Effect of Polypropylene Fiber Length on the Flexural and Compressive Strength of Compressed Stabilized Earth Blocks

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ABSTRACT
Earthen masonry is generally brittle, weak and poor in damage resilience. There is historic evidence that natural fibers such as straw and horsehair have been used to reinforce earthen masonry to prevent desiccation cracks and improve tensile strength. However, fibers have also been known to negatively affect mechanical properties such as compressive strength (an important quality control parameter for load bearing masonry) by creating voids and lowering density. This paper reports on findings of a study directed at investigating the feasibility of avoiding such problems in compressed and stabilized earth blocks through optimizing the fiber length when using soil from Newberry, Florida. Standard polypropylene fibers were selected for the study. The two different lengths of fibers studied were 54 mm and 27 mm. The test results showed a general improvement in compressive strength of the fiber reinforced matrices compared to the unreinforced ones. While an improvement in modulus of rupture (MOR) was observed for matrices reinforced with 54 mm fibers, results varied for the other fiber-reinforced matrices. An improvement in post-initial crack behavior was observed for all fiber-reinforced matrices compared to the unreinforced ones. The 54 mm fibers yielded the best results based on the influence on MOR, compressive strength, and deformability compared to the other matrices.

INTRODUCTION
Earth has been used as a construction material since early civilization. Adobe, molded earth, wattle and daub, and cob are all forms of earthen construction that have been in existence for centuries. Globally, about a third of the human population resides in earthen shelters. In developing countries, the number is estimated to be as high as 50% (Minke, 2009). The use of locally available materials is highly encouraged by proponents of the green building movement. It is generally accepted that earthen masonry is a green material considering that at it uses indigenous soils
thus reducing the use of manufactured materials (UN-Habitat, 2009). Some of the benefits of using compressed and stabilized earth blocks (CSEBs) include lower embodied energy levels compared to alternative materials (Mesbah et al. 2004; Minke, 2009; Kestner et al. 2010). For example, compared to a ton of fired clay bricks, a ton of 12% ordinary Portland cement (OPC) stabilized CSEBs uses only 42% of the energy input needed for the fired bricks and generates 62% of the equivalent CO₂ emissions generated by the fired bricks (Oti & Kinuthia 2012). The embodied energy of CSEBs largely depends on the type and quantity of chemical stabilizers and the type of presses used (Morton, 2008). The large-scale deployment would therefore make both ecological and economic sense. However, there are concerns with the use of earthen masonry based on it being brittle, weak and poor in damage resilience.

Some of these concerns are being addressed by exploring the use of CSEBs, which are stronger and more dimensionally stable than their unstabilized counterparts (Morel et al, 2007). CSEBs are produced by mixing soil with a stabilizer, slightly moistening the mixture, and compressing the mixture either manually or mechanically in a mold usually made of steel. Using between 4-10% of OPC as a stabilizing agent in CSEB production can result in a significant increase in compressive strength, water resistance, and dimensional stability of the blocks compared to traditional adobe. Such enhancements can promote the use of CSEBs in applications where the acceptable masonry options have been previously limited to fired clay and concrete masonry units (CMUs) (Morel et al, 2007). Despite the strength improvement achieved through using CSEBs, they are still brittle and considered weak compared to mainstream walling materials such as CMUs and fired clay bricks. Within the hurricane-prone Florida context, there is a further need to quantify the adequacy of earthen masonry with respect to resistance to high wind loads.

The aim of this study is to evaluate the technical feasibility of incorporating polypropylene (PP) fibers into CSEBs to enhance post-cracking damage resiliency, which is a key attribute in structures that are required to resist high wind loads. The work builds on the historic precedence of natural fibers being used as reinforcement in earthen masonry. Specific examples include the use of straw to reinforce sunbaked bricks, and horsehair to reinforce masonry mortar and plaster (ACI 544.1R, 1996). In modern applications, synthetic fibers are being incorporated in brittle, cementitious materials exhibiting low tensile strength and strain capacities to improve properties such as plastic shrinkage cracking, impact resistance, and toughness or ductility (Mesbah et al, 2004; Mohr et al, 2004; ACI 544.1R, 2010). When used in CSEBs, fibers create a network with the matrices that reduces shrinkage and improves tensile and shearing strengths (Rigassi, 1995; Namango, 2006; Morton, 2008). Studies investigating these parameters use both natural and synthetic fibers. It has been demonstrated that sisal (Namango 2006), coconut fiber (Khedari et al. 2005; Obonyo, 2011), straw (Binici et al. 2005), polyethylene (Elenga et al. 2011) can all be feasible options. On the basis of ecological metrics, natural fibers are preferable for CSEB reinforcement because of their being derived from renewable resources that are generally readily available at affordable costs. However when untreated, the fibers may have a negative impact on the mechanical properties of matrices (Elenga et al.
The highly alkaline environment created through OPC hydration degrades untreated fibers, which negatively affects the durability of concrete (ACI 544.1R, 1996). This has resulted in a growing interest in the use of synthetic fibers. For this reason, alkali resistant PP fibers were selected for this study.

