An Investigation of Bond Strength in Straw Bale Construction

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Abstract

The bond strength of plastered straw bales is an important factor to consider when examining the performance of straw bale construction. There is not currently literature available specifically examining the bond strength between the plaster layer and the straw. The experiment discussed in this paper investigates how the bale type, plaster type and bale orientation can affect the bond strength of a plastered straw bale. It was found that the behavior of bond failure follows a linear response pattern until reaching a maximum load plateau. The failure occurs suddenly at the plateau. The average displacement to this plateau was determined to be 10.37 mm for bales plastered flat and 5.67 mm for bales on edge. It was found that bales plastered flat developed 205% higher bond strength on average than bales plastered on edge. It was found that there are no significant differences in bond strengths between wheat, hemp and flax bales. When comparing plaster types, it was found that a mason's cement mix had an average bond strength 47 % higher than a clay plaster mix. It was also determined that there is a positive relationship between plaster compressive

strength and bond strength in straw bale application. The combination providing the highest bond strength in the experiment was hemp bales plastered flat with mason's cement. The combination providing the lowest bond strength was wheat bales plastered on edge with clay plaster.

Preface

The research described in this report was completed during my summer research term in the Civil Engineering Department at Queen's University. I would like to acknowledge the significant contributions of Dr. Colin MacDougall and Mr. Stephen Vardy to the work described herein. I would also like to thank Mr. Kevin Hollingshead for his time and hard work in the lab.

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1.0 Introduction

Straw bale construction is quickly becoming widely accepted as a viable form of environmentally sustainable construction. With increasing concerns over the effect of greenhouse gas emissions on the atmosphere, more scientific research is now being focused on green building techniques than ever before. Straw bale construction is notable as a green building material due to its low embodied energy, ease of construction and widespread availability. Straw bale construction generally consists of straw bales stacked flat or on edge and plastered on each side with an earthen or cement plaster. Figure 1 shows typical straw bales with plaster applied in both the flat and on-edge positions

Figure 1: Straw Bales

The plaster provides structural strength while the straw possesses good insulation properties, allowing straw bale construction to be used as both insulation and as a load bearing structural member. Research has shown that straw bale walls can provide two-and-a-half times more insulation than a wood-framed house with conventional insulating materials (Grepo, 1996). Additionally, research completed by Vardy & MacDougall (2006), found that the load capacity of straw bale walls is comparable to conventional construction methods. These results, along with the environmental benefits, make straw bales an attractive replacement for timber in residential and small scale commercial construction.

However, continued research is needed to overcome the current obstacles preventing the widespread use of the technology. The deficit of research on some specific properties of straw bale construction, such the bond strength between the plaster and the straw, provides the motivation behind the work discussed in this paper. There is little available literature regarding the bond strength of plaster to straw fibers. Parker A, et al. (2006) examined the failure mode of reinforcement meshes while resisting lateral loads. This experiment tested failure methods that are similar to this experiment; however specific bond strength values were not determined. Bond strength governs local buckling failure which is a common failure mode in compressive loading of straw bale walls. Proper understanding of bond strength is necessary for the continued advancement of predictability in straw bale construction. This paper compares the bond strength developed while varying plaster type, bale type and bale orientation. Testing these combinations allowed for the effect that each variable has on bond strength to be examined as well as how the variables can be combined to optimize results.

2.0 Experimental Materials

2.1 Bales

The bales used in this experiment were prepared by and purchased from local farmers. For comparison, wheat, hemp and flax bales were used in this experiment. They were dry when purchased and were stored in the lab to ensure they were not exposed to moisture before testing or during curing. All bales tested were two string bales of similar size and density. The bales used were not screened for any further specific properties to simulate conditions used by straw bale builders.

2.2 Plaster Mix Components

The plasters prepared for this experiment consisted of sand, clay, cement, lime and water combined in different ratios. The clay used was Turface: Professional Mound Clay purchased in 50lbs bags and stored in a dry area to prevent clumping. The cement used was Highbond Mason's Cement Type N. This cement was selected to provide a bond strength that would allow for application to a vertical surface, as would be required in straw bale construction. The lime used was Bondcrete Lime powder. This lime was selected to be consistent with mix designs in previous research.

