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ES4A2A1
African Field Course
Group Project Report



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Course leader	THT	
Marker	THT/CEO	
Work Set Date	Week 49	
Submission Deadline:-		
Day	Date	Time
Thursday	24 th October	2.00pm
Return to Student by:	End of week 6	

DATE SUBMITTED... 24/10/2013

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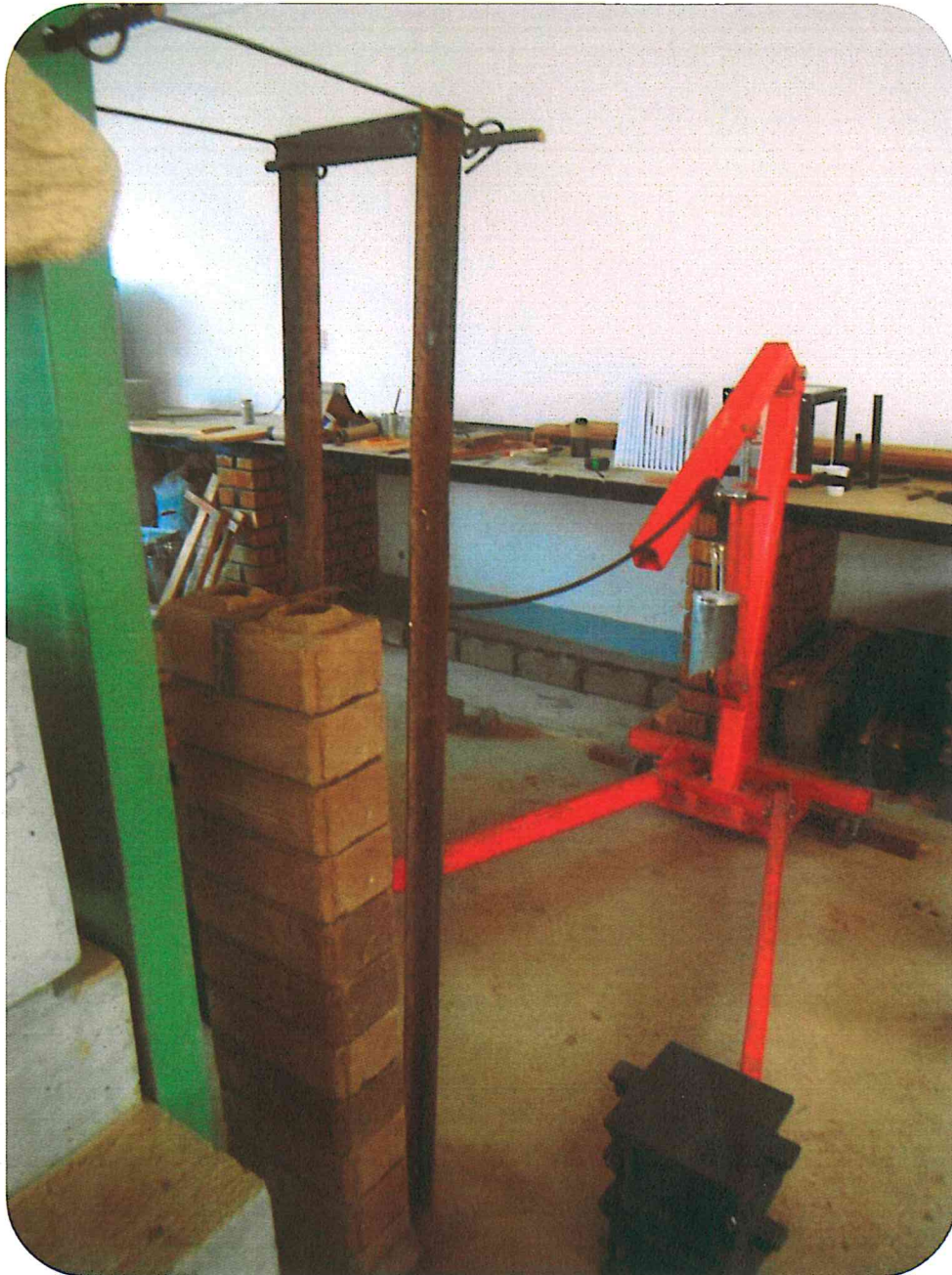
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ES4A2 African Field Course

Testing the shrinkage and lateral stiffness of walls using mortarless, interlocking, stabilised-soil bricks.



University of Warwick
Report Covering Experiments Conducted on 02-14/09/13
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Table of Contents

1.0 Introduction (MLC)	2
2.0 Aims and Objectives (MLC)	2
3.0 Background Research	2
3.1 Mortarless Construction (HP)	2
3.2 Green Bricks (MLC)	3
3.3 Soils (PR)	4
4.0 Lateral Stiffness Test	4
4.1 Apparatus and Method (MLC)	4
4.2 Results (ES)	7
4.3 Analysis (ES)	8
5.0 Shrinkage Test	12
5.1 Apparatus and Method (HP)	12
5.2 Results (PR)	14
5.3 Analysis	19
6.0 Evaluation	21
6.1 Stiffness Test (ES)	21
6.2 Shrinkage Test (PR)	21
7.0 Further Work (HP)	22
8.0 Conclusion (MLC)	22
9.0 References	23
APPENDICIES	24
Appendix A - How to Make a Brick using a Tanzanian Block Press (MLC)	24
Appendix B1 – Results for Cured and Green Brick Towers (ES)	29
Appendix B2 – Stiffness Comparison (ES)	31
Appendix B3 – Load-Movement Graphs (ES)	33
Appendix C1 – Brick Shrinkage Graphs (PR)	36
Appendix C2 – Shrinkage Wall Data (PR)	40

1.0 Introduction (MLC)

1/3 of the globe's population live in earth-built homes (Oram, 2013). With the vast majority of these homes built in difficult or troublesome locations, at the mercy of the ever increasing effect of Mother Nature due to global warming, it is a top priority to ensure these earth-built homes can meet the demands and strengths that are required of them.

In the country of Uganda – located in the heart of Africa, directly on the equator – the demands placed on the local structures are not as severe as one might find elsewhere in the world. However, the low-cost construction techniques employed in this region mean that buildings are generally very weak in comparison to their developed world counterparts.

One popular method is to use mortarless brick construction – using bricks of interlocking shape rather than using mortar. This technique produces walls and structures of reasonable strength in every department except for laterally.

In Uganda, this severe lack of lateral strength makes the building susceptible to strong winds, flooding, burglary, seismic activity, accidental collisions, and generally makes the structure much less stable and more dangerous.

Improving the lateral stiffness of this technique is essential to increasing the safety and prosperity of the many people living in these types of structures, as well as providing people round the world with a low-cost construction solution that meets their needs. ✓

2.0 Aims and Objectives (MLC)

Ultimately the aim was to modify the current mortarless construction technique to increase lateral stiffness of the completed structure.

One suggested method was to lay the bricks 'green' instead of placing after curing. Therefore we would conduct experiments and testing to compare the effectiveness of these two methods.

However, laying 'green' presents possible practical ^{problems} issues such as the bricks shrinking too much during curing to allow further bricks to be placed. Therefore all practical aspects affecting the use of this technique ^{sh}would be investigated and analysed.

We planned to finish the testing and analysis with a recommendation as to whether this technique should be employed or not.

3.0 Background Research

3.1 Mortarless Construction (HP)

Traditionally, walls in the developed world contain alternate layers of blocks and mortar. This technique helps with bonding and gives the wall strength and straightness and the bricks are made by firing. Mortar-less construction makes use of interlocking bricks of stabilized soil (ISSB) and as the name suggests, uses no mortar. The ISSB is a compressed block of moistened soil, mixed with a little cement, which is cured rather than fired (HYT Uganda, 2012).

The advantages shown below express why mortar-less brickwork is a worthwhile area of research and potentially a favourable masonry method over traditional techniques.

- It is cheaper. [£]Cost savings of ISSB versus fired brick is in the range of 20-30% (Positive Planet, 2012). The technique does not use mortar (due to the interlock feature and the uniformity of each block), which costs much more per litre than bricks/blocks so mortar-less construction should save money. ✓ The presses that create the blocks are also affordable, reducing cost. A further factor that reduces cost is the fact that blocks are made on site so there are no

fewer breakages. It is common for 20% of fired bricks to be damaged when they reach a site (Positive Planet, 2012). ✓

- It is better for the environment. Since the ISSB is not fired, no trees are chopped down to fuel brick kilns, making ISSB far more environmentally friendly. This helps decrease deforestation and increases conservation of local flora and fauna. And CO₂ emissions drastically reduced. (HYT Uganda, 2012) The making of 3000 ISSB blocks will save 10 tonnes of trees.

- It saves time. ISSB is quicker to build with. The blocks are also made on site, ^{maybe (+ maybe not)} reducing costs further (HYT Uganda, 2012) ✓

- Used in earthquake technology. Interlocking mortar-less masonry blocks, unlike standard brick walls which are solid, allow slight movement. When a steel reinforcement is added, this construction technique dissipates the energy of seismic wave better than traditional masonry (Laster C A, 2012). ^{interesting}

- It has water and sanitation benefits. The bricks are weather resistant and can be used in the construction of septic and water tanks (Soft Power Education, 2012). ISSB water tanks are approximately half the cost of plastic tanks (Positive Planet, 2012). Interlock on all four sides ensures maximum resistance against water pressure.

- It can increase community capacity and education. The technique eliminates the need for skilled labour, as once a foundation has been laid, an unskilled person can simply stack the bricks on top (which fit neatly together) and a strong and durable structure. This factor also decreases cost of labour. The presses are also very easy to transport making them easily accessible to the rural poor. The simple operation of the presses can facilitate community participation (Positive Planet, 2012) which can promote proactive behaviour and generate local skills and income.

The technique of mortar-less construction is certainly viable, confirmed by existing work on the subject. But without reliance on mortar for strength and form, the geometry of bricks must be more complex and required to be more accurately produced. There is also concern regarding the low lateral stiffness of un-mortared walls, which will be explored in this report.

3.2 Green Bricks (MLC)

The term, 'green', denotes when a brick has been made but has not yet cured. This means the brick is weaker and softer as the cement has not set and thus the soil has not yet stabilised. In addition, the brick may shrink so severely that future courses may not actually fit on top and interlock properly – although this is largely affected by the interlocking shape the bricks use. These factors could mean the bricks are less practical to lay and use, however, there are some potential benefits. Due to the bricks being softer when laid, the surfaces of the brick may fit much more tightly together, increasing surface area contact – essential to improving lateral stiffness. In addition, if the bricks shrink significantly this could give a much tighter and stronger fit around the interlock and between bricks, again increasing lateral stiffness.

With dry-stacked bricks, ^{only} approximately 1% of the surface area of the brick is actually mobilised as a contact area between bricks above and below (Kintingu, 2009). This small contact area means that when lateral force is applied, a hinge-like mechanism is formed causing bricks to rotate and topple over. Increasing contact area can reduce formation of a hinge and therefore a 'green' bricks tendency to increase this contact area can in theory improve lateral strength.

In addition, when walls are mortared, the wall will act like one large continuous beam rather than several interacting elements. This also reduces formation of a hinge and second moment of area about the longitudinal axis is increased. Research has shown this can increase lateral stiffness by roughly 100 times (Thomas, 2013). Although not as strong as a mortared contact, as the 'green' bricks cure in position they will stick to the bricks above and below, potentially mimicking to some degree the effect of a mortared contact and ultimately improving lateral strength. ✓

3.3 Soils (PR)

Within interlocking stabilised soil brick construction, the materials used to make the brick are a key component. Often low quality stabilised bricks are a result of poor material choice (Kintingu, 2009). Hence the choice of soil and particle size plays a vital role. Material choice can affect the brick's workability significantly meaning that soil identification and testing is necessary (Kintingu, 2009).

It is vital that there is enough clay content in the soil used to make bricks, if there is too much (+9%) the brick becomes extremely sticky resulting in numerous problems such as it becomes harder to eject from the ISSB mould. Alternatively, too little clay can cause the brick to crumble therefore it is extremely important to use a soil with a clay content of ideally 2.5% (Thomas, 2013 and Kintingu, 2009). (57)

If the particle is too large, the soil is less cohesive as a soil's cohesion '*depends in its fines fraction*' (Kintingu, 2009). Expansive materials such as clay also indicate that shrinkage will occur in the brick, this is because expansive materials contain water which then evaporates. If the raw materials available are not within the specified clay content range, there are a number of ways to remedy and 'stabilise' the soil by adding cement or sand depending on what the problem is.

In order to assess the clay content of a soil, a crude test of rubbing between the fingers to see if any residue remains can be used. Alternate tests involve drying a ball of clay in the sun and seeing if it falls apart (if it does there is no clay present), the ribbon test which moulds a sample into a cigar-like shape and the longer it takes to break the greater the clay value (Oram, 2013). The bottle test is another way of measuring the clay content. This is further described in Section 5.1.1.

4.0 Lateral Stiffness Test

4.1 Apparatus and Method (MLC)

4.1.1 Making the Bricks

See Appendix A for a detailed illustrated method.

As recommended, a suitable mixture ratio was experimentally found (Oram, 2009) and, working as a team to improve speed and efficiency, the bricks were made.

Lifting scales (measuring to the nearest 0.01kg), buckets and covers to keep the mixture dry were all used to ensure the desired quantities of all elements of the mixture were put into each brick. This meant the bricks were as consistent as possible given the lack of resources to perform any sort of quality control.

For our experiment, a Tanzanian block press was available to use. This press is the kind that might be used in poor, remote areas due to its simplicity, portability and ability to fully function without any need for electricity or power supply. The press did not have the capability to vibrate the brick mixture but could be compressed with a force of around 7 tons. ✓

The mould was measured with a Vernier calliper to ^{check} ensure that when bricks were placed on top of one another, the contact area would be on the top and bottom surfaces of the brick and not on the interlock itself. A clearance of 0.6mm was found so the blocks worked as desired and as a result the tests performed would be meaningful and could be translated to other interlocking block designs.

With the machine's simplicity, however, came faults. Quite often some of the mixture would be left stuck in the mould after the brick was ejected. Pre-compressing the mixture and coating the sides with engine oil were attempted methods to reduce this but in the end it was found that simply cleaning the mould regularly with a trowel and brush and lightly coating the walls with dry sand was enough to get relatively consistent and satisfactory bricks. ✓

The compressing and ejection stage required quite a high degree of force and so some members of the team would not have been able to make bricks on their own – a potential hurdle to the machine's practicality. This large force required also meant that sometimes the bricks were ejected quite violently and subsequently some were broken before they were even picked up. After producing around 200 bricks, the high forces took their toll on the compressing lever arm as it failed, requiring repair before production could continue.

When stacking the bricks, a small systematic error was noticed in one particular place on the top surface of the brick causing a small lump. *(‘small’ might be small enough to sand out during green placement, but needs removal if bricks are laid already cured.)* ✓

4.1.2 Building the Columns

When assembling the columns, different approaches were required for ‘green’ and cured bricks.

