Figure 2b). A steel plate was placed on the block to which the load was applied at the midpoint. The CEBs rested on two steel plates which were placed on rollers. 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 0.25mm/min until failure, and the peak applied load was recorded (in kilonewtons) for each sample.

The moment of inertia of each block was calculated given the measured width and height of the CEBs. The moment induced at the midspan of the block was calculated given the peak applied load.

4 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.

4.1 Compression

The Forney Testing Machine was used to test two blocks stacked un-bonded. Three repetitions were completed for the coarse soil with and without *Phragmites* and fine soil unreinforced, and four repetitions were completed for fine soil with *Phragmites*. Table 3 summarizes the peak compressive strength of each prism type, given the peak load achieved and surface area to which the load was applied. A strength increase of 11% was achieved for the course-grained soil with the addition of *Phragmites*. The fine-soil block strength increased about 3% with the addition of *Phragmites.*

Table 3: Results of compression test showing peak compressive strength of the CEBs.

Code	Length (mm)	Width (mm)	Height (mm)	Load Surface Area (mm^2)	Peak Dry Strength (MPa)
0	355	180	78	63,900	12.7 ± 0.6
0F	355	180	78	63,900	14.1 ± 0.7
1	355	180	78	63,900	10.6 ± 0.7
1F	355	180	78	63,900	10.9 ± 0.8

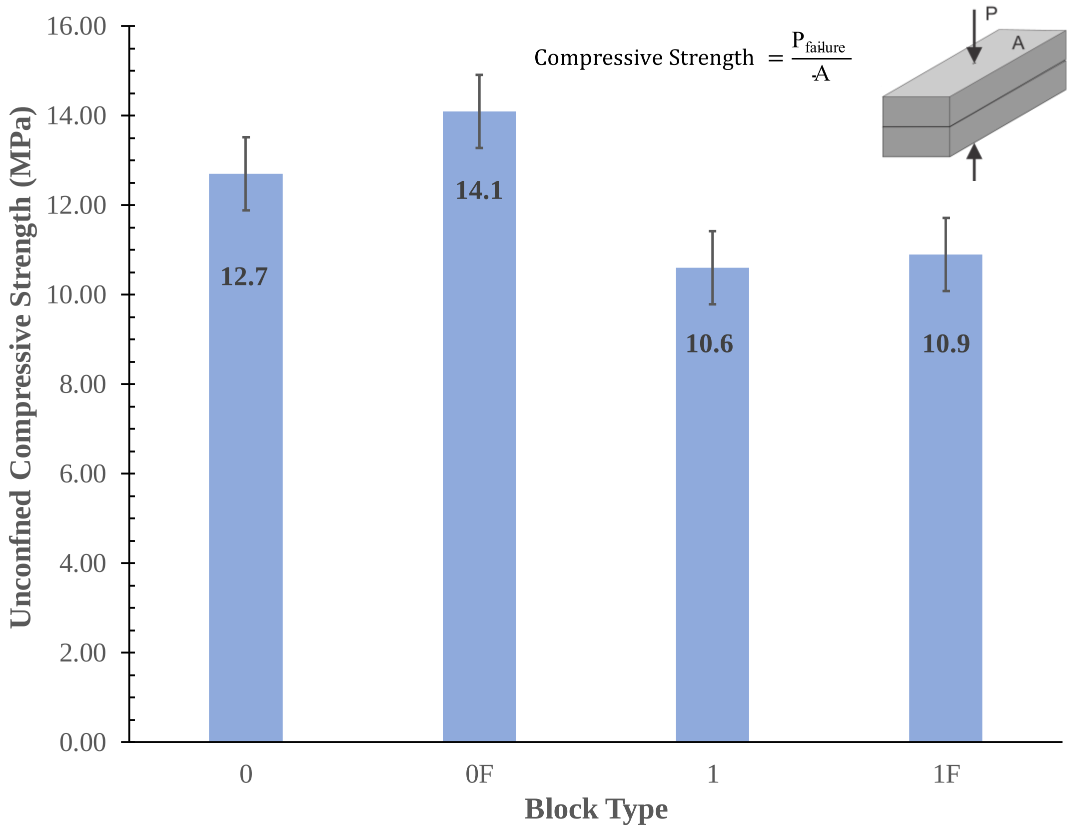
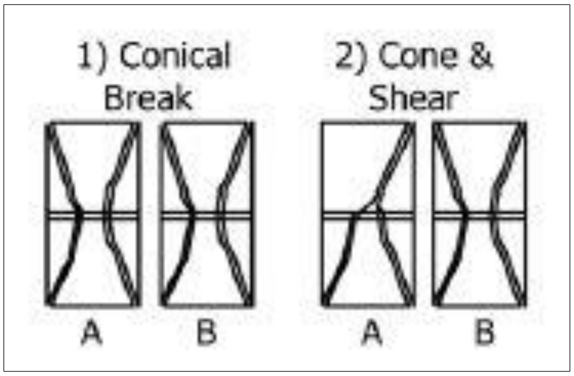


Figure 3: Unconfined compressive strength for each prism type.