2.3 Plaster Mix Design

There were three plaster mixes prepared for this experiment; clay-plaster, mason's cement and cement-lime plaster. The clay-plaster mix design was selected for workability and to be consistent with previous research. It is also is the most environmentally friendly plaster tested as it contains no cement and is completely earthen material based. Straw fibers were added to this mix as is common practice in construction. The Mason's cement plaster had a water-cement ratio of 0.93 by mass. This water-cement ratio was selected to be consistent with previous research and to result in a plaster that can be easily applied to vertical faces of straw bales. A cement-lime plaster was also tested. This mix reduced the amount of cement required in the plaster by adding lime and had a water-cement ratio of 1.31. This water-cement ratio allowed for proper workability of the plaster during application. Reducing the cement content in the plaster reduces the environmental impact while still retaining the desirable attributes realized by including cement in the mix. The ratios, by mass, for each mix design are shown in Table 1.

Table 1: Plaster Mix Properties by mass

Plaster Type	Sand	Clay	Highbond Cement	Lime	Water
Clay	5.7	3.5	0	0	1
Mason's Cement	4.4	0	0.9	0	0.9
Cement-Lime	6.6	0	0.5	0.6	1.4

3.0 Experimental Procedure

3.1 Bale Preparation

The purchased bales required preparation to ensure consistent bale dimensions and surface conditions for each test. A jig was used to create bale specimens that had consistent dimensions and surfaces. This jig was developed by Vardy and MacDougall (2006) and has been used previously to create reliable bale specimens for compression testing. Two jigs were used in this experiment, one for bales plastered flat and one for bales on-edge. In the bales plastered flat, the fibers are horizontally orientated and the plaster is applied onto the ends of the fibers. Figure 2 illustrates the bond created between the straw and the plaster in a bale plastered flat.

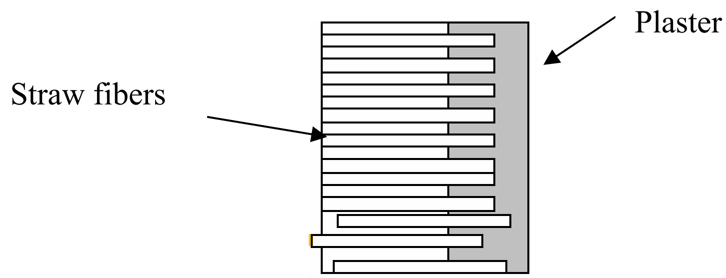

Figure 2: Fibers plastered flat

The bales plastered flat were compressed by the jig to a height of 330mm and then trimmed on each side to a width of 405 mm. The bales were carefully trimmed on the two exposed faces using a weed-cutter.

The dimensions of the jig provided a guide for trimming the bales and allowed for consistent specimens to be obtained using this method (Vardy and MacDougall, 2004). The length of the bales was allowed to vary because it did not affect the test area for this experiment. As shown in Figure 3, after the bales had been trimmed, edging was installed on the jig to provide a guide for plaster application. The edging extends 25 mm from the face of the bale on each side and creates a rectangular area for the plaster to be applied on each side with dimensions of 600 mm by 330 mm.

Figure 3: Edging installed on a jig

For the bales plastered on-edge, the fibers are orientated vertically and the plaster is applied perpendicular to the fibers. Figure 4 illustrates the bond created between the plaster and a bale plastered on-edge.

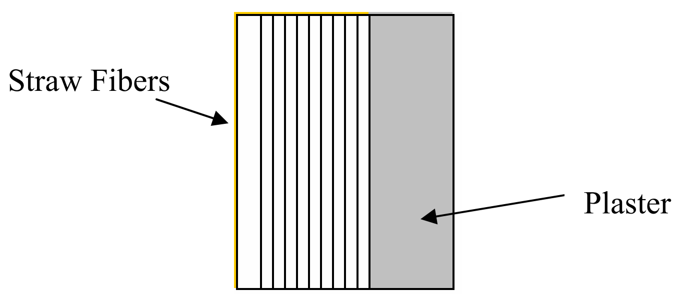

Figure 4: Fibers plastered on edge

Some additional steps were taken during the trimming of the on-edge bales due to the fact that the bale ties did not allow for trimming to be completed on the faces to be plastered. Since the ties prevent trimming of the bales on the two faces to be plastered when on-edge, the bales were cut using the same jigs as the bales plastered flat. After trimming was complete the on-edge bales were removed from the jigs, rotated so that the desired faces were exposed and placed in another set of jigs designed for bales plastered on-edge. Edging was then installed on these jigs to create a plaster area of 600 mm by 405 mm.