It is also known that fibers can reduce density, create voids, result in micro-fractures at fiber-soil interfaces, and reduce compressive strength (Rigassi, 1995; Khedari et al. 2005; Namango, 2006; Morton, 2008). There is therefore a need to further investigate strategies for minimizing such negative results. There are also some discrepancies in findings by different researchers. For example, While Binici, et al. (2005), Namango, (2006), and Elenga et al. (2011) reported increases in compressive strength after fiber reinforcement, Khedari et al. (2005) reported a decrease in compressive strength. The premise of this paper is that the successful inclusion of fiber depends on type of material, length and diameter (aspect ratio), deformation geometry, and content (ACI 544.1R, 2010). For this research commercially available macro polypropylene (PP), fibers were used. PP fibers have been successfully used as secondary reinforcement in cementitious materials with some researchers demonstrating the significant role PP fibers can have on the mode and mechanisms of failure (Singh, 2011). Because CSEBs have some unique, masonry-specific limitations, there is a need for a comprehensive study of PP fibers as reinforcement to validate these findings. Material properties of PP fiber reinforced composites are affected by fiber volume, fiber geometry and length (aspect ratio), fiber surface conditions, method of production, and composition of the matrix (Banthia and Gupta, 2006; ACI 544.1R, 2010). The initial set of experiments focused on the influence of fiber length on the flexural and compressive strength of tested specimens. All the other fiber parameters were kept constant.

MATERIALS AND EXPERIMENTAL PROGRAM

Materials

The materials used included local soil (from Gainesville/Newberry, Florida), commonly available Type I ordinary Portland cement, and; commercially available “MasterFiber MAC Matrix” macro synthetic PP fibers obtained from BASF Corporation. The fiber is “stick-like” with an embossed surface to create deformations that provide mechanical anchorage. The fibers were used as both the commercially available length of 54 mm fibers and lengths of 27 mm cut from full-length fibers (Prochazka et al., 2010). The physical properties of the soil is presented in Table 1. The PP fibers used had a specific gravity of 0.91, tensile strength of 584 MPa and melting point of 160 °C.

Preparation of Specimens

Oven dried soil was run through a manual sifter with a 3.40 mm² mesh size to remove lumps for block production. The samples produced consisted of 4 plain and 16 PP fiber-reinforced CSEBs. The mix design is presented in Table 2. PP fibers were gradually introduced after the initial dry mixing of the sand and OPC. Mixing continued for 3 minutes to yield a uniform, thoroughly mixed batch with well-dispersed fibers. The dry batch was watered gradually while continuously mixing the
batch. The process lasted an additional 2 minutes upon which the soil-cement-fiber-water matrix was visually deemed to be homogeneous. A target moisture content of 9% obtained from the proctor compaction test was used as a guide when determining the required quantity of water.

A heavy-duty steel mold lined with form board was filled with matrix, covered with a form board lid, and compressed 51 mm down at a rate of 223 N/min. Compression was done using a Test Mark CM-500 series compression machine with a maximum compression capacity of 2,224 kN. All blocks were produced using 8.62 kg of matrix as part of an effort to minimize variations in block densities. The maximum compression pressure for each block was 1.6 MPa. The nominal dimensions of blocks produced were 413 mm (length) x 102 mm (width) x 102 mm (height). After de-molding, the fresh samples were left in situ for 24-hours prior to being moved and stacked. They were moist-cured under plastic sheets for 7 days and tested 28 days after fabrication.