When stacking cured bricks, previous research (Kintingu, 2009) has found that the best way to make the column straight and level is to try each brick in both orientations and use a spirit level to see which is best. In addition, the spirit level should be used to slightly adjust bricks when in position to make placement as consistent as possible. ✓

Particularly due to the bricks having a small lump on them due to the systematic error of the press (Section 4.1.1), sanding and wire-brushing the bricks, to ensure optimum contact area, was also performed.

In contrast, because the ‘green’ bricks began to stick to one another as soon as they come into contact, they could only be placed once and couldn’t be rotated or nudged to improve positioning. Replacing them may have caused surface damage, and handling needed to be reduced anyway due to the brick’s fragility. ✓

They also couldn’t be wire-brushed or sanded down due to their softness, but this wasn’t an issue as it was the flexibility of the surfaces that allowed slight surface imperfections to be overcome and full contact area to be clearly visibly mobilised. ✓

As visible in Figure 1, the columns were built with each brick being placed directly above the one below with no stagger, as one would find in a regular wall. The decision to build in this arrangement was made because time and resources were limited. Also, it doesn’t affect the test and it’s results as all columns were built in the same way and the experiment was performed as a means of comparison between techniques, not to find accurate values for when a wall might fail.

To make the results statistically viable, 3 of each type of column were built. Due to limitations on time and resources, only 1 cured column was built but then the bricks randomly rearranged in between tests to mimic the effect of having 3 separate columns. This could not be done with the ‘green’ bricks though as they could only be placed once, as covered in earlier in this section. In addition, each column was tested 3 times to ensure no errors were made when taking readings, to give the results increased validity, and see if there was any effect of hysteresis.

The base brick was attached to the floor with a weak cement so that none of the displacements observed were from sliding of the whole column which would detrimentally affect the accuracy of the conclusions drawn.

It was observed when stacking the cured bricks that there was a large clearance in the interlock areas to allow sliding of the bricks over one another. This showed that the contact areas were in the desired areas and not on the interlocks themselves. This also



Figure 1: One of the completed brick columns

shows that shrinkage, unless extremely dramatic, would not be a problem for the 'green' bricks. However the large freedom of movement perhaps allows too much movement and, as a result, too much variability when placing bricks.

4.1.3 The Testing Apparatus

Due to the limited time and resources available, a testing apparatus was constructed by modifying other equipment.

The full arrangement is visible in Figure 2.

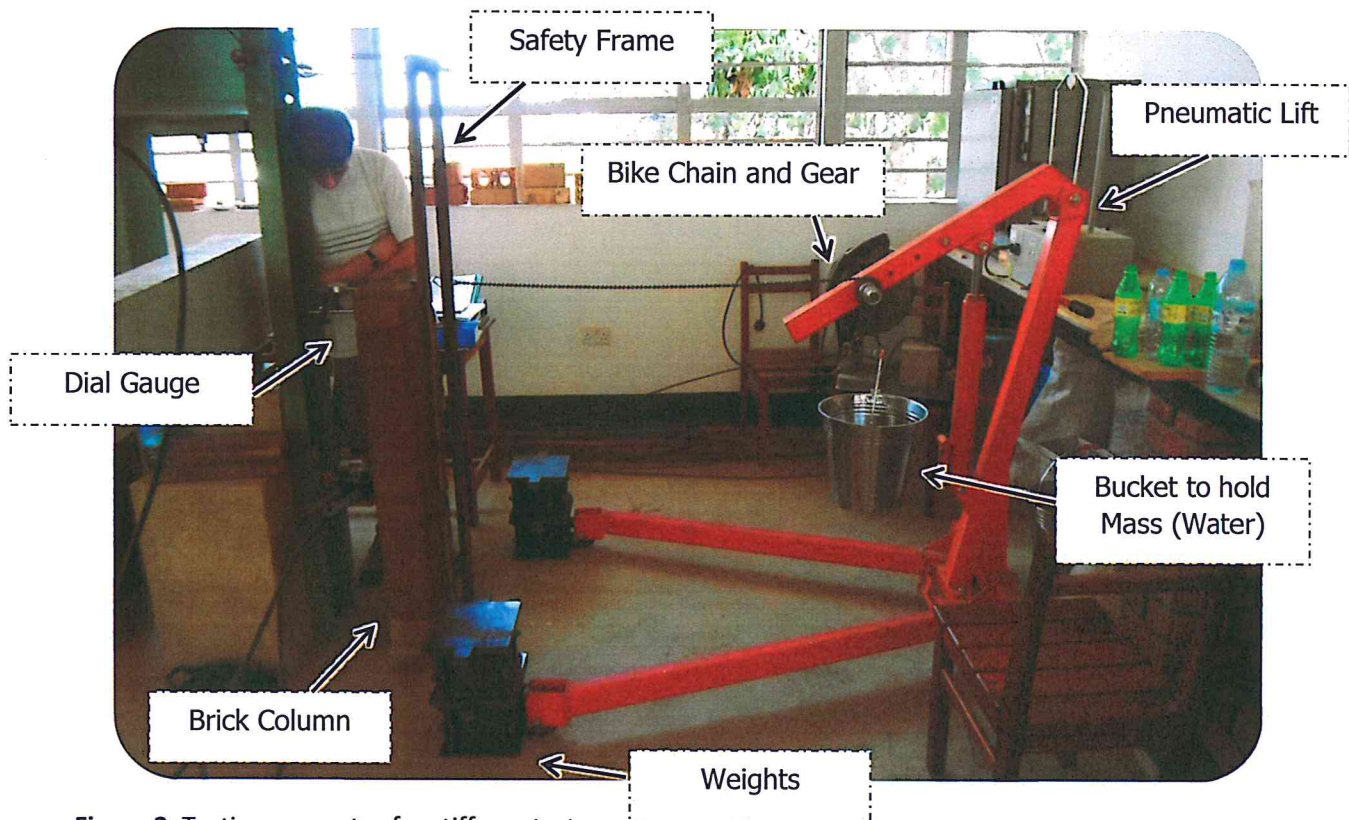


Figure 2: Testing apparatus for stiffness test

The red frame is a pneumatic lift. It was portable – allowing it to be moved from column to column – as well as rigid and allowed for its height to be adjusted. This meant the lateral force could be applied in a completely perpendicular direction, yielding relevant results. Large weights were placed next to the wheels of the lift to keep it completely static during testing.

A bike gear was attached to the lift and a bike chain separated in one place and rested on the gear. One end of the chain was attached to the mass whilst the other was attached to the steel bar which wrapped over the top brick to apply the lateral force. This arrangement was ideal as the bike gear and chain combination meant friction was negligibly low. It also transferred vertical loading into horizontal loading making applying of a specified force much simpler. In comparison to string and rope, the bike chain did not suffer from any sort of change in length when under loading meaning the relationship between loading and displacement was unaffected. The only undesirable factor was the mass of the chain between the gear and mass could not be neglected and had to be factored in to the results afterwards. *I think it doesn't affect the horizontal force on the column.*

For safety, a portal frame was constructed out of scrap metal and using a nearby welder. Not only did this protect people from falling columns of bricks but also prevented the bricks from being damaged allowing the test to be repeated.

Positioning of the apparatus in relation to the columns was kept the same for each test to ensure consistency.

To measure the displacement, a dial gauge was mounted to a separate steel frame at the same height as the lateral load. The dial gauge was accurate enough to detect the small displacements we saw in the column before failure, with a tolerance of 0.01mm. Loading was applied by adding water to a bucket, but this had to be slow and in small increments as otherwise the dial gauge would spin too fast to read.

4.2 Results (ES)

All the loading and movement values were recorded, and the incremental, mean, and 1 mm movement stiffness values worked out. These are displayed in Appendix B1.

As shown in Table 1, from the sample of columns analysed, the Green Brick columns had an increase in mean collapse load compared to the Cured Brick columns of 3.1 N, or 11%, and the minimum and maximum collapse loads also increased by similar amounts.

For stiffness measurement, the 1mm stiffness value is used throughout the results and analysis sections because it was judged to be the most reliable due to the fact that it filters out the noise generated measurement-to-measurement as the loading was increased. (from 'cured' to 'green')

Amongst the columns tested, there was an increase in the 1mm stiffness value of 11000 N/m, or 68%, and the minimum and maximum 1mm stiffness's increased in percentage terms by a similar amount (as shown in Table 1).

Table 1: Summary of Initial Results				Percentage Increase
	Cured Brick	Green Brick	Increase	
Min Collapse Load (N)	22.8	25.5	2.8	12
Mean Collapse Load (N)	26.8	29.9	3.1	11
Max Collapse Load (N)	31.8	35.9	4.1	13
SD of Collapse Load (N)	3.17	3.49	0.321	10
SD of Est of Mean Collapse Load (N)	1.06	1.16	0.107	10
Coeff of Var of Collapse Load (N)	0.118	0.117	-0.001	-1.2
Min 1mm Stiffness (N/m)	7994	21429	13436	168
Mean 1mm Stiffness (N/m)	16624	27902	11278	68
Max 1mm Stiffness (N/m)	21504	35589	14085	66
SD of 1mm Stiffness (N/m)	4425	4621	197	4.4
SD of Est of Mean of 1mm Stiffness (N/m)	1475	1540	66	4.4
Coeff of Var of 1mm Stiffness (N/m)	0.266	0.166	-0.101	-38

If collapse load test was done first, then some brick-to-brick bonds were broken before the stiffness tests, affecting their results. This is illustrated by the residual displacement after failure.

"1mm stiffness" = $1000 \times \text{Force to displace 1mm}$
 ↳ was this obtained by interpolation between data points before and after 1mm displacement?
 (discussed later)

Were the green bricks cured (for some days) between placement and stiffness testing? I hope so as one would expect the stiffness of 'green mortar' to be low.

4.3 Analysis (ES)

The *Results* section of this report states the values of collapse load and stiffness of the 'sample' of columns used. However, it is important to note the distinction between the 'sample' of columns and the 'population' of columns. The 'population' of columns refers to all the columns in the whole world manufactured and assembled using this particular ISSB technique. The 'sample' of columns refers to the columns built and tested during group T2's experiments at UMU (Uganda Martyrs University). For the purpose of the analysis, the sample size of Cured Brick columns and Green Brick columns were each taken as either 9, 6, or 3 depending on whether Runs 1, 2, and 3, or Runs 2, and 3, or Run 1 were used in the analysis.

4.3.1 Analysis Method

To determine whether the difference in recorded stiffness values was statistically significant, a statistics book (Murphy and Hayslett, 1985) was consulted to test hypotheses about the difference of 2 means using the t-distribution. For the purpose of this analysis, the Cured Brick columns are *sample 1* and the Green Brick columns are *sample 2*. The means and sizes of *samples 1* and *2* are \bar{x}_1 and \bar{x}_2 , and n_1 and n_2 respectively. The means of *populations 1* and *2* are μ_1 and μ_2 respectively (but called u_1 and u_2 in the spreadsheet).

In this method, the random variable t is given by

$$t = \frac{\overbrace{(\bar{x}_1 - \bar{x}_2)}^{\text{measured}} - \underbrace{(\mu_1 - \mu_2)}_{\text{unknown or inferred trial values}}}{\sqrt{s_p^2 \left(\frac{1}{n_1} + \frac{1}{n_2} \right)}} \quad \text{Equation 1}$$

In which s_p^2 is called the pooled sample variance and is equivalent to

$$s_p^2 = \frac{(\text{Sum of Squares of Sample 1}) - (\text{Sum of Squares of Sample 2})}{(\text{DOF of Sample 1}) + (\text{DOF of Sample 2})} \quad \text{Equation 2}$$

The sum of squares of each of the samples was calculated using Equation 3, where the subscripts are 1's for *sample 1* and 2's for *sample 2*.

$$\text{Sum of Squares of Sample 1} = \sum x_{1i}^2 - \frac{(\sum x_{1i})^2}{n_1} \quad \text{Equation 3}$$

In Equation 2, 'DOF' is the *Degrees of Freedom* of the sample. This is 1 less than the number of items in the sample. Therefore, for a combined sample $n_1 + n_2$ the number of degrees of freedom is given by

$$DOF = n_1 + n_2 - 2 \quad \text{Equation 4}$$

So to calculate s_p^2 , Equation 4, along with Equation 3 used for both samples 1 and 2 was plugged into Equation 2. This was then used in Equation 1 to find t .

The value of t calculated was compared to the borderline value of t in a lookup table for a particular number of degrees of freedom at different confidence levels. If the calculated value of t was more negative than the limiting value of t , then the hypothesis was accepted. Conversely, if the calculated value of t was less negative than the

limiting value of t , then the hypothesis was rejected. This is the opposite way round to that described in the text (Murphy and Hayslett, 1985), because the difference of the means $\mu_1 - \mu_2$ is negative.

The confidence levels tested to were 90%, 95%, 97.5%, 99% and 99.5%.

The estimate of the difference of the means of the populations to each of the aforementioned confidence levels was tested by generating different hypotheses H_0, H_1, H_2, H_3 , etc each with a proposed difference of the means of the populations $\mu_1 - \mu_2 = -\Delta_0$.

In order to carry out tests on hypotheses using the t-distribution, 3 assumptions were made:

- 1) the populations are normal - hopefully
- 2) the populations have the same variance - not very likely
- 3) the samples of the 2 populations are random. - hopefully

4.3.2 Analysis of Stiffness Results

In Appendix B2 *Stiffness Comparison* each hypothesis of the difference of the means of the populations is accepted or rejected.

Scenario 1

Cured Sample: Trials 1,2,3, Runs 1,2,3, and Green Sample: Green 1,2,3, Runs 1,2,3 (Sample Size: $n_1=n_2=9$)

If all 3 runs from each Green column and each trial of the Cured Brick column are counted as separate pieces of data, then the sample sizes are $n_1=n_2=9$ and therefore 16 degrees of freedom. This gives much more reliability to the results that a smaller sample size.

Making this assumption, Appendix B2 *Scenario 1* shows there is a 99.5% certainty that the increase in stiffness from cured brick to green brick columns is at least 5000 N/m, or 30%. At the 90% confidence level the increase is at least 8400 N/m, or 51%. The percentage increases in stiffness at each confidence level are summarised in Table 2.

Table 2: Summary of Scenario 1, 1mm Deflection Stiffnesses	
Confidence	1mm Stiffness Increase
99.5%	30%
99%	34%
97.5%	40%
95%	45%
90%	51%

✓
Good

Scenario 2

Cured Sample: Trials 1,2,3, Run 1, and Green Sample: Green 1,2,3, Run 1 (Sample Size: $n_1=n_2=3$)

In Appendix B2 *Scenario 2*, the sample size is treated as $n_1=n_2=3$ and therefore 4 degrees of freedom. If that is the case then the null hypothesis H_0 (where the population means are equal) cannot be rejected. This is due to the small sample size.

↓
This seems odd, as run 1 gave significantly higher stiffness to green bricks

Scenario 3

Cured Sample: Trials 1,2,3, Runs 1,2,3, and Green Sample: Green 1,2,3, Run 1 (Sample Size: $n_1=9$ $n_2=3$)

As shown in Appendix B2 *Scenario 3*, there is a 15% increase in sample mean stiffness of Green Brick columns on *Run 1*, compared to the average of all of *Runs 1,2,3* from the same columns.