3.2 Plaster Mixing and Application

After the bales were trimmed and fitted with edging, the required plaster mixes were created. The plaster was mixed in roughly 23 liter batches. The mix components were added by weight and were mixed together dry until the mix appeared homogenous. The mixer was then run until complete mixing of the added water was achieved throughout the mix. The plaster was then applied to the bales immediately after mixing. The curing period selected for these bales was 28 days. Each bale was plastered lying flat, with one side overturned. The plaster was applied first by hand, pressing the plaster into the straw fibers. Then, a trowel was used to create a smooth and even surface. After the first side was plastered, it was covered with clear plastic and allowed to cure for 12-24 hours. The bale was then turned over and the second side was plastered and covered with clear plastic for 12-24 hours. After this period, the bale was positioned upright with both sides remaining covered in plastic for an additional 3 days before the bale was removed from the jig. The plaster was not wetted during the curing process. After removal from the jigs, the bales were stored in the lab at room temperature and humidity without any cover until the 28 day curing period was reached. Figure 5 shows a flat and an on-edge bale after plaster has been applied to one side.

Figure 5: Bales plastered on first side

3.3 Testing Procedure

The testing was performed using a modified DYNA Proceq pull-off testing device manufactured by Hoskin Scientific as shown in Figure 6. The original disc used by this device was 50 mm diameter. To allow for cutting of the plaster discs without damaging the plaster, a modified disc of 101.6 mm was used. The size of the plastered area allowed for several trials to be completed on each side of the bales. Initially, a 101.6 mm diameter circle is cut in the plaster using a handheld hole saw. A circular steel disk of the same diameter was then glued to the cut out circle using LePage 5 minute adhesive epoxy. This disc is a modified version of the standard 50 mm diameter disk used by the pull-off device. The pull off device was attached to the disk and set at a fixed height above the plaster. A dial gage was used to measure the displacement as the pull off test was performed. The dial gauge was magnetically connected to a piece of steel that was set on the bale to provide a steady support. This test apparatus was chosen over more specialized equipment due to the time restraints of a summer research term. It avoided the need to construct or purchase new equipment and still allowed for an accurate investigation into the plaster-straw bond strength.

Figure 6: Testing apparatus

Once the apparatus was set up, the test was performed by slowly pulling off the plaster disk with the pull-off device while recording load and displacement values. The load readings were recorded from the load cell built into the device. The load cell records at 0.01 N/mm^2 intervals assuming a 50mm diameter pull-off disc is being used. This is equivalent to 2.42 kPa intervals for the 101.6 mm diameter test disc in this experiment. The dial gauge records to an accuracy of 0.01 mm. After the pull-off device was extended though its full range, the device was then manually lifted up off of the plaster and the maximum load recorded. This was done to ensure that the maximum bond strength had been realized during the test. All tests completed in this experiment had reached their maximum bond strength before the device was extended to its full length. Four trials were attempted on each side of a bale. The holes were cut in a row along the middle of the bale avoiding the bale ties in the case of the bales on-edge.

3.4 Plaster Cube Tests

A set of 3 cubes was created for each plaster mix to determine average plaster strength after 28 days. A standard Unite-o-matic universal materials testing machine was used to crush the cubes in accordance with ASTM C 109/C 109M. The maximum load during testing was recorded using a data acquisition system and used to determine the plaster strength and to ensure that the plaster mixes used were reasonably consistent across multiple mix batches.

4.0 Results and Discussion

A summary of all statistical analysis done in this section can be found in Appendix 2. The null-hypothesis (no difference between means) was rejected at all levels of confidence greater than 95% (i.e. there is a less than 5% chance that there is no difference).