### Table 1: Physical properties of soil

<table>
<thead>
<tr>
<th>Property</th>
<th>Composition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Liquid Limit (%)</td>
<td>33%</td>
</tr>
<tr>
<td>Plastic Limit (%)</td>
<td>(non-plastic)</td>
</tr>
<tr>
<td>Plasticity Index (%)</td>
<td>-</td>
</tr>
<tr>
<td>Sand (%)</td>
<td>87.3%</td>
</tr>
<tr>
<td>Clay (%)</td>
<td>12.2%</td>
</tr>
<tr>
<td>Silt (%)</td>
<td>1.5%</td>
</tr>
<tr>
<td>Optimum Moisture Content</td>
<td>9%</td>
</tr>
<tr>
<td>Maximum Dry Density</td>
<td>1784.5 kg/m³</td>
</tr>
</tbody>
</table>

### Table 2: Matrix Mix Proportions

<table>
<thead>
<tr>
<th>Mix Type</th>
<th>OPC Content</th>
<th>PP Fiber Content (Weight Fraction %)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>54 mm</td>
</tr>
<tr>
<td>#1</td>
<td>8%</td>
<td>-</td>
</tr>
<tr>
<td>#2</td>
<td>8%</td>
<td>0.2%</td>
</tr>
<tr>
<td>#3</td>
<td>8%</td>
<td>-</td>
</tr>
<tr>
<td>#4</td>
<td>8%</td>
<td>0.14%</td>
</tr>
<tr>
<td>#5</td>
<td>8%</td>
<td>0.06%</td>
</tr>
</tbody>
</table>

### Tests

Flexural strength testing was done using ASTM C293. A total of four samples were tested for each mix design. A Tinius Olsen compression machine with a maximum load capacity of 400 kN was used. The machine was set up with a mounting jig to record mid-span deflection. Two linear variable displacement transducers (LVDTs) with a stroke of ±17.8 mm were mounted on either side of the centerline of samples to record mid-span deflection. The rate of compression was set at 267 N/min until failure for the un-reinforced samples, and until a displacement of
10 mm was reached for the fiber reinforced samples. The values for flexural strength were computed using the equation;

\[ R = \frac{PL}{bdl} \]  

Where: \( R \) = modulus of rupture, \([N/mm^2]\); \( P \) = maximum applied load indicated by the testing machine, \([N]\); \( L \) = span length, \([305 mm]\); \( b \) = average width of specimen at the fracture \([mm]\); \( d \) = average depth of specimen at the fracture \([mm]\).

Portions of blocks broken in fracture were used for compressive strength testing. Cubes of size 102 mm x 102 mm were obtained from tested samples with a band saw. These were capped with a thin layer of gypsum plaster prior to testing to create an even surface to facilitate the uniform transfer of stresses between platens and specimens. A total of five cubes were tested for each of the four mix designs. The testing was done through applying uniaxial compression using a Tinius Olsen compression machine with a maximum load capacity of 400 kN. The rate of compression was set at 623 N/s until failure. This test set-up and procedure complied with ASTM D1634.

RESULTS AND DISCUSSION

Flexural Strength

Failure of all 20 tested samples occurred at the middle third of the span length. Each tested sample exhibited linear elastic characteristics prior to initial crack, which occurred at peak load. The load-deflection responses of the fiber-reinforced samples were different from the unreinforced ones. Typical load-deflection curves of the tested samples are presented in Figure 1. Mix type #2 yielded the highest average MOR followed by mix types #5, #1, #3, and #4 in that order. The average MOR of mix type #2 was 26% more than mix #1 (plain matrix). Mix #4 yielded the lowest MOR, which was 24% lower than mix #1 (plain matrix). The MOR for Mix #3 was 11.8% lower than mix #1 (plain matrix), while mix #5 was 2.5% higher than mix #1 (plain matrix).

In general, the fiber-reinforced matrices performed better in post crack behavior compared to the plain matrix. The findings also suggest that fibers affect the brittle behavior of the matrices. The unreinforced samples exhibited catastrophic failure in all instances. None of the fiber-reinforced matrices underwent complete failure even at 10 mm deflection. There was an observation of the fibers bridging the cracks (see Figure 1) explaining why there was not catastrophic failure.