This is probably because after the column has been pulled over in *Run 1*, the bond between one or more touching pairs of bricks is broken and hence the future stiffness is reduced.

However, due to the reduced sample size, the stiffness increase at each confidence level is significantly reduced (see Table 3). Infact, above the 90% confidence level, the null hypothesis cannot be rejected.

Table 3: Summary of Scenario 2 1mm Deflection Stiffnesses

Confidence	1mm Stiffness Increase
99.5%	Cannot reject H_0
99%	Cannot reject H_0
75.5%	Cannot reject H_0
95%	Cannot reject H_0
90%	10%

Scenario 4

Cured Sample: Trials 1,2,3, Runs 1,2,3, and Green Sample: Green 1,2,3, Runs 2,3 (Sample Size $n_1=9$ $n_2=6$)

As shown in Appendix B2 *Scenario 4*, there is a 19% reduction in sample mean stiffness of Green Brick columns when *Runs 2* and *3* are averaged instead of the *1st run* of each column. This is due to the mechanism outlined for *Scenario 3*.

In *Scenario 4*, the null hypothesis cannot be rejected.

4.3.3 Analysis of Hysteresis Effect

It was observed that there was considerable movement hysteresis if the column was nudged at all, so it was decided to conduct 3 runs on each Cured Brick column trial, and on each Green Brick column.

As shown in Appendix B3, successive runs on each column produced hysteresis. With the exceptions of *Cured Brick Column 1 Trial 3*, and *Green Column 1*, the movement from the start progressed further with every run.

Cured Brick Column 1 Trial 1 showed a similar amount of hysteresis between each run. There were 2mm of hysteresis to *Run 2*, and an additional 1.5mm to *Run 3*. *Green Column 2* also showed similar amounts of hysteresis between runs with the slightly larger amount of hysteresis occurring between *Run 1* and *Run 2*.

With *Cured Column 1 Trial 2*, and *Green Column 3*, the hysteresis is considerably smaller (by a factor of $\frac{1}{4}$) between *Runs 2* and *3* than between *Runs 1* and *2*.

On the other hand, with *Cured Brick Column 1 Trial 3*, and *Green Column 1*, the hysteresis was negative between *Runs 2* and *3* meaning that the columns returned closer to their original positions after finishing *Run 2* than when starting *Run 2*. This can be explained by the taking of a 1 hour break between *Run 2* and *Run 3* that did not happen with the other columns.

In general, it can be seen that the amount of additional hysteresis between successive runs decreases with each run. This can be explained by the increase in the stabilising moment as a column bends and the centre of pressure moves to the touching edges in a bending column. The pressure times contact area provides a force acting eccentrically to the opposing weight of the bricks which acts through their middle.

The plastic behaviour of the bricks, in conjunction with the 1 hour time delay between *Runs 2* and *3*, and the stabilising moment on a bent column, would explain why *Cured Brick Column 1 Trial 3* and *Green Column 1* showed *Run 3* starting with a smaller absolute movement than *Run 2*.

5.0 Shrinkage Test

5.1 Apparatus and Method (HP)

In order to examine clay content and shrinkage in the bricks we used and the walls made from them, 4 tests were carried out;

1. Bottle test
2. Soil shrinkage testing
3. Daily brick shrinkage measurement
4. Daily wall shrinkage measurement

Apparatus

- 8.5 x green bricks, 1 termite/6 sand
- 6.5 x cured bricks, 1 termite/6 sand
- 8.5 x green bricks, 1 sand/6 termite
- 6.5 x cured bricks, 1 sand/6 termite
- Metal callipers
- Meter ruler
- Oven
- 4 x half pipe soil shrinkage apparatus, comprising 30cm of 2 inch piping cut in half lengthways and 2 wooden end pieces.
- Metal mixing tray
- 7 Plastic bottles
- Permanent marker

5.1.1 Bottle Test

A bottle test was carried out on 7 samples, collected from the University and also from the brick-makers' yard. These were:

Termite Soil (campus)	Pit (campus)
Campus	Campus Edge
Entrance (brick makers')	Between trees (brick makers')
Behind trees (brick makers')	

It is a crude field test to examine the clay content of the soil. Each bottle was filled up $\frac{1}{3}$ with the soil and $\frac{2}{3}$ with water, and the bottle was vigorously shaken, causing the particles of soil to fall to the bottom in order of particle size.

After the first 30 seconds, all the sand collected at the bottom, and the level of solid particles was marked on the bottle with a permanent marker. After 30 minutes, all silt reached the bottom, and a second marker mark was made. And finally, after 12 hours, all clay had collected at the bottom, and a third mark made for the height of the soil at this time. The heights of the sand, clay and silt for each sample-filled bottle were recorded and a percentage content of each was calculated.

5.1.2 Soil Shrinkage Test

The soil was crushed with rocks, measured and sieved. Water was then added to it, to a level that was just beyond the liquid limit state. The mixture was poured from the metal tray in which the mixing had been carried out, into the half pipe apparatus. This (pre-weighed and recorded) apparatus consisted of 4 30cm lengths of length-ways-halved 2 inch piping, attached to two wooden ends for stability and levelling.

This method was repeated for each of the soil samples (pure sand, 6 sand/1 termite, 1 sand/6 termite, 2 sand/5 termite). The four samples were left for 24 hours in an oven at 95degree C.



Figure 3: Soil samples in oven

On removal from the oven (Figure 3), the width of the cracks in the samples were measured, and the percentage shrinkage calculated for each sample.

5.1.3 Daily Block Shrinkage

The widths of two individual green bricks of the ratio 1 termite soil: 6 sand, were measured at 4 intervals along the length of the brick, using metal calipers. The measurement points are shown in Figure 4.

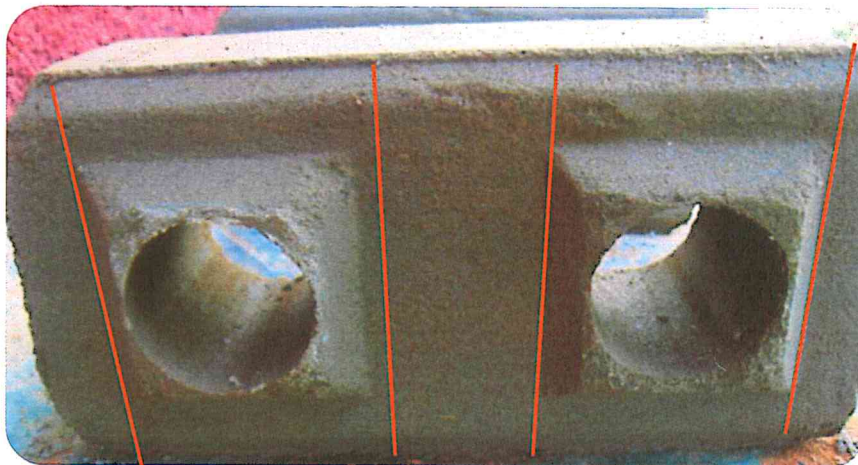


Figure 4: Measurement points when examining shrinkage of bricks

The 4 measurements were taken on each brick, daily, for a 7-day period and recorded. This method was also carried out on two green bricks of the ratio 1 sand soil: 6 termite soil.

5.1.4 Daily Wall Shrinkage

The final shrinkage test was measuring the shrinkage of a course of bricks (Figure 5). This experiment was to discover the effects of laying green bricks on top of cured bricks. 6.5 (6 full bricks and 1 half brick) cured bricks of each ratio (6

termite/1 sand and 1 termite/6 sand) were laid to create 1 bottom course of each brick type. These were laid to fit between 2 existing concrete walls supporting a work surface in the lab.

A second course, consisting of 6.5 green bricks of each brick ratio were laid onto their corresponding cured bottom course. The course length, widths of brick (measured at the same four places as the daily brick shrinkage measurement), lengths of each brick and widths of gaps between bricks were all measured and recorded.

These measurements were taken and recorded every day, at the same time for 5 days.

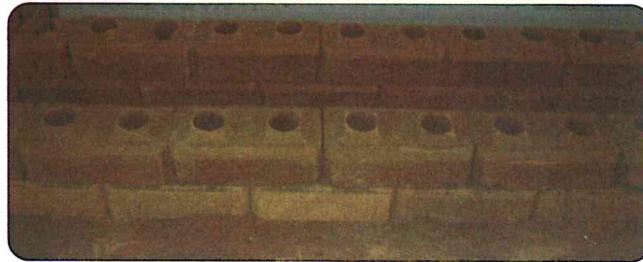


Figure 5: Shrinkage wall test

5.2 Results (PR)

5.2.1 Bottle Test

Overall 7 different soil samples were tested. The following tables highlight the percentage of each material present in the soil along with observations. The first four samples tested are listed in the table below followed by a picture of the experiment. The order written in the table corresponds to the bottles in the image going left to right.

Table 4: First set of soil samples

Location	Depth of Material (mm)			% Present in Sample			Observations after 24 hours
	Sand	Silt	Clay	Sand	Silt	Clay	
Campus	41	5	0	89.1	10.9	0.0	Fairly clear above the sediment
Campus Edge	33	7	0	82.5	17.5	0.0	Fairly cloudy
Termite Mound	43	8	2	81.1	15.1	3.8	Clearest of the samples above the sediment
Pit	37	13	2	71.2	25.0	3.8	Very cloudy, large proportion of material still unsettled



Figure 6: First set of soil samples

Following the changes in our method as previously stated, three more bottle tests were carried out. All these samples were taken from the Brickmaker's site, just outside the UMU campus. Both images were taken after 24 hours.

Table 5: Second set of soil samples

Location	Depth of Material (mm)			% Present in Sample			Observations after 24 hours
	Sand	Silt	Clay	Sand	Silt	Clay	
Entrance	24	3	0	88.9	11.1	0.0	Quite clear above sediment
In-between Trees	74	15	-6	89.2	18.1	-7.2	Clearest above sediment, deposited material lowered
Behind Trees	77	4	1	93.9	4.9	1.2	Still very cloudy, plenty of clay still in suspension



Figure 7: Second set of soil samples

5.2.2 Soil Shrinkage Test

When compiling the results for the soil shrinkage test, the gaps at the end were noted to be cracks also. The moulds were the same dimensions and weighed between 0.195-0.199kg. The weight of the cup used when measuring the soil and water was 0.043kg, this was subtracted from the values in the table.

The images below show both sets of experiments followed by a summary table of results.

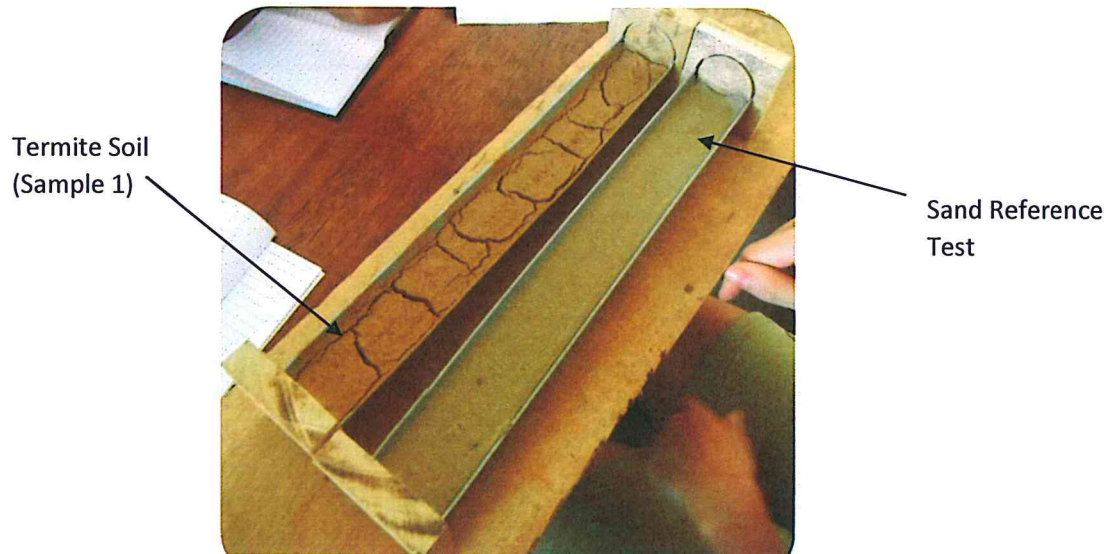


Figure 8: First shrinkage experiment



Figure 9: Second shrinkage experiment

Table 6: Raw shrinkage data

	Soil Type	Weight of Soil (kg)	Weight of water(kg)	Pipe Surface	Time in Oven (hours)	Top of pipe to top of soil (cm)	No. of Cracks	Total Crack Width (cm)
1	Termite Soil	0.412	0.150	Not- oiled	19	0.8	10	0.24
2	Sand	0.392	0.126	Not-oiled	19	0.7	0	0.00
3	Termite Soil	0.357	0.125	Oiled	24	0.8	11	0.28
4	Behind Trees	0.411	0.146	Oiled	24	0.9	6	0.18
5	Inbetween Trees	0.276	0.098	Oiled	24	1.1	3	0.07

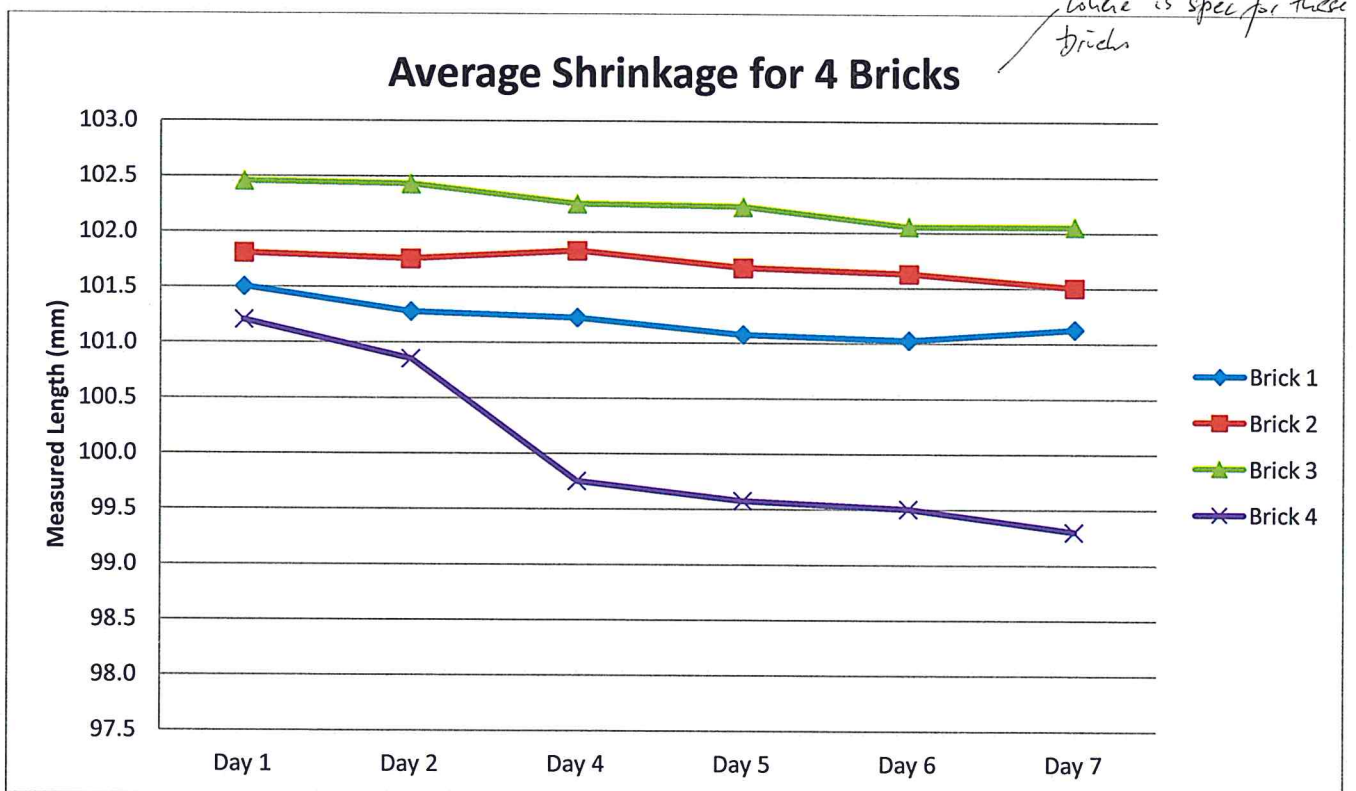
Table 7: Shrinkage results *for unstabilised soil, from liquid limit to over dry.*

	Soil Type	% Shrunk By (with initial length of 29cm)
1	Termite Soil	0.83%
2	Sand	0%
3	Termite Soil	0.97%
4	Behind Trees	0.62%
5	Inbetween Trees	0.24%

of stabilised soil?