According to ASTM C1314, the blocks mainly demonstrated a conical break or cone and shear failure mechanism (ASTM 2018) as shown in Figure 4. The graphical representation of the data in Figure 3 shows that there is likely no statistical significance between the strength of the blocks with *Phragmites* and the unreinforced blocks. The strength of fine soil with *Phragmites* is greater than the average fine soil strength unreinforced, but the standard deviations associated with each value place these results in the same strength range. This is also the case for the coarse soil block types. The stress range for the coarse soil type with *Phragmites* coincides with the stress range for the fine soil type unreinforced, indicating that there is likely no statistical significance between these values.

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 shows that the stress range for the coarse soil block type is outside of the fine soil block type, which may indicate some statistical significance, but will require further statistical analysis. The compressive strength increased 20% from the use of fine soil to coarse soil for the unreinforced blocks and 29% from the use of fine soil to coarse soil for the blocks reinforced with *Phragmites.*



a) ASTM Modes of Failure *(ASTM 2018)*

b) Unreinforced fine soil failure

Figure 4: CEB versus failure modes after being loaded to failure in compression.

4.2 Flexure

The Unit-O-Matic Testing Machine was used to test all the blocks in three-point bending to determine the flexural strength. Three repetitions were completed for the fine soil without reinforcement and coarse soil with *Phragmites*. Four repetitions were completed for coarse soil without reinforcement and fine soil with *Phragmites.*

Table 4 summarizes the peak flexural strength of each block type, given the peak load achieved during loading. The addition of *Phragmites* reduced the flexural capacity of the coarse soil blocks by about 5% and the fine soil blocks by about 25%. There was a 72% increase in flexural capacity from the fine soil blocks to coarse soil blocks with *Phragmites*, and a 36% increase in flexural capacity from the unreinforced fine soil blocks to the unreinforced coarse soil blocks.

Table 4: Results of flexure tests showing peak flexural strength of the CEBs.

Code	Length (mm)	Width (mm)	Height (mm)	Moment of Inertia (mm^4)	Peak Strength (MPa)
0	355	178	76	6581680	1.92 ± 0.91
0F	355	178	77	6771906	1.82 ± 0.51
1	355	179	79	7294026	1.41 ± 0.52
1F	355	179	77	6924768	1.06 ± 0.15

Figure 5 shows a graphical representation of the results of this test. The standard deviation for the dry coarse-grained soil with and without fibre place the flexural stress of each block type in the same stress range. This indicates that there is likely no statistical significance associated with the addition of *Phragmites* to the coarse-grained soil on the flexural strength of the blocks. Similarly, the fine-grained soil blocks with and without fibres are in the same stress range indicating no statistical significance associated with the addition of *Phragmites* to the fine-grained blocks on the flexural strength of the CEBs. 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 indicates that there is likely no statistical significance; however, this should be confirmed by a more in depth statistical analysis.

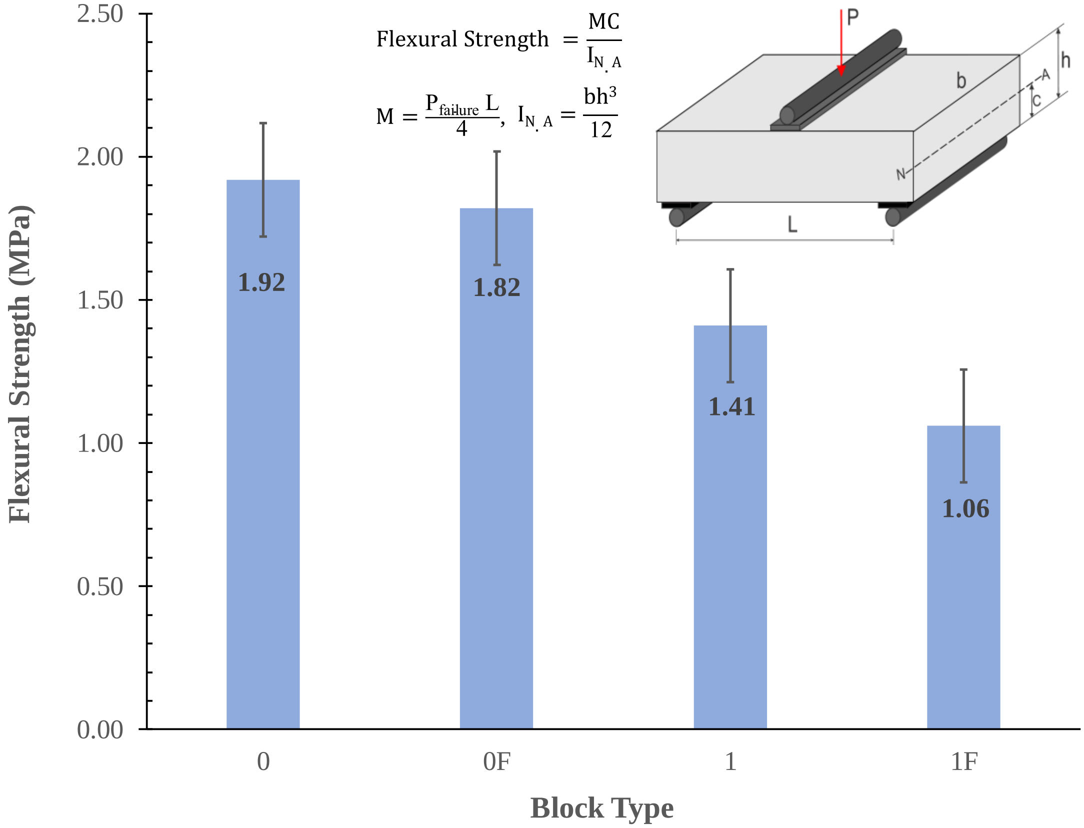


Figure 5: Average flexural strength of each block type.