The blocks reinforced with 54 mm long fibers had the best performance. The increase in peak load recorded for the specimens reinforced with the 54 mm fibers compared to the unreinforced specimens can be attributed to the fibers contributing to the bonding of particles surrounding individual fibers. This opposes particle movement and delays crack formation (Namango, 2006; Tang et al. 2006; Elenga et al. 2011). Similar to the observations made in this study, Bagherzadeh et al. (2012) reported a flexural strength increase in PP fiber reinforced lightweight cement composites compared to the unreinforced composites. They also observed longer PP fibers (12 mm) to perform better in flexural strength compared to shorter fibers (6
mm). The fibers at the crack zone bear the tensile stress transferred from the fracture section (Zhang et al. 2010). Kaufmann et al. (2004) and Bagherzadeh et al. (2011) established a relationship between increased aspect ratio of PP fibers and the ability of fibers to bridge micro cracks. In this study, the 54 mm (aspect ratio 42) fibers had a higher aspect ratio compared to the 27 mm fibers (aspect ratio 21).

![Typical load-deflection curves for blocks](image)

**Figure 1: Typical load-deflection curves for blocks**

The maximum post crack load for the matrices reinforced with 54 mm fibers was about 40% of the peak load recorded for the matrices. Extensible PP fibers do not totally pull out of matrices when composites reach peak strength. Gradual fiber slipping and stretching results in a high post-peak strength even at high deformation levels (Consoli et al. 2009). Comparing the results from the different matrices in this study, matrices with different proportions of the shorter fibers (27 mm) did not sustain as much fiber slippage as matrices with only 54 mm fibers. The subsequent more gradual failure after initial crack of all the fiber-reinforced matrices suggested an improved performance in ductility that can be attributed to the fibers. The MOR for each of the mix types is presented in Table 3. Some PP fiber reinforced specimens were tested to complete failure to investigate fiber matrix interaction at failure surfaces. Both fiber pullout and breakage was observed.

**Compressive Strength**

The compressive strength results are presented in Table 4. At 0.2% of PP fiber content by weight, compressive strength was 84%, 35%, 31%, and 35% higher for mix types #2, #3, #4, and #5 respectively, compared to the un-reinforced specimens. Patel et al. (2012) attributed similar observations made in compressive strength of PP fiber reinforced concrete specimens to the confinement provided by the PP fiber bonding. Binici et al. (2005) attributed observed increases in compressive strength of mud bricks to the interface layers and geometric shape of the fibrous reinforcing materials used. Resistance to fiber sliding has also been cited as a reason for such
increases (Prasad et al. 2012). In this study, the matrix reinforced with only 54 mm fibers (mix # 2) recorded the highest compressive strength. The findings were similar to the findings by Bagherzadeh et al. (2012) who observed longer PP fibers (12 mm) to perform better in compressive strength compared to shorter fibers (6 mm) at 28 days. They also observed the fiber reinforced matrices in their study to perform better in compressive strength compared to the unreinforced ones (Bagherzadeh et al. 2012).

There was no significant difference between the values recorded for mix # 3 and mix #5 even though both had different proportions of 54 mm and 27 mm fibers respectively. Cracks typically formed before peak load was reached during testing. This observation was true for both plain and fiber reinforced specimens. A typical “hour glass” type failure mode was observed for all tested specimens.

**Table 3. Modulus of Rupture of Tested Blocks**

<table>
<thead>
<tr>
<th>Mix Type</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>Average</th>
<th>Std. Dev.</th>
<th>COV (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td># 1</td>
<td>0.75</td>
<td>0.85</td>
<td>0.84</td>
<td>0.81</td>
<td>0.82</td>
<td>0.03</td>
<td>3.86</td>
</tr>
<tr>
<td># 2</td>
<td>1.16</td>
<td>0.90</td>
<td>1.06</td>
<td>1.00</td>
<td>1.03</td>
<td>0.11</td>
<td>10.68</td>
</tr>
<tr>
<td># 3</td>
<td>0.95</td>
<td>0.65</td>
<td>0.63</td>
<td>0.65</td>
<td>0.72</td>
<td>0.15</td>
<td>21.34</td>
</tr>
<tr>
<td># 4</td>
<td>0.76</td>
<td>0.50</td>
<td>0.58</td>
<td>0.66</td>
<td>0.63</td>
<td>0.11</td>
<td>17.79</td>
</tr>
<tr>
<td># 5</td>
<td>0.89</td>
<td>0.82</td>
<td>0.86</td>
<td>0.79</td>
<td>0.84</td>
<td>0.04</td>
<td>5.23</td>
</tr>
</tbody>
</table>