5.2.3 Daily Block Shrinkage

As stated previously, measurements were taken over a week on four different bricks. The dimensions of each brick were noted at four specific points (ABCD). The full set of data acquired along with separate graphs for each brick are listed in Appendix C1. The graph below shows the mean shrinkage across the 4 points, plotted for each brick during the week.



Graph 1: Average shrinkage for 4 bricks

The table below states the average shrinkage for each brick.

Table 8: Average shrinkage for each brick

	Brick 1	Brick 2	Brick 3	Brick 4
Difference (mm)	0.5	0.3	0.4	1.9
		0.2%		1.35%

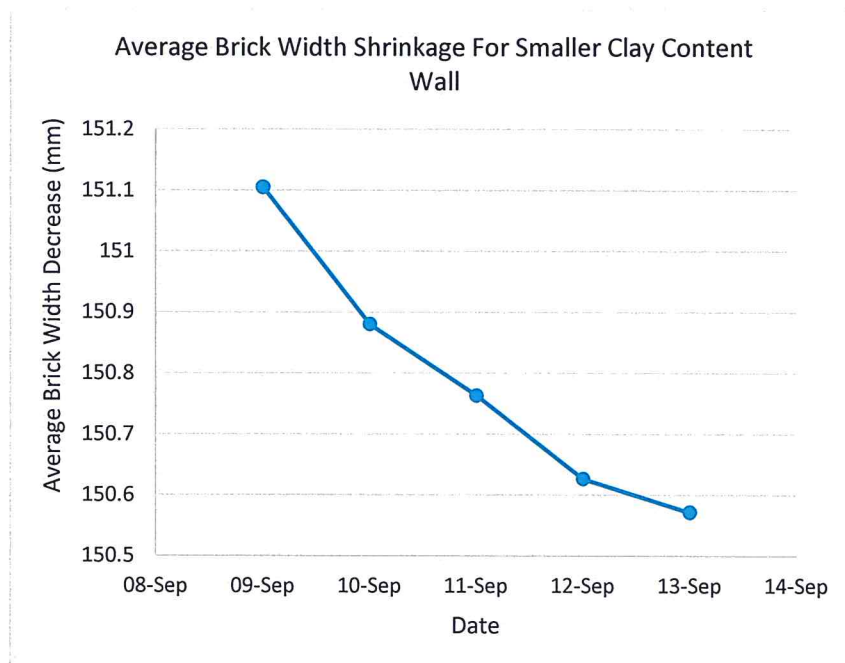
These are mean width shrinkage figures.
Did you check that
length shrinkage as %
≠ width shrinkage as %

After assessing both Graph 1 and Table 8, it can be seen that Brick 4 shrunk the most with 1.9mm and Brick 2 shrunk the least with 0.3mm. Bricks 1 and 2 were made with lower clay values (1 part clay soil to 6 parts sand) and showed an average shrinkage of 0.4mm. The average shrinkage of bricks 3 and 4 was 1.2mm, these bricks were made from a mix which had a greater clay content (6 parts clay soil to 1 part sand).

5.2.4 Daily Wall Shrinkage

As previously mentioned, two walls were constructed in order to assess the shrinkage of green bricks with both little and large quantities of clay in their mix. Results were taken over 5 days where the gaps in between the bricks along with the brick lengths and shrinkage (across 4 points ABCD) were measured.

The first wall consisted of a smaller clay content. The raw data can be found in Appendix C2. The following graph shows the average measurements of all 7 bricks and their decrease in width over 5 days after placing them on the course whilst still green.



So shrinkage not completed in 4 days

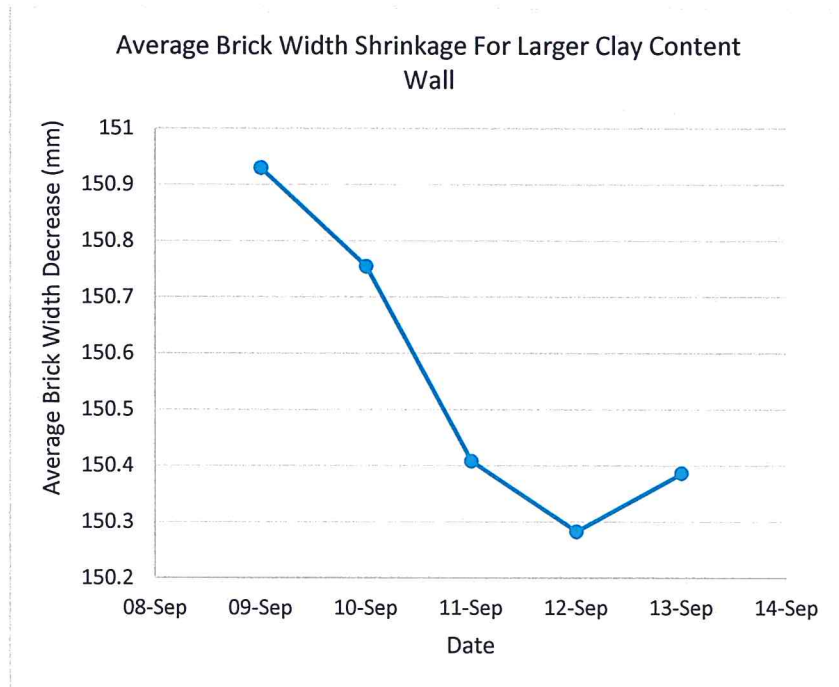
Graph 2: Average brick width shrinkage for smaller clay content wall

The average amount a green brick with a small clay content shrunk by in the wall was 0.58mm. Each of the six gaps between the seven bricks were also measured. Here the gap width increased with an average of 0.9mm. The length of each brick showed a decrease average of 1.9mm. This is a decrease of less than 1%.

agree

So expect $0.9 \times \frac{300}{150} = 1.8\text{mm}$ in length

For the wall made out of green bricks with a greater clay content (Graph 3), the results showed that the average brick shrunk in width by 0.70mm. The following graph shows the trend of measured shrinkage present in the greater clay content bricks.



Graph 3: Average brick width shrinkage for larger clay content wall

The average gap width increase was 0.9mm, similar to that for the smaller clay content wall. The length of each brick decreased by approximately by 2.3mm.

This does not seem compatible. Gap increase should equal length decrease.

5.3 Analysis

5.3.1 Bottle Test (PR)

After looking at the results from the bottle test, it can be seen that on both occasions most of the material fell within the first half an hour suggesting little/no clay. We used the bottle test because we didn't require clay content to a great accuracy and just required a general idea. The bottle test was also appropriate as it was economically viable and the resources were easy and cheap to obtain. The bottle test is a very crude, approximate test, unfortunately, the result were very inaccurate and unreliable to base our decision of material choice on.

One reason why the bottle test may not have worked is that the clay and sand may not have separated completely, despite drying all samples, crushing them and putting them through a sieve. We also used bigger bottles with the second set of samples as this can often improve the reliability of the test. Unfortunately this appears to have had little effect on either. ✓

The termite clay soil had a value of 3.8% clay, this was the highest we had recorded despite believing that the samples from the brick-makers' contained more. The termite clay soil had a sufficient clay content, was extremely local and was easy to harvest therefore after further experimentation (discussed in the soil shrinkage test) it became our selected soil material for the brick making process. ✓

5.3.2 Soil Shrinkage Test (HP)

By observation we can see that the sand sample was a sound reference point as there was virtually no shrinkage. ✓ Good
This confirmed that the method was sufficiently reliable for the scope of what we needed to find out. As seen in

Table 7, all the soil samples shrank by less than 1 percent but the termite soil shrank by the most. For this reason, and also due to availability, we chose the termite soil in the bricks for further experimentation.

This more accurate representation of shrinkage in the soil (related to the clay content), confirmed the results of the bottle test- that the termite soil had the highest clay content, and therefore the highest percentage of shrinkage.

It may be noted that the tests gave more consistent results when the half-pipe apparatus was oiled. This is why a second termite soil sample was tested- an oiled version. We can see in Figure 8 the effects of the lack of oiling- where the cracking also happens on the side of the piping, not just at intervals along the length of the sample.

Although a test piece of piping was put into the oven to find out whether it would melt at a given temperature (it was found that it would be fine at 95 degrees Celsius), Figure 9 shows that there was some warping in the apparatus. This may have slightly affected the shrinkage percentage measurements and recordings.

5.3.3 Daily Block Shrinkage (HP)

The average shrinkage for the lesser-clay block was found to be 0.4mm (width-ways) and the average shrinkage for the blocks with the higher clay content was 1.2mm. This difference was significant enough to confirm that the block with the higher clay content (more of the termite soil compared to sand content) shrank more than that of a lesser content.

It may be noted that the third day of results was omitted from the results. This is because there was a very obvious but consistent difference in reading on this day – the readings were, on average, 0.3 mm smaller than those on the other days. This was due to human inconsistency- a different person did the measuring on this day. It can be seen in Table 8 that brick 3, which had a higher clay content, actually had a shrinkage length in between those of bricks 1 and 2, which has the lesser clay content. This suggests that although an average shrinkage for each brick type was an expected result, the individual results may not be as accurate or reliable as we had hoped. This may be due to human error, or perhaps the accuracy for the calipers used. The measurements being taken were extremely small- especially the differences between them day to day. Something else which may have affected the shrinkage measurements was changed in whether each day- including changes in humidity. There were also many other people working at the same site that the experiment took place- the blocks may have been knocked or tampered with- which could considerably affect the width measurements.

5.3.4 Daily Wall Shrinkage (PR)

There was a large scope for error within this experiment thus making the data unreliable. For example, the bricks were handled a lot, they were moved and carried from the machine to various places before being stationed on the wall course. This gives the chance for the outer layer on the brick to be worn away in some places therefore distorting the results. The wall length was 6.5 bricks; creating the half brick was extremely difficult and was not done accurately. The brick was roughly split in half by hand, this therefore altered the reliability of the brick length measurements as the edge was not smooth. The apparatus used to measure the lengths wasn't very accurate or reliable either, a large 30cm ruler had to be used to measure the brick lengths, and this only measured to whole millimetres therefore each measurement had an uncertainty of +/- 0.5mm.

Overall, the daily wall shrinkage experiment confirmed the initial hypothesis that more shrinkage will occur with a greater clay content in the brick mix. In this case, the bricks made from a greater amount of clay content decreased in width by 0.12mm more than those with a smaller clay content. For both mixes, the gap widths in-between each brick increased by 0.9mm on average. This indicates that once placed on the course, the bricks shrink individually and do not group together and shrink even though they are tightly touching when placed.

This leads on to this experiment indicating that factoring in the spacing between two bricks when placing bricks on the course is not needed. This cannot be confirmed or drawn upon as a conclusion as there is not enough evidence to support this, in an ideal situation there would be the opportunity to test this further by experimenting on more than two courses and a wall greater than 6.5 bricks long. This issue resulted in the max spacing being tested. One

brick was placed overlapping the centre of two bricks beneath. The bottom two bricks were pulled apart to the max limit it would reach, this was a 3.8mm gap.

6.0 Evaluation

6.1 Stiffness Test (ES)

The limiting factor in analysing the stiffness data to find useful conclusions was the lack of data points. When the sample size was taken as two groups of nine, the number of degrees of freedom in the t-distribution was enough to accept hypotheses at confidence levels above 90%. However, when the number of degrees of freedom was lowered because only the 1st Runs from each Green Brick column were being considered, then in most cases the null hypotheses could not be rejected, despite the fact that the population mean stiffness of 1st Runs was higher than the population mean stiffness of all of Runs 1,2,3.

During the analysis, it was assumed that the statistical *population* of both column types had the same values of stiffness variance (and standard deviation). Although this is reasonable to assume (given that the variance of the *samples* only differed by 4.4%) it cannot be guaranteed. This assumption could be tested using the F-distribution as described by (Murphy and Hayslett, 1985).

One decision that was made early on was which measure of stiffness to use. The 1mm stiffness was chosen because it was relatively easy to calculate, and more stable than the incremental stiffness. However, it was potentially vulnerable to anomalous data points which reduce the measured stiffness around the 1mm deflection region, and are evident by the kinks in several of the load-deflection graphs. This data could be 'cleaned' by interpolating from the next highest data point and ignoring the anomalous results. Alternatively, more complex curve fitting could take place in Matlab and the gradient outputs of the graphs be used as the stiffness values. ✓

One potential area for error was by accidental damage to the Green Brick columns. Given that the columns were curing in a teaching laboratory, it is possible that some columns may have been knocked or pushed by other students. If this occurred, then the join between green bricks would have been disturbed, potentially resulting in a loss of strength of the join, and allowing the column to bend more easily in the subsequent experiments.

6.2 Shrinkage Test (PR)

There were a number of ways in which we ensured our experiments were as efficient and as accurate as possible. When taking measurements of the shrinkage tests, simple things such as ensuring measurements were taken at the exact same place on the brick by aligning these points with the grooves increased the accuracy of our results.