All the blocks failed in flexure. Some shear cracks were noted to occur in some of the samples; however the main failure mechanism was a flexural crack at the midspan of the block. Figure 6a) shows an unreinforced fine soil block with a flexural crack at midspan.

The reduction in flexural capacity seen with the addition of Phragmites is possibly due to the size and stiffness of the fibres. Figure 6b) shows a large fibre that is bridging a flexural crack in the block. The large size of the fibre in combination with its inflexible nature impedes the bonding capabilities, and therefore instead of acting as reinforcement to the CEB the fibre created a point of weakness and pulls out of the block when loaded.

a) Flexural cracks after being loaded to failure   b) Fibre bridging flexural crack

Figure 6: Cracking in CEBs after being loaded to failure in three-point bending.

The results from this investigation are preliminary and there is continuing work underway at Queen's University to further optimize the use of natural fibres in CEB construction by testing different fibre types, volumes and lengths to improve the flexural strength of the blocks.

4.3 Block Construction

Due to manufacturing constraints, there was a slight variance of the height of the blocks typically ranging from 75mm to 80mm. Larger block thicknesses will result in high flexural capacity that may not be representative of the average flexural capacity of the CEBs. To circumvent this inconsistency in block height, the soil mixture should be weighed prior to compression to ensure the same amount of soil is being used in each block. Also, the compacting pressure and duration should remain constant for the entire sample of blocks being constructed to ensure as much consistency between blocks as possible.

After the blocks came out of the hydraulic press machine they were transported by hand to where they were stacked and dried. As the blocks were still wet during this process some pre-cracks formed and areas where the soil had crumbled away resulted in loss of surface area. The pre-cracks resulted in an initial lower flexural strength than could have been achieved with an uncracked section, and the loss in surface area decreases the ultimate compressive strength of the blocks. Developing a new method to minimize transportation of the blocks until after they have reached air-dry state should help to circumvent this issue.

4.4 Comparison of Compressive and Flexural Strength Values from Literature

Australia's 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). The strengths of all the block types in this investigation exceed this minimum value. A study by Mak et al. (2015) found that the compressive values for clay-sized materials with the addition of 5% cement stabilizer and no fibre reinforcement was 10.60 ± 0.41 MPa (Mak, Maracle and MacDougall 2015), which is similar to the values of compressive strength of the fine-grained soil specimens both with and without fibre reinforcement tested in this investigation.

In the initial stages of this investigation it was predicted that the *Phragmites* would improve the flexural properties of the CEBs by bridging cracks during loading and thus extending the peak load carrying capacity. A study conducted by Donkor and Obonyo (2016) considered the effects of polypropylene fibres in earth blocks. The study concluded that the fibres did improve post-crack performance of the blocks, however both fibre pullout and fracture were observed during specimen testing (Donkor and Obonyo 2016). This is similar to what was observed in this investigation, where the natural invasive *Phragmites* pulled out from the block due to lack of bond between the soil mixture and the fibres.

The peak flexural strength of the CEBs with no fibre reinforcement determined by Donkor and Obonyo was found to be 0.47 ± 0.03 MPa which is 76% less than the coarse-grained unreinforced blocks tested in this investigation and 67% less than the fine-grained unreinforced blocks tested in this investigation. The peak flexural strength in Donkor and Obonyo's experiment occurred at a fibre content of 0.6% and was found to be 0.84 ± 0.12 MPa. Even at the optimum volume content this flexural strength is still less than both the coarse-grained and fine-grained specimens with a 0.5% volume of *Phragmites*.

5 CONCLUSIONS

Four block types were tested in direct 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. It was predicted that the fibres would contribute tensile and flexural capacity to the CEBs, but would have little effect on the unconfined compressive strength. From the results, the addition of *Phragmites* to the blocks likely had no statistically significant effect on the flexural capacity of either the coarse-grained soil or the fine-grained soil blocks. The fibres may have some significant effect on the compressive strength of the blocks, however further statistical analysis must be completed to confirm this. There is more evidence to show that the soil gradation used in the block may have a greater effect on the performance of the blocks in both compression and in flexure. Additional studies and tests should be conducted to determine the effects of soil gradation on the mechanical properties of CEBs. To improve the effectiveness of the *Phragmites* fibres, better bond must be created between the fibres and the soil mixture to prevent pull-out of the fibres from the block. Other types of natural fibres should be considered that may have better bond potential, and different fibre volumes should be tested to determine the optimum content of that fibre in compressed earth blocks.

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