*Coefficient of variation

**Table 4: Compressive Strength Results**

<table>
<thead>
<tr>
<th>Mix Type</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>Average</th>
<th>Std. Dev.</th>
<th>COV (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td># 1</td>
<td>2.34</td>
<td>2.40</td>
<td>2.10</td>
<td>2.26</td>
<td>2.31</td>
<td>2.28</td>
<td>0.11</td>
<td>4.98</td>
</tr>
<tr>
<td># 2</td>
<td>4.36</td>
<td>4.62</td>
<td>3.94</td>
<td>3.74</td>
<td>4.36</td>
<td>4.20</td>
<td>0.35</td>
<td>8.47</td>
</tr>
<tr>
<td># 3</td>
<td>3.37</td>
<td>3.85</td>
<td>3.08</td>
<td>2.29</td>
<td>2.81</td>
<td>3.08</td>
<td>0.59</td>
<td>19.03</td>
</tr>
<tr>
<td># 4</td>
<td>2.57</td>
<td>3.76</td>
<td>2.85</td>
<td>3.07</td>
<td>2.69</td>
<td>2.99</td>
<td>0.47</td>
<td>15.74</td>
</tr>
<tr>
<td># 5</td>
<td>2.48</td>
<td>3.14</td>
<td>3.66</td>
<td>3.08</td>
<td>3.06</td>
<td>3.09</td>
<td>0.42</td>
<td>13.57</td>
</tr>
</tbody>
</table>

*Coefficient of variation

**Influence of Fiber Length on Flexural and Compressive Strength**

Two-sample t-tests were conducted to compare the difference in means of compressive strength and the difference in means of flexural strength for the two fiber lengths that were used in the experimental program to determine if the length of the fiber reinforcement had an effect on strength values. The means used for the test were obtained from recorded compressive and flexural strength data for block specimens reinforced with only 54 mm and only 27 mm fibers. The alternative hypothesis that longer fibers increased the mean strength of the blocks was compared against the null hypothesis that length had no effect on the mean strength of matrices. The results of the t-tests are summarized in Table 5. The null hypothesis of there being no difference between the means of compressive strength and no difference between the
means of flexural strengths were rejected at the 95% confidence level, indicating that length of fiber had a statistically significant effect on strengths for the 54 mm and 27 mm fiber reinforced CSEB’s in this study.

Table 5: Average Flexural and Compressive Strength t-test Results for 54 mm and 27 mm fibers

<table>
<thead>
<tr>
<th></th>
<th>Calculated t-value</th>
<th>P-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Compressive Strength</td>
<td>3.662</td>
<td>0.0032</td>
</tr>
<tr>
<td>Flexural Strength</td>
<td>3.327</td>
<td>0.0079</td>
</tr>
</tbody>
</table>

**SUMMARY AND CONCLUSIONS**

The use of ecological and economical CSEBs in structural applications has been greatly impeded by concerns over its adequacy in terms of physical and mechanical properties. As previously indicated, earthen masonry is generally weak, brittle, and exhibit low tensile strength and strain capacities. Fibers can be used to improve properties such as plastic shrinkage cracking, impact resistance, and toughness or ductility. Unfortunately, fibers have also been known to have adverse effects on some desirable properties.

Previous studies have reported variable results for both properties in fiber reinforced matrices. The premise of this paper is that such effects can be minimized through optimizing both the selection and inclusion of the fiber. In the preceding sections, the authors have demonstrated this through identifying engineered PP fibers as a feasible option and further investigating the effect of PP fiber length on the flexural and compressive strength of CSEBs. On the average, specimens reinforced with 54 mm fibers performed better in both flexural and compressive strength compared to the unreinforced specimens and specimens reinforced with different variations of 27 mm fibers. The highest flexural and compressive strength values were recorded at reinforcement with 54 mm fibers and at 0.2% fiber content by weight making them the better performing fiber in this study. The incorporation of fibers into the matrices prevented catastrophic failure of the tested samples during the MOR test.

The findings have shown that such fibers can enhance the performance of CSEBs especially with respect to preventing catastrophic failure and improving post-initial crack performance. In subsequent experimental work, the sample size will be increased to validate these initial findings. The authors will further investigate the optimum quantity of fibers for the soil used in the research. Further work involving microstructural characterization will be done to validate the desirable impact of specific geometric attributes such as embossment and fibrillation which can be used to inform the recycling of plastic waste as reinforcing fibers. Follow up studies will also involve performing an LCA analysis. Due to their ability to naturally breakdown at the end of their service life, earthen building materials do not need to be disposed of in a landfill (Kestner et al. 2010). The inclusion of PP fibers into matrices brings into question the need for a reevaluation of the end of service life options of the material.
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