In regards to brick making, the efficiency of the technique was improved in a number of ways by paying attention to quality control. For example, each team member became skilled at their own specific job therefore creating an assembly line. One person would know how high to fill the mould, this was important as overfilling tends to cause poor top surfaces where excess material was taken out whilst under filling means the brick is not compressed enough thus affecting strength and durability. Another person would clean the mould effectively which was necessary in order to make sure that the brick would eject easily and remain in a good condition. Throughout the process, we learnt that a simple scattering of sand at the bottom of the mould would prevent the soil from sticking and causing damage when the brick is extracted. All of these things contributed towards saving time and decreasing waste. The number of rejected bricks decreased therefore increasing the productivity and overall efficiency. ✓

There were also a number of limitations to our work, for example, when different people take measurements it is often up to a certain degree of interpretation when reading instruments. Therefore we found that some sets of data were out by a specific amount on days where the measurer had changed. The main limitation was the time constraint, it was difficult selecting the material, making the bricks and then having sufficient time to conduct the experiments and take readings. If there was the opportunity to repeat this experiment, numerous repetitions would be made over a longer time period in order to gain a wider range of more accurate and reliable results.

7.0 Further Work (HP)

This relatively short report is just a touch on the surface of experimentation with mortar-less brickwork, but forms a sound basis for a range possible areas of further work.

As mortar-less construction has many advantages, more research must be carried out to improve it for more widespread use, and to encourage low-income communities to adopt the technology in construction. For this reason, the further work explored in this section is particularly geared towards more practical applications, especially in Ugandan communities that could benefit from these methods.

Firstly, more realistic forces on a wall and more realistic ratios could be researched. The force on the column in this report was not an entirely realistic model. With longer time and larger material allowances for experimentation, tests on actual walls, rather than simple columns and small two-course walls could be done.

Experimentation could also be done into the quality control of blocks. Blocks made with existing machines, and by relatively unskilled labour, can often vary in quality and size. Further design adaptations could be made to the machines to ensure further ease of quality brick production. It would be valuable research to repeat the experiment completed in this report, but using different ISSB block machines. This could be used to compare their variability and reliability and form a basis for improving their design.

Another idea is to research using ISSB for other building elements, as opposed to just walls, for example making machines that can make adaptable blocks for intersections/ y wall connection etcetera. Adaptable ISSB wall construction could be taken further to allow the introduction of electrical and plumbing systems. Roof construction is often up to 50 per cent of the overall cost of a building in Uganda (UN Habitat, 2009). Using ISSB in roofing in arches or domes could reduce construction cost.

In some areas, there is an insufficient amount of available suitable soil for making ISSB bricks, and cement is also often not easy to come by and therefore relatively expensive. There are several other potential alternative stabilizers and soil mixes, which after compression can produce structurally sound, cost effective and environmentally friendly soil blocks. Specific stabilisers can be used depending on the shrinkage of the soil used to make a block.

There are also various social and environmental factors needed to be further considered. Local economic development models to be explored. There is a need to further sensitize community groups in regard to business and self-help opportunities using ISSB.

8.0 Conclusion (MLC)

In terms of laying blocks on other blocks, whether they're green or cured, shrinkage is not an issue. No matter what the combination of blocks is, the bricks made by the Tanzanian block press always allow sufficient clearance and brick-to-brick contact area is always in the desired place. In fact, the clearance is so large that too much variability is allowed when placing brick upon brick. This aspect is not an issue for laying cured bricks as they can be adjusted and repositioned, but presents a practical problem when constructing 'green' brick walls as they can only be placed once. This leads to poorly constructed, non-straight walls.

Many factors affect the viability of the green-on-green technique – not just the resultant increased wall stiffness of approximately 51% at the 90% confidence level. These factors are mostly practical or economical in nature and so even though this technique does produce walls of increased strength, the benefit does not appear to be so significant that this technique can just replace the existing one. Careful consideration needs to be taken of all elements of the construction process, in a variety of scenarios, to decide whether it is actually worthwhile and appropriate.

and some discussion of them would have been welcome.
Indeed would you recommend 'green' laying to achieve 50% increase in stiffness and what might increase that stiffness further (more clay, wetter mix, weight on newly-laid brick?)

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APPENDICES

Appendix A - How to Make a Brick using a Tanzanian Block Press (MLC)

Step 1: Clean mould and coat lightly with dry sand



Step 2: Fill press with mixture



Step 3: Fill press until almost overflowing, then use lid to initially compact the soil before filling up to same level again



Step 4: The lid is then closed and lever arm brought into position. Lever arm is then pulled down until it can go no further to fully compress the mixture.



Step 5: The lever arm is brought across to the other side of the press and pulled down again after the lid has been opened. This ejects the compressed brick.



Step 6: Finally, carefully remove the brick from the mould and leave to cure



Appendix B1 - Results for Cured and Green Brick Towers (ES)

Results for Cured Brick Tower

Chain length (links)	114										
Mass of chain (kg)	0.483										
Mass of bucket (kg)	0.764										
Mass of trowel (kg)	0.509										
		Total Load (N)	Applied Mass (kg)	Vertical Chain Length (links)	Vertical Chain Mass (kg)	Dial Gauge (mm)	Movement from start of Trial (mm)	Movement from start of Run (mm)	Incremental Stiffness (N/m)	Mean Stiffness (N/m)	1mm Movement Stiffness Value (N/m)
Trial 1 Run 1		0.00 5.41 7.99 12.94 17.85 22.75 27.66 31.82	0 0.509 0.764 1.264 1.764 2.264 2.764 3.184	0 10 12 13 13 13 13 14	0.000 0.042 0.051 0.055 0.055 0.055 0.055 0.059	41 40.59 40.145 39.965 39.64 39.35 39.01 37.57	0.00 0.41 0.85 1.04 1.36 1.65 1.99 3.43	0.00 0.41 0.85 1.04 1.36 1.65 1.99 3.43	13192 5808 27481 15092 16914 14426 2890	13192 9349 12503 13121 13788 13897 9276	11889
		#VALUE!	3.25	collapse	#VALUE!						
Trial 1 Run 2		0.00 5.41 7.99 12.94 17.85 22.75 27.66 30.44	0 0.509 0.764 1.264 1.764 2.264 2.764 3.044	0 10 13 13 13 13 13 14	0.000 0.042 0.055 0.055 0.055 0.055 0.055 0.059	39 38.79 38.41 38.15 37.925 37.45 33.3	2.00 2.21 2.59 2.85 3.08 3.55 7.70	0.00 0.21 0.59 0.85 1.08 1.55 5.70	25757 19819 18865 21800 10326 672	25757 21932 20994 21163 17842 5341	21107
		#VALUE!	3.16	collapse	#VALUE!						
Trial 1 Run 3		0.00 5.41 7.99 12.94 17.85 22.75 27.66 28.92	0 0.509 0.764 1.264 1.764 2.264 2.764 2.889	0 10 12 13 13 13 13 14	0.000 0.042 0.051 0.055 0.055 0.055 0.055 0.059	37.5 37.23 36.91 36.71 36.32 36.04 35.65 34.8	3.50 3.77 4.09 4.29 4.68 4.96 5.35 6.20	0.00 0.27 0.59 0.79 1.18 1.46 1.85 2.70	20033 8077 24733 12577 17518 12577 1492	20033 13548 16380 15123 15582 14949 10712	15703
		#VALUE!	3.14	collapse	#VALUE!						
Trial 2 Run 1		0.00 5.41 7.99 12.94 17.85 22.75 27.66	0 0.509 0.764 1.264 1.764 2.264 2.764	0 10 12 13 13 13 13	0.000 0.042 0.051 0.055 0.055 0.055 0.055	43.5 43.28 43.12 42.79 42.05 40.8 39.21	0.00 0.22 0.38 0.71 1.45 2.70 4.29	0.00 0.22 0.38 0.71 1.45 2.70 4.29	24586 16154 14990 6628 3924 3085	24586 21036 18226 12307 8426 6446	15906
		#VALUE!	3.03	collapse	#VALUE!						
Trial 2 Run 2		0.00 5.41 8.04 12.94 17.85 22.75 26.77	0 0.509 0.764 1.264 1.764 2.264 2.674	0 10 13 13 13 13 13	0.000 0.042 0.055 0.055 0.055 0.055 0.055	40.1 39.94 39.84 39.55 38.84 37.73 36.05	3.40 3.56 3.66 3.95 4.66 5.77 7.45	0.00 0.16 0.26 0.55 1.26 2.37 4.05	33806 26262 16914 6908 4419 2394	33806 30904 23528 14163 9599 6610	17592
		#VALUE!	2.76	collapse	#VALUE!						
Trial 2 Run 3		0.00 5.41 7.99 12.94 17.85 22.75	0 0.509 0.764 1.264 1.764 2.264	0 10 12 13 13 13	0.000 0.042 0.051 0.055 0.055 0.055	39.43 39.22 39.12 38.88 38.03 37.08	4.07 4.28 4.38 4.62 5.47 6.42	0.00 0.21 0.31 0.55 1.40 2.35	25757 25847 20611 5771 5163	25757 25786 23528 12747 9681	17820
		#VALUE!	2.76	collapse	#VALUE!						
Trial 3 Run 1		0.00 5.45 7.99 12.94 17.89 22.79 24.89	0 0.509 0.764 1.264 1.764 2.264 2.474	0 11 12 13 14 14 15	0.000 0.047 0.051 0.055 0.059 0.059 0.064	31.08 30.67 30.08 29.96 28.76 28.02 26.07	0.00 0.41 1.00 1.12 2.32 3.06 5.01	0.00 0.41 1.00 1.12 2.32 3.06 5.01	13294 4310 41221 4122 6628 1078	13294 7994 11554 7710 7448 4969	7994
		#VALUE!	2.61	collapse	#VALUE!						
Trial 3 Run 2		0.00 5.45 7.99 12.94 17.89 22.79 24.02	0 0.509 0.764 1.264 1.764 2.264 2.389	0 11 12 13 14 14 14	0.000 0.047 0.051 0.055 0.059 0.059 0.059	27.53 27.31 27.19 27.08 26.79 26.4 24.15	3.55 3.77 3.89 4.00 4.29 4.68 6.93	0.00 0.22 0.34 0.45 0.74 1.13 3.38	24775 21193 44969 17057 12577 545	24775 23511 28756 24171 20170 7106	21504
		#VALUE!	2.48	collapse	#VALUE!						
Trial 3 Run 3		0.00 5.45 7.99 12.98 17.89 22.30 22.79 23.81	0 0.509 0.764 1.264 1.764 2.214 2.264 2.364	0 11 12 14 14 14 14 15	0.000 0.047 0.051 0.059 0.059 0.059 0.059 0.064	27.97 27.72 27.64 27.42 27.12 24.95 24.53 21.43	3.11 3.36 3.44 3.66 3.96 6.13 6.55 9.65	0.00 0.25 0.33 0.55 0.85 3.02 3.44 6.54	21802 31789 22673 16350 2034 1168 330	21802 24223 23603 21043 7385 6626 3641	20099
		#VALUE!	2.455	collapse	#VALUE!						

Mean	16624
Stan Dev	4425
SD of est of Mean	1475
Coeff of Variation	0.266157108

Results for Green Brick Towers

Chain length (links)	114											
Mass of chain (kg)	0.483											
Mass of bucket (kg)	0.740											
Mass of trowel (kg)	0.486											
	Total Load	Applied Mass	Vertical Chain Length	Vertical Chain Mass	Dial Guage	Movement from start of Trial	Movement from start of Run	Incremental Stiffness	Mean Stiffness	1mm Movement Stiffness Value		
	(N)	(kg)	(links)	(kg)	(mm)	(mm)	(mm)	(N/m)	(N/m)	(N/m)		
Green 1 Run 1	0	0	0	0.000	37.50	0.00	0.00					
	5.266	0.486	12	0.051	37.45	0.05	0.05	95753	95753			
	7.841	0.740	14	0.059	37.40	0.10	0.10	57219	78413			
	12.788	1.240	15	0.064	37.16	0.34	0.34	20611	37611			
	17.693	1.740	15	0.064	37.16	0.34	0.34	#DIV/0!	52038			27643
	22.598	2.240	15	0.064	36.74	0.76	0.76	11679	29734			
	27.503	2.740	15	0.064	34.32	3.18	3.18	2027	8649			
	#VALUE!	2.923	collapse	#VALUE!								
Green 1 Run 2	0	0	0	0.000	36.52	0.98	0.00					
	5.266	0.486	12	0.051	36.60	0.90	-0.08	-65830	-65830			
	7.841	0.740	14	0.059	36.73	0.77	-0.21	-19807	-37339			
	12.788	1.240	15	0.064	36.58	0.92	-0.06	32977	-213131			29211
	17.693	1.740	15	0.064	36.14	1.36	0.38	11148	46560			
	21.421	2.120	15	0.064	34.97	2.53	1.55	3186	13820			
	22.598	2.240	15	0.064	34.33	3.17	2.19	1839	10319			
	24.560	2.440	15	0.064	31.25	6.25	5.27	637	4660			
	25.786	2.565	15	0.064	29.50	8.00	7.02	701	3673			
	26.563	2.640	16	0.068	27.85	9.65	8.67	471	3064			
	#VALUE!	2.675	collapse	#VALUE!								
Green 1 Run 3	0	0	0	0.000	37.01	0.49	0.00					
	5.266	0.486	12	0.051	36.95	0.55	0.06	87774	87774			
	7.841	0.740	14	0.059	36.90	0.60	0.11	51497	71284			
	12.746	1.240	14	0.059	36.75	0.75	0.26	32700	49024			21429
	17.693	1.740	15	0.064	36.34	1.16	0.67	12065	26407			
	20.145	1.990	15	0.064	35.44	2.06	1.57	2725	12831			
	22.598	2.240	15	0.064	34.42	3.08	2.59	2404	8725			
	25.541	2.540	15	0.064	30.78	6.72	6.23	809	4100			
	#VALUE!	2.623	collapse	#VALUE!								
Green 2 Run 1	0	0	0	0.000	41.50	0.00	0.00					
	5.142	0.486	9	0.038	41.44	0.06	0.06	85696	85696			
	7.717	0.740	11	0.047	41.41	0.09	0.09	85829	85740			
	12.663	1.240	12	0.051	41.33	0.17	0.17	61832	74489			
	17.568	1.740	12	0.051	41.24	0.26	0.26	54500	67570			
	22.515	2.240	13	0.055	41.11	0.39	0.39	38050	57730			35589
	27.420	2.740	13	0.055	40.91	0.59	0.59	24525	46474			
	32.325	3.240	13	0.055	39.94	1.56	1.56	5057	20721			
	#VALUE!	3.407	collapse	#VALUE!								
Green 2 Run 2	0	0	0	0.000	39.08	2.42	0.00					
	5.142	0.486	9	0.038	39.04	2.46	0.04	128543	128543			
	7.717	0.740	11	0.047	38.99	2.51	0.09	51497	85740			
	12.663	1.240	12	0.051	38.89	2.61	0.19	49466	66648			
	17.568	1.740	12	0.051	38.72	2.78	0.36	28853	48800			28075
	22.515	2.240	13	0.055	38.37	3.13	0.71	14133	31711			
	27.420	2.740	13	0.055	36.80	4.70	2.28	3124	12026			
	28.695	2.870	13	0.055	30.03	11.47	9.05	188	3171			
	#VALUE!	2.936	collapse	#VALUE!								
Green 2 Run 3	0	0	0	0.000	38.14	3.36	0.00					
	5.183	0.486	10	0.042	38.06	3.44	0.08	64791	64791			
	7.717	0.740	11	0.047	38.00	3.50	0.14	42222	55119			
	12.663	1.240	12	0.051	37.86	3.64	0.28	35333	45226			22331
	17.568	1.740	12	0.051	37.56	3.94	0.58	16350	30290			
	22.473	2.240	12	0.051	37.03	4.47	1.11	9255	20246			
	25.809	2.580	12	0.051	35.10	6.40	3.04	1728	8490			
	27.420	2.740	13	0.055	30.60	10.90	7.54	358	3637			
	#VALUE!	2.837	collapse	#VALUE!								
Green 3 Run 1	0	0	0	0.000	39.40	0.00	0.00					
	5.183	0.486	10	0.042	39.39	0.01	0.01	518329	518329			
	7.758	0.740	12	0.051	39.33	0.07	0.07	42914	110831			
	12.705	1.240	13	0.055	39.26	0.14	0.14	70665	90748			
	17.610	1.740	13	0.055	39.14	0.26	0.26	40875	67730			
	22.515	2.240	13	0.055	38.98	0.42	0.42	30656	53606			32627
	27.420	2.740	13	0.055	38.69	0.71	0.71	16914	38619			
	32.366	3.240	14	0.059	37.80	1.60	1.60	5558	20229			
	35.898	3.600	14	0.059	32.70	6.70	6.70	692	5358			
	#VALUE!	3.680	collapse	#VALUE!								
Green 3 Run 2	0	0	0	0.000	35.15	4.25	0.00					
	5.183	0.486	10	0.042	35.10	4.30	0.05	103666	103666			
	7.758	0.740	12	0.051	35.03	4.37	0.12	36784	64651			
	12.705	1.240	13	0.055	34.87	4.53	0.28	30916	45374			
	17.610	1.740	13	0.055	34.70	4.70	0.45	28853	39133			24515
	22.556	2.240	14	0.059	34.27	5.13	0.88	11504	25632			
	27.461	2.740	14	0.059	32.74	6.66	2.41	3206	11395			
	32.366	3.240	14	0.059	27.91	11.49	7.24	1016	4470			
	#VALUE!	3.236	collapse	#VALUE!								
Green 3 Run 3	0	0	0	0.000	34.50	4.90	0.00					
	5.183	0.486	10	0.042	34.50	4.90	0.00	#DIV/0!	#DIV/0!			
	7.758	0.740	12	0.051	34.52	4.88	-0.02	-128743	-387908			
	12.705	1.240	13	0.055	34.40	5.00	0.10	41221	127047			
	17.651	1.740	14	0.059	34.22	5.18	0.28	27481	63040			29698
	22.556	2.240	14	0.059	33.88	5.52	0.62	14426	36381			
	27.461	2.740	14	0.059	32.66	6.74	1.84	4020	14925			
	32.366	3.240	14	0.059	29.51	9.89	4.99	1557	6486			
	#VALUE!	3.259	collapse	#VALUE!								