4.1 Pull-off Failure Behavior

An example of a typical pull off result is shown in Figure 7. The tests shown in Figure 7 were done on wheat bales plastered flat with clay plaster. Other bale/plaster combinations showed similar load-displacement behavior to the results shown in this figure. In the case of the flat bale tests, the force applied increased roughly linearly with displacement until a maximum force was reached at an average of 10.5 mm of displacement. A plateau is then reached as the displacement increases and the load remains at maximum until a sudden loss of load occurs. The on-edge bales behave similarly with the exception of a much more gradual increase in load leading to the plateau at a lower force value. It can be observed from the load-displacement response of both flat and on-edge bales that the maximum load occurs at the initial plateau following the linear response of the specimen. The maximum load from this plateau was used to calculate the bond strengths reported herein.

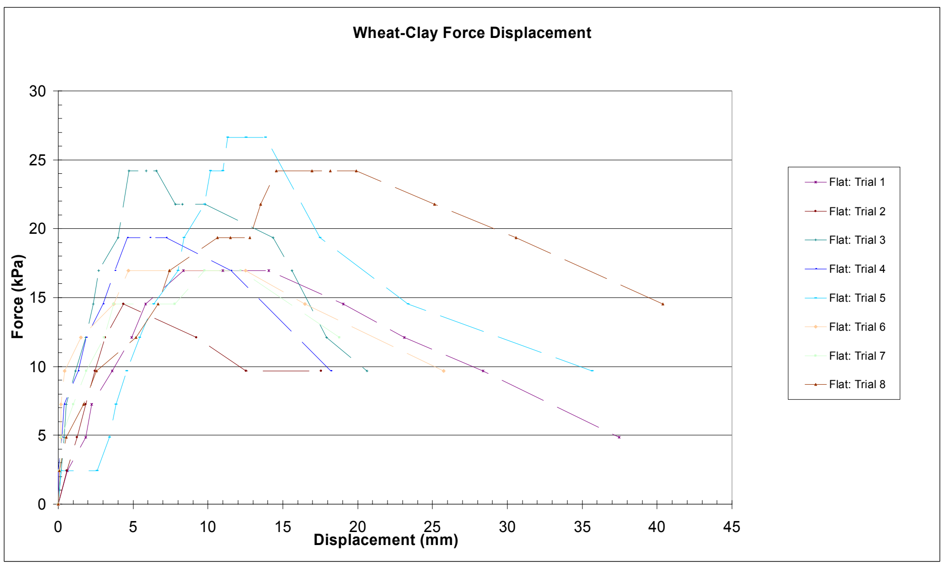

Figure 7: Plot of force vs. displacement for pull-off trials

Using the load-displacement data obtained in this experiment, some comparisons can be made between the displacements at the maximum load for different tests. A table of these results can be found in Appendix 1. For bales plastered flat, the average displacement to the plateau was 5.67 mm compared to 10.37 mm for bales plastered on-edge. There were no other significant differences in displacement to maximum when examining other variables. It was apparent through observation during testing that tests that reached a higher displacement value before reaching maximum bond strength were more dependent on the pull-out resistance of the straw fibers. Tests that produced smaller displacements were more likely to have failed on the interface between the straw and the plaster.

4.2 Maximum Bond Strength

Table 2 shows the results of the bond strength testing for each bale-plaster-orientation combination tested in this experiment. High, low and average values are given for each test as well as the average and standard deviation values used for analysis of this data. It should be noted that the load cell on the pull-off device reads in 0.01 N/mm^2 or 2.4 kPa intervals.

Table 2: Bond Strength Results

Bale Type	Plaster Type	Bale Orientation	# of Trials	High Bond Strength (kPa)	Low Bond Strength (kPa)	Average Bond Strength (kPa)	Standard Deviation (kPa)
Wheat	Clay	On edge	4	4.8	4.8	4.8	0.0
		Flat	8	26.6	14.5	20.0	4.4
	Cement-Lime	On edge	5	9.7	4.8	6.8	2.7
		Flat	8	46.0	16.9	29.4	9.3
	Mason's Cement	On edge	8	19.4	4.8	8.8	4.7
		Flat	8	58.1	14.5	33.6	13.8
Hemp	Clay	On edge	8	12.1	4.8	8.5	2.9
		Flat	8	55.7	21.8	33.0	11.0
	Cement-Lime	On edge	8	19.4	4.8	9.7	4.3
		Flat	7	53.3	9.7	23.2	16.3
	Mason's Cement	On edge	7	31.5	4.8	15.6	10.7
		Flat	8	84.7	26.6	46.6	23.7
Flax	Clay	On edge	7	14.5	2.4	6.9	4.3
		Flat	6	33.9	14.5	23.8	8.4
	Cement-Lime	On edge	7	16.9	4.8	9.3	4.3
		Flat	7	60.5	14.5	39.4	14.8
	Mason's Cement	On edge	6	16.9	4.8	10.1	5.6
		Flat	7	67.8	12.1	31.8	18.4

Note: Tests that do not have 8 trials were either damaged before testing or experienced failure of the epoxy during testing.