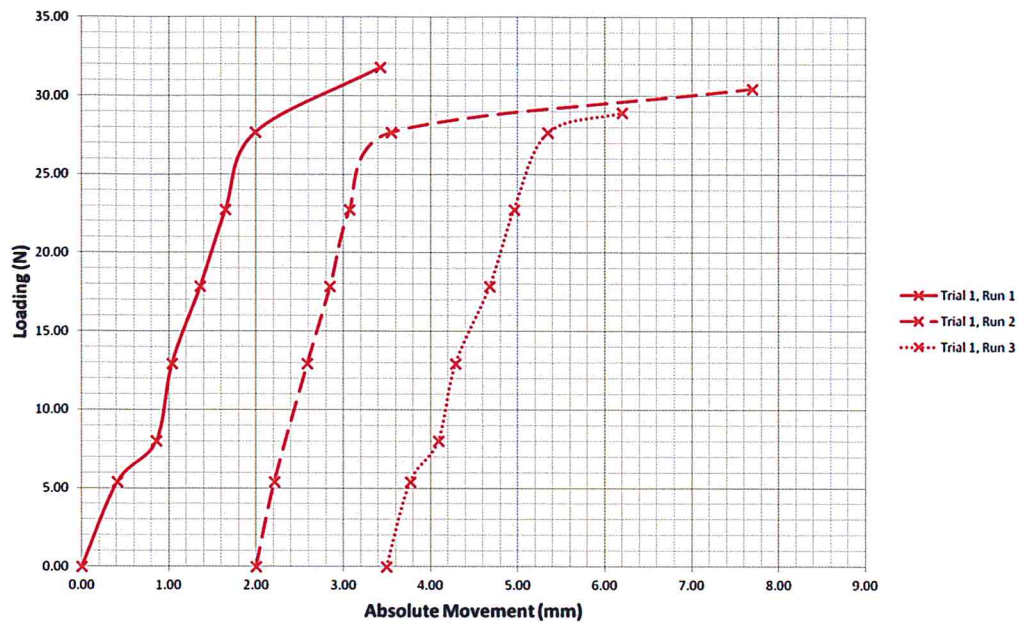
Mean	27902
Stand Dev	4621
SD of Estimate of Mean	1540
Coeff of Variation	0.165625041

Appendix B2 - Stiffness Comparison (FS)

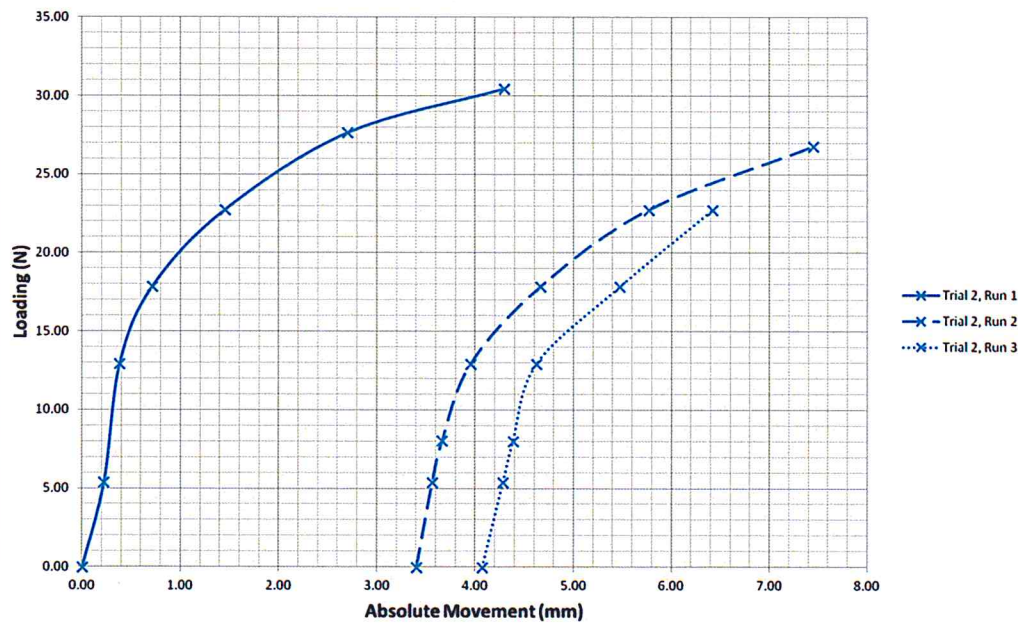
Stiffness Comparison		Scenario 1										Scenario 2										
		Sample Size is Treated as 9 of Cured and 9 of Green (18 total)										Sample Size is Treated as 3 of Cured and 3 of Green (6 total)										
Degrees of Freedom		16										4										
Percentage Certainty			90	95	97.5	99	99.5			90	95	97.5	99	99.5								
alpha			0.1	0.05	0.025	0.01	0.005			0.1	0.05	0.025	0.01	0.005								
limiting t-value			-1.337	-1.746	-2.12	-2.583	-2.921			-1.533	-2.132	-2.776	-3.747	-4.604								
Sum of squares from sample 1			156611733	156611733	156611733	156611733	156611733			315943190.3	315943190.3	315943190.3	315943190.3	315943190.3								
Sum of squares from sample 2			170848477	170848477	170848477	170848477	170848477			2074222378	2074222378	2074222378	2074222378	2074222378								
Pooled sample variance, s_p^2			20466263.1	20466263.1	20466263.1	20466263.1	20466263.1			597541392.1	597541392.1	597541392.1	597541392.1	597541392.1								
Mean of sample 1, u_1 (N/m)			16624	16624	16624	16624	16624			11930	16624	16624	16624	16624								
Mean of sample 2, u_2 (N/m)			27902	27902	27902	27902	27902			31953	31953	31953	31953	31953								
t-value assuming difference of the means of the population of:			Percentage Difference																			
Null Hypothesis: $H_0: u_1-u_2=0$			-5.288	-5.288	-5.288	-5.288	-5.288	-5.288		-1.003	-0.768	-0.768	-0.768	-0.768	-0.768	-0.768						
$H_1: u_1-u_2<0$			FALSE	FALSE	FALSE	FALSE	FALSE	FALSE		TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE						
$H_2: u_1-u_2<-5000$			-2.944	-2.944	-2.944	-2.944	-2.944	-2.944		-0.753	-0.518	-0.518	-0.518	-0.518	-0.518	-0.518						
$H_3: u_1-u_2<-5100$			-2.897	-2.897	-2.897	-2.897	-2.897	-2.897		-0.748	-0.513	-0.513	-0.513	-0.513	-0.513	-0.513						
$H_4: u_1-u_2<-5700$			-2.616	-2.616	-2.616	-2.616	-2.616	-2.616		-0.718	-0.482	-0.482	-0.482	-0.482	-0.482	-0.482						
$H_5: u_1-u_2<-5800$			-2.569	-2.569	-2.569	-2.569	-2.569	-2.569		-0.713	-0.477	-0.477	-0.477	-0.477	-0.477	-0.477						
$H_6: u_1-u_2<-6700$			-2.147	-2.147	-2.147	-2.147	-2.147	-2.147		-0.668	-0.432	-0.432	-0.432	-0.432	-0.432	-0.432						
$H_7: u_1-u_2<-6800$			-2.100	-2.100	-2.100	-2.100	-2.100	-2.100		-0.663	-0.427	-0.427	-0.427	-0.427	-0.427	-0.427						
$H_8: u_1-u_2<-7500$			-1.772	-1.772	-1.772	-1.772	-1.772	-1.772		-0.627	-0.392	-0.392	-0.392	-0.392	-0.392	-0.392						
$H_9: u_1-u_2<-7600$			-1.725	-1.725	-1.725	-1.725	-1.725	-1.725		-0.622	-0.387	-0.387	-0.387	-0.387	-0.387	-0.387						
$H_{10}: u_1-u_2<-8400$			-1.350	-1.350	-1.350	-1.350	-1.350	-1.350		-0.582	-0.347	-0.347	-0.347	-0.347	-0.347	-0.347						
$H_{11}: u_1-u_2<-8500$			-1.303	-1.303	-1.303	-1.303	-1.303	-1.303		-0.577	-0.342	-0.342	-0.342	-0.342	-0.342	-0.342						

Stiffness Comparison		Scenario 3										Scenario 4									
		Sample Size Treated as 9 Cured and 3 Green (only 1st Runs selected) (12 total)										Sample Treated as 9 Cured and 6 Green (only 2nd&3rd Runs selected)(15 total)									
Degrees of Freedom		10										13									
Percentage Certainty																					
alpha																					
limiting t-value																					
Sum of squares from sample 1																					
Sum of squares from sample 2																					
Pooled sample variance, s_p^2																					
Mean of sample 1, u_1 (N/m)																					
Mean of sample 2, u_2 (N/m)																					
t-value assuming difference of the means of the population of:																					
Null Hypothesis: $H_0: u_1 - u_2 = 0$																					
$H_1: u_1 - u_2 < 0$																					
$H_2: u_1 - u_2 < -1$																					
$H_3: u_1 - u_2 < -100$																					
$H_4: u_1 - u_2 < -1600$																					
$H_5: u_1 - u_2 < -1700$																					

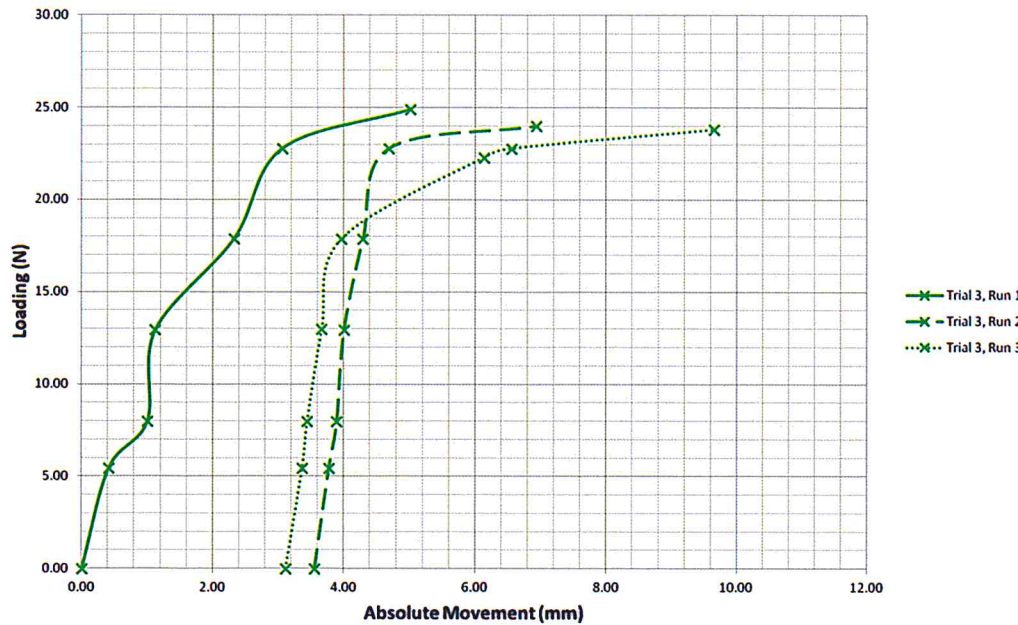
Cured Brick Column 1, Trial 1



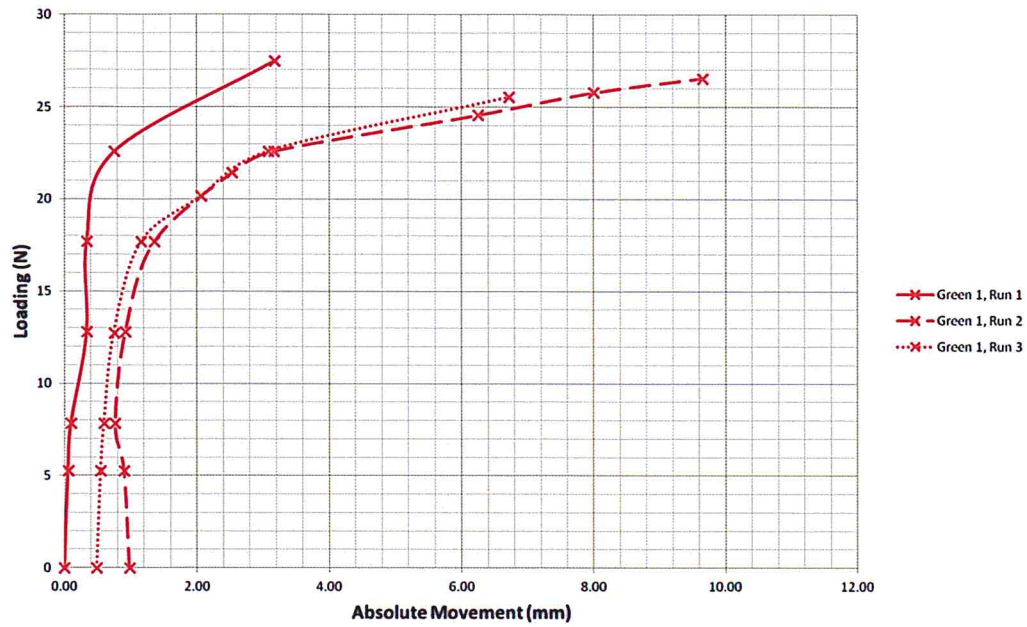
Cured Brick Column 1, Trial 2



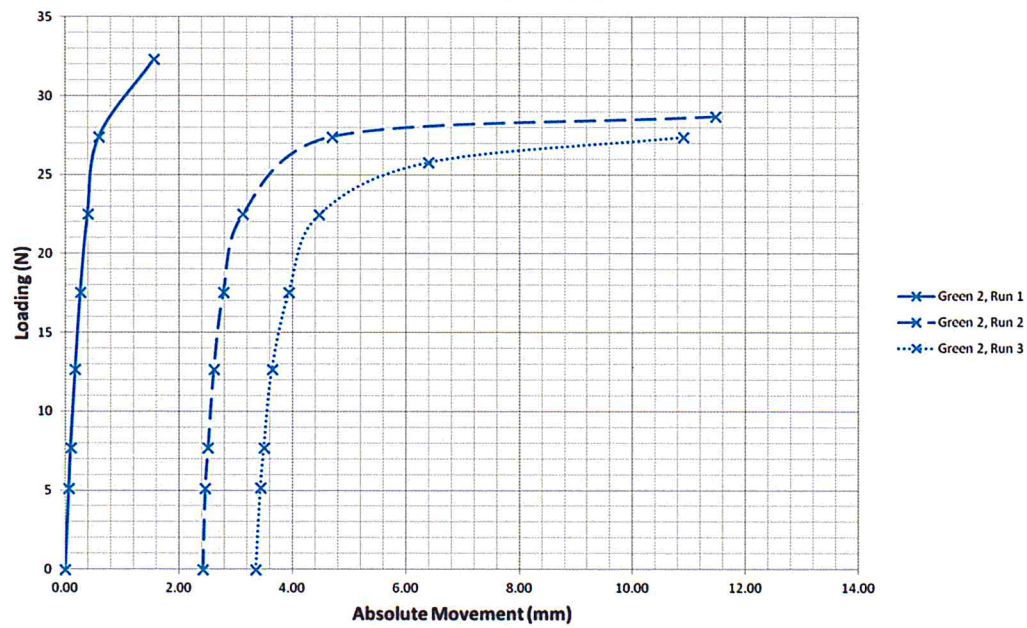
Cured Brick Column 1, Trial 3



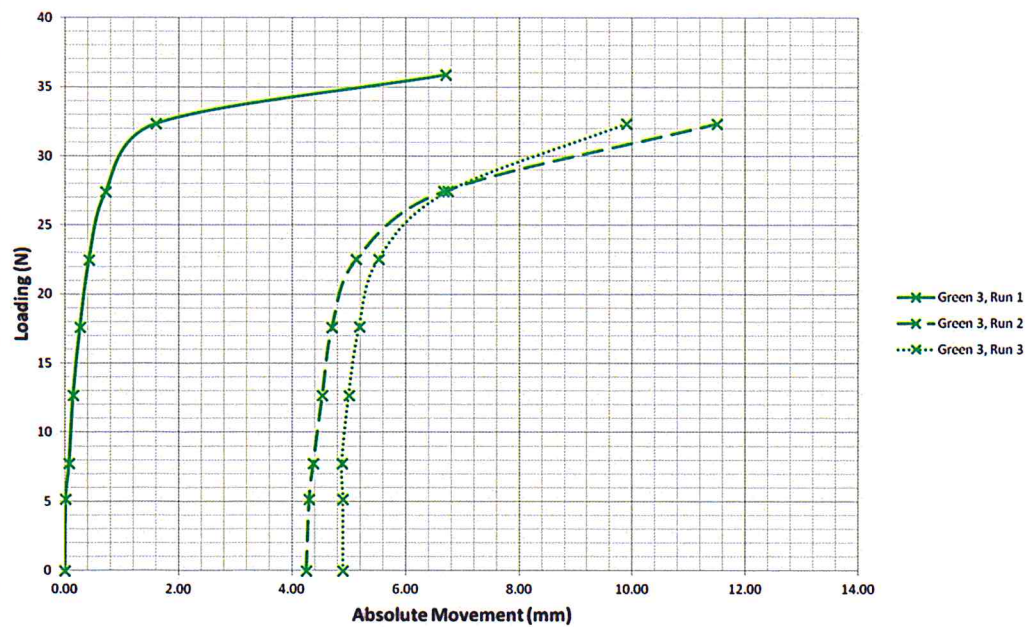
Green Column 1

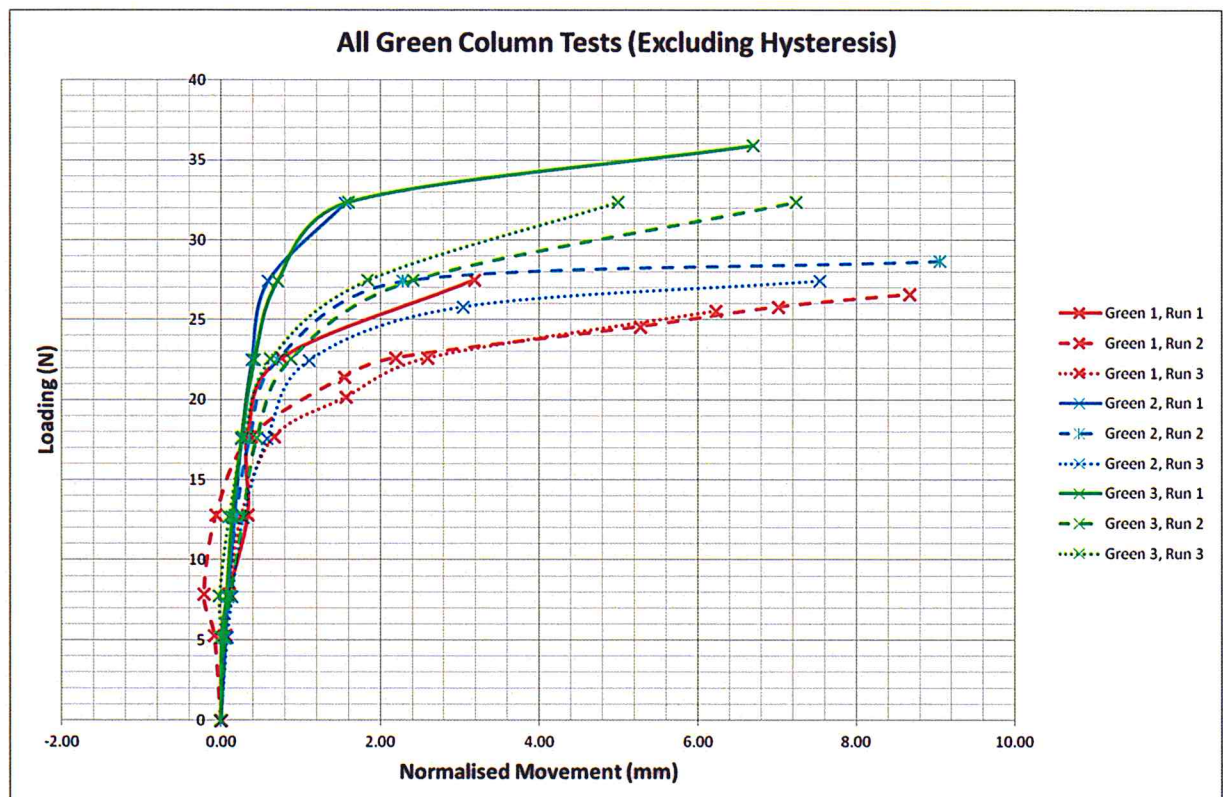
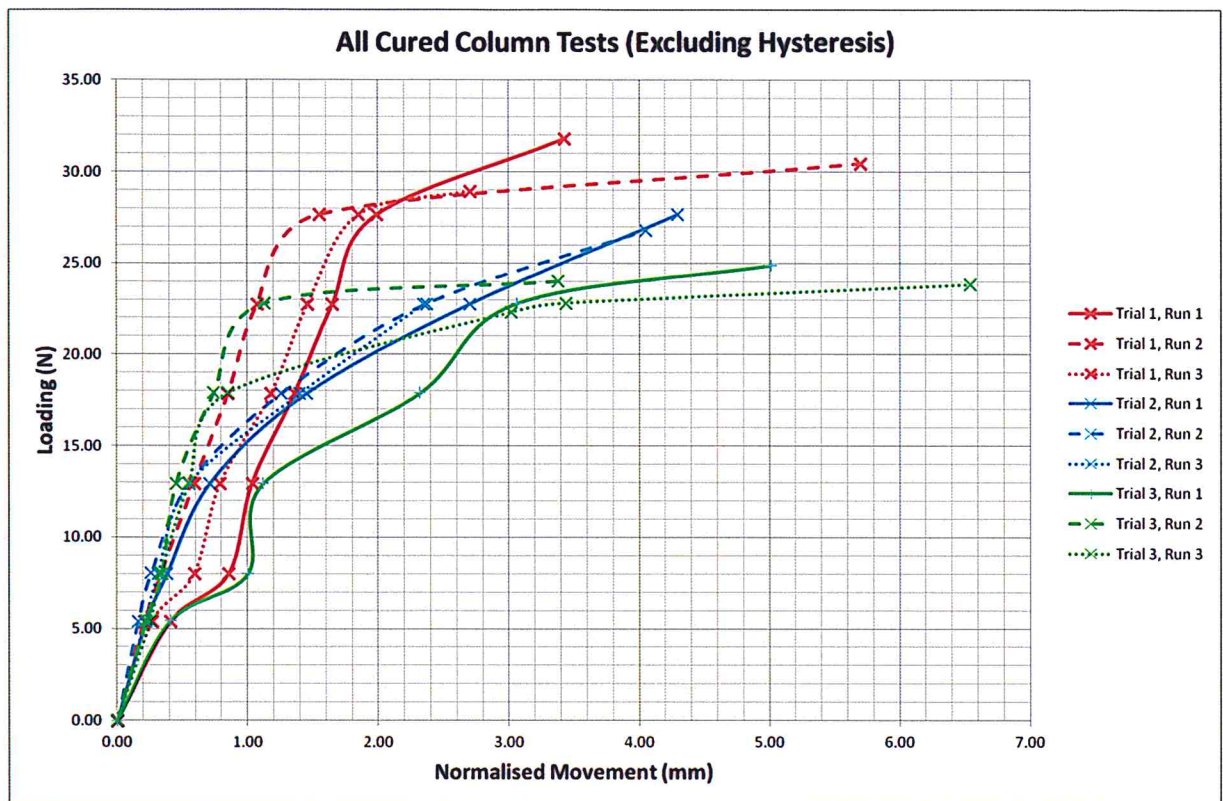


Green Column 2



Green Column 3





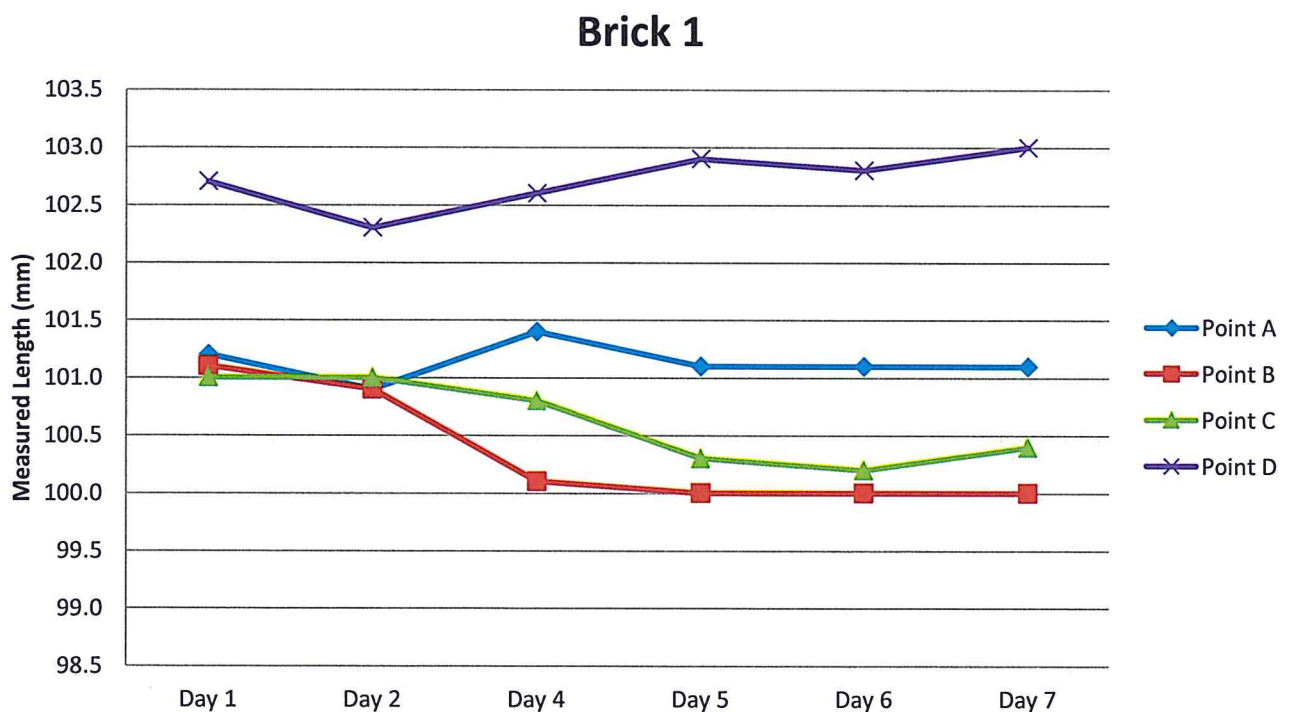
Appendix C1 – Brick Shrinkage Graphs (PR)

Brick 1

Data Table

	A	B	C	D	Mean
Day 1	101.2	101.1	101.0	102.7	101.5
Day 2	100.9	100.9	101.0	102.3	101.3
Day 4	101.4	100.1	100.8	102.6	101.2
Day 5	101.1	100.0	100.3	102.9	101.1
Day 6	101.1	100.0	100.2	102.8	101.0
Day 7	101.1	100.0	100.4	103.0	101.1
Largest Diff	0.5	1.1	0.8	0.7	0.5