4.3 Comparison of Bale Orientation

These results allow for a direct comparison of the plaster to straw bond strength between bales plastered flat and bales plastered on edge.

Table 3: Comparing average bond strength across all trials

Test	Average Bond Strength (kPa)	Standard Deviation (kPa)	Number of Trials
On-edge	9.2	5.6	60
Flat	31.4	15.83	66

Figure 8 shows a comparison of flat and on edge bond strength across all tests completed during this experiment. It should be noted that there is some variation in the number of trials of some tests between flat and on-edge tests. However, this variation can be considered negligible because of the large number of total trials in the experiment and because of the random nature of the incomplete trials.

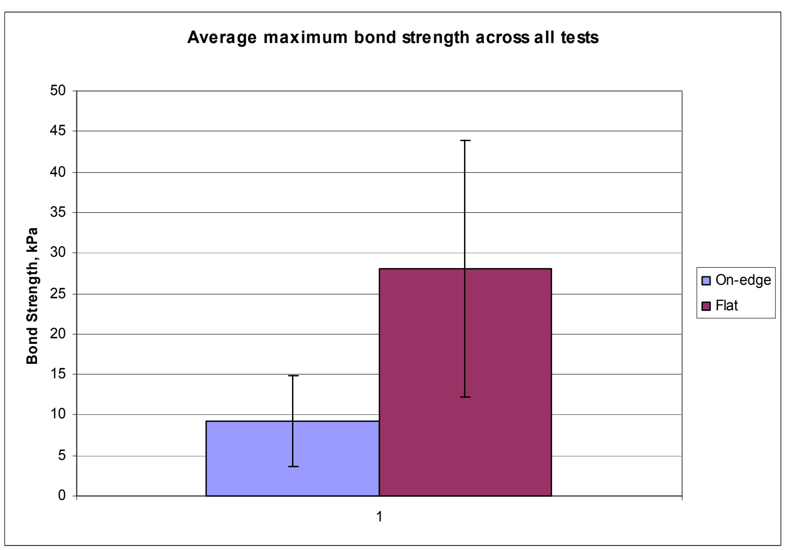

Figure 8: Plot comparing flat and on-edge bales across all trials.

The error bars on Figure 8 represent one standard deviation. It is apparent from these results that flat bales produced, on average, much higher bond strength when compared across all tests than on-edge bales. However, due to the variability of the data collected, statistical analysis is required to confirm this conclusion. Using the independent t-test produces a p value of $p < 0.005$. This allows us to conclude, within 99.5% confidence, that bales plastered flat produced higher bond strength than bales plastered on-edge.

The average maximum bond strength across all tests for bales plastered flat was 31.4kPa compared to 9.2kPa for bales plastered on edge. This difference may be attributed to the roughness of the surface created by the orientation of straw fibers. When plastered flat, the plaster can penetrate down between the straw fibers and bond with more total surface area. Also, when plastered flat, the fibers are running into the bale and this appears to create a much stronger resistance as the fibers must be pulled out from deep into the bale. When plastered on edge, the fibers attached to the plaster run along the surface of the bale. This can be observed by comparing the test specimens after pull off. Figure 9 shows a disc from a bale plastered flat and a bale on edge. The disc from the bale plastered flat has considerably more and longer straw fibers attached to it.

Figure 9: Example of pull off disc from flat (left) and on-edge (right) wheat bales

Figure 10 shows a comparison of flat and on edge bond strength for each bale type / plaster type combination tested in this experiment.