Graph Illustrating the Shrinkage for Brick 1 over 4 Points

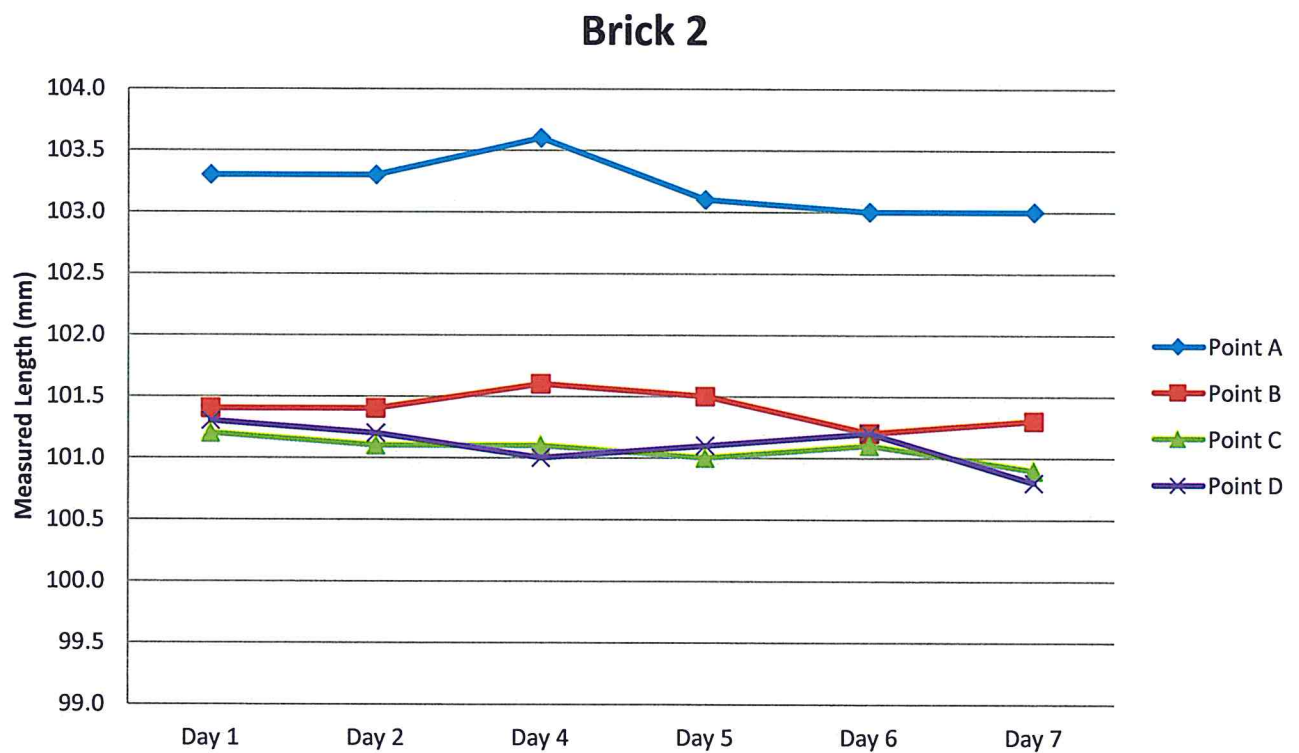


Brick 2

Data Table

	A	B	C	D	Mean
Day 1	103.3	101.4	101.2	101.3	101.8
Day 2	103.3	101.4	101.1	101.2	101.8
Day 4	103.6	101.6	101.1	101.0	101.8
Day 5	103.1	101.5	101.0	101.1	101.7
Day 6	103.0	101.2	101.1	101.2	101.6
Day 7	103.0	101.3	100.9	100.8	101.5
Largest Diff	0.6	0.4	0.3	0.5	0.3

Graph Illustrating the Shrinkage for Brick 2 over 4 Points

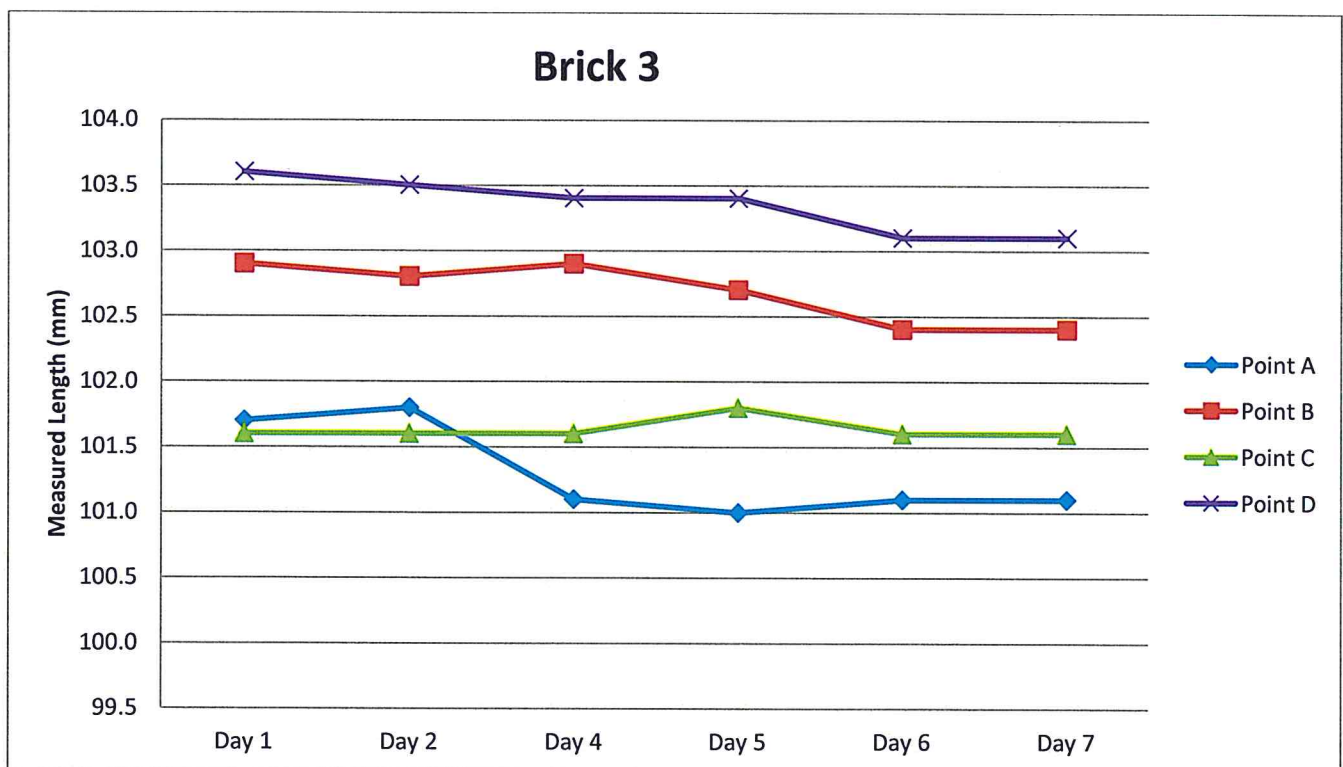


Brick 3

Data Table

	A	B	C	D	Mean
Day 1	101.7	102.9	101.6	103.6	102.5
Day 2	101.8	102.8	101.6	103.5	102.4
Day 4	101.1	102.9	101.6	103.4	102.3
Day 5	101.0	102.7	101.8	103.4	102.2
Day 6	101.1	102.4	101.6	103.1	102.1
Day 7	101.1	102.4	101.6	103.1	102.1
Largest Diff	0.8	0.5	0.2	0.5	0.4

Graph Illustrating the Shrinkage of Brick 3 over 4 Points

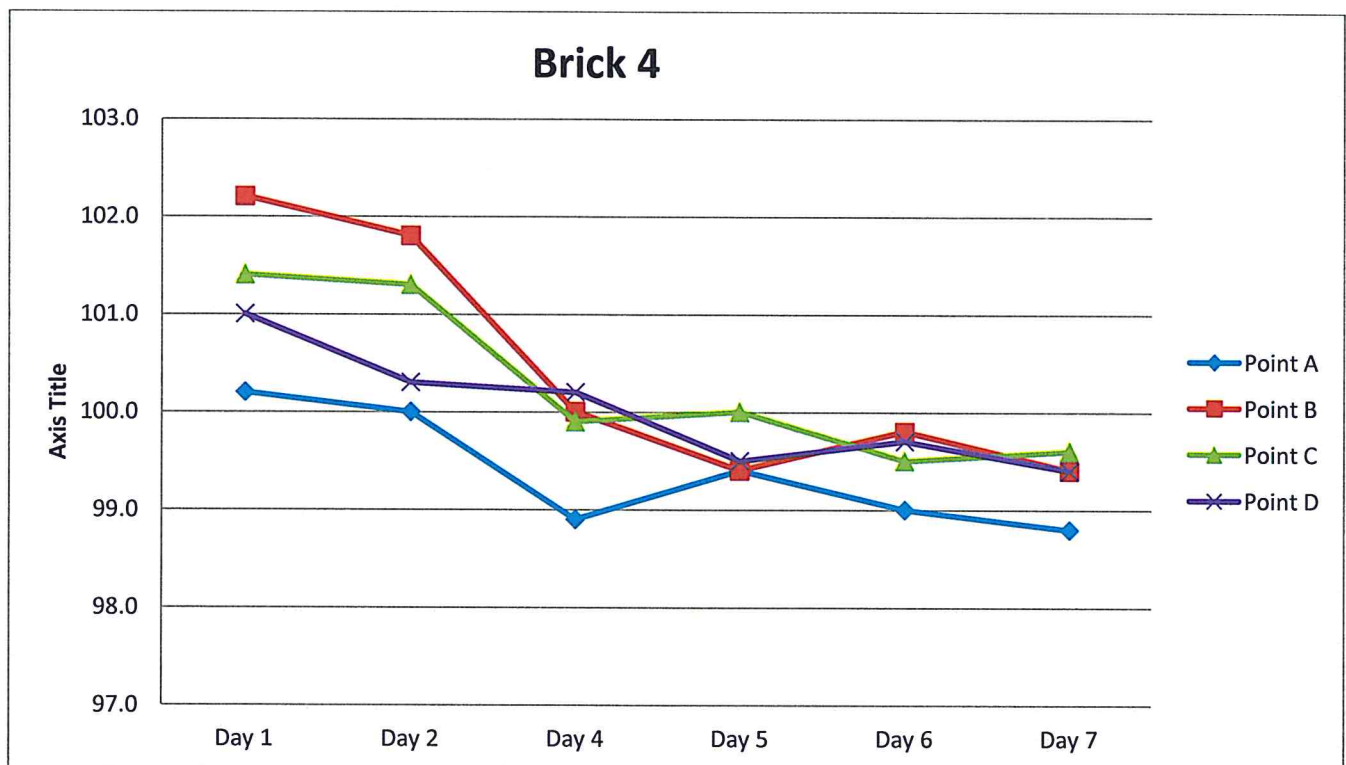


Brick 4

Data Table

	A	B	C	D	Mean
Day 1	100.2	102.2	101.4	101.0	101.2
Day 2	100.0	101.8	101.3	100.3	100.9
Day 4	98.9	100.0	99.9	100.2	99.8
Day 5	99.4	99.4	100.0	99.5	99.6
Day 6	99.0	99.8	99.5	99.7	99.5
Day 7	98.8	99.4	99.6	99.4	99.3
Largest Diff	1.4	2.8	1.9	1.6	1.9

Graph Illustrating the Shrinkage of Brick 4 over 4 Points



Appendix C2 – Shrinkage Wall Data (PR)

Small Clay Content Wall

Date	Average Brick Width Measurement Across Points ABCD (mm)							Average (mm)
	1	2	3	4	5	6	7	
09/09/2013	151.00	150.80	150.90	151.03	151.58	150.90	151.53	151.10
10/09/2013	151.20	150.65	150.55	150.65	150.90	150.78	151.43	150.88
11/09/2013	151.10	150.50	150.45	150.58	150.68	150.78	151.27	150.76
12/09/2013	151.00	150.45	150.35	150.48	150.45	150.43	151.23	150.63
13/09/2013	151.05	150.28	150.45	150.38	150.43	150.33	151.10	150.57
Difference	0.20	0.53	0.55	0.65	1.15	0.57	0.43	0.58

Date	Gap Measurements Inbetween Bricks (mm)						Average (mm)
	1-2	2-3	3-4	4-5	5-6	6-7	
09/09/2013	3.1	2.0	4.1	3.1	3.0	2.8	3.0
10/09/2013	3.7	2.2	4.5	3.4	3.5	3.0	3.4
11/09/2013	4.0	2.2	4.5	3.3	3.6	3.4	3.5
12/09/2013	4.0	2.3	4.5	3.3	3.9	3.2	3.5
13/09/2013	4.0	2.3	5	3.5	4.1	4.5	3.9
Difference	0.9	0.3	0.9	0.4	1.1	1.7	0.9

Date	Length of Brick Measurements (mm)							
	1	2	3	4	5	6	7	
09/09/2013	140	297	298	298	296	296	297	
10/09/2013	139	295	298	296	296	296	295	
11/09/2013	136	295	296	296	296	296	295	
12/09/2013	136	295	296	296	296	296	295	
13/09/2013	136	295	296	295	296	296	295	
Difference	4.0	2.0	2.0	3.0	0.0	0.0	2.0	Average = 1.9

Large Clay Content Wall

Date	Average Brick Width Measurement Across Points ABCD (mm)							Average (mm)
	1	2	3	4	5	6	7	
09/09/2013	151.20	150.48	150.85	150.80	151.30	150.90	150.98	150.93
10/09/2013	151.20	150.30	150.80	150.80	151.05	150.75	150.375	150.75
11/09/2013	150.25	150.23	150.43	150.55	150.58	150.60	150.225	150.41
12/09/2013	150.25	150.08	150.38	150.43	150.45	150.23	150.175	150.28
13/09/2013	151.00	150.28	150.48	150.23	150.25	150.30	150.175	150.39
Difference	0.95	0.40	0.48	0.58	1.05	0.68	0.80	0.70

Date	Gap Measurements Inbetween Bricks (mm)						Average (mm)
	1-2	2-3	3-4	4-5	5-6	6-7	
09/09/2013	3.0	2.0	3.3	1.3	2.2	3.3	2.5
10/09/2013	3.0	2.8	3.7	1.2	3.7	3.4	3.0
11/09/2013	3.1	2.9	3.9	2.2	3.7	3.3	3.2
12/09/2013	3.1	3.0	3.8	2.7	3.7	3.3	3.3
13/09/2013	2.9	2.0	3.0	2.6	3.7	3.3	2.9
Difference	0.2	1.0	0.9	1.5	1.5	0.1	0.9

Date	Length of Brick Measurements (mm)							
	1	2	3	4	5	6	7	
09/09/2013	137	297	296	296	297	296	298	
10/09/2013	139	296	295	294	295	295	296	
11/09/2013	138	296	296	294	294	294	295	
12/09/2013	138	296	296	294	294	295	294	
13/09/2013	139	295	296	294	294	295	294	
Difference	2.0	2.0	1.0	2.0	3.0	2.0	4.0	Average = 2.3