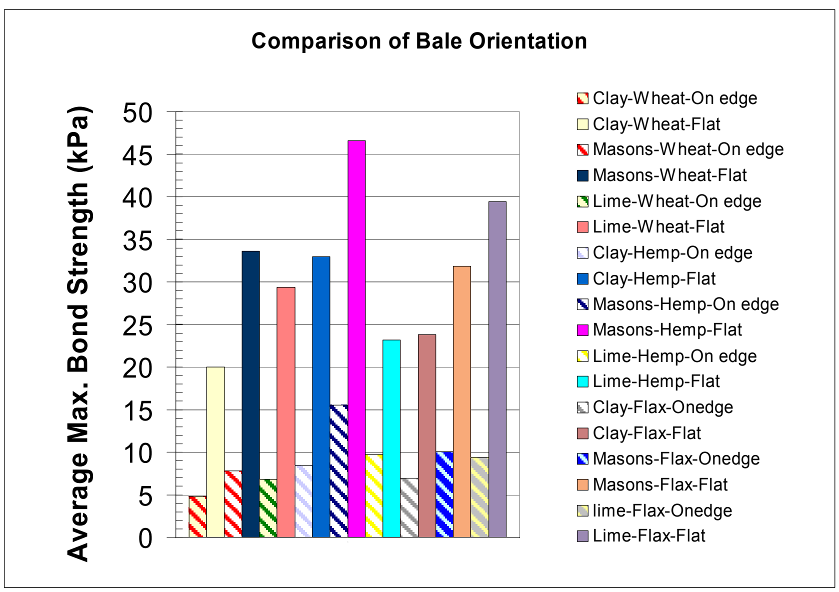

Figure 10: Comparison of Bale Orientation

There is a clear difference between the bond strength of the bales plastered flat and the bales plastered on-edge for all test groups. All of the differences in mean values have been statistically confirmed using the individual t-Test. The consistency of this trend across all tests further strengthens the conclusion that flat bales produce a higher bond strength than on edge bales overall.

4.4 Comparison of Bale Types

These results also allow for a direct comparison of the plaster to straw bond strength between wheat, hemp and flax bales. Table 4 shows the mean bond strength and standard deviation for each bale type.

Table 4: Comparing bale types across all tests.

Test	Average Bond Strength (kPa)	Standard Deviation (kPa)	Number of Trials
Wheat	18.9	13.4	40
Hemp	22.9	18.9	46
Flax	20.4	16.3	40

Figure 11 shows a comparison of the bond strength developed by different bale types across all tests completed during this experiment.

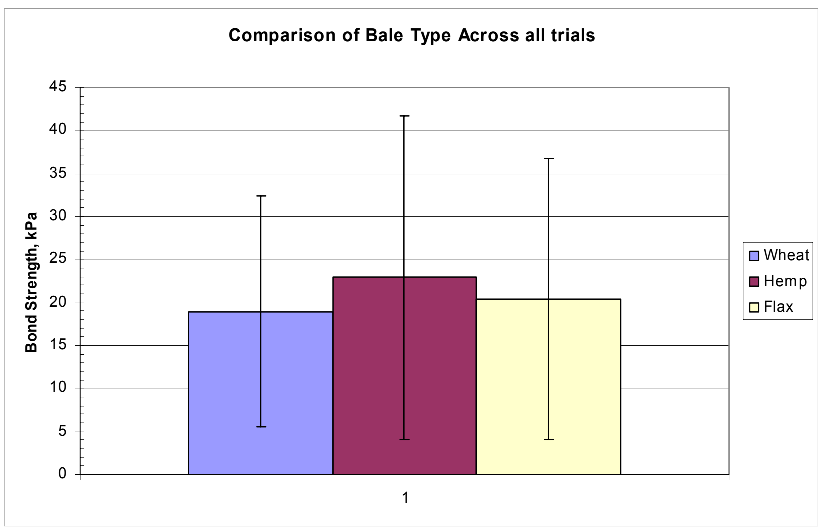

Figure 11: Comparison of Bale types across all trials.

It is clear from Figure 8 that although there is a difference in mean bond strength, the variability of other factors (orientation, plaster) prevents comparison of bale type across all tests. Use of the individual t-test confirms that there is no statistical difference between these mean values. However, when looking at individual tests, conclusions may be able to be developed on a more specific basis. Figure 9 shows the results of each test with a comparison of bale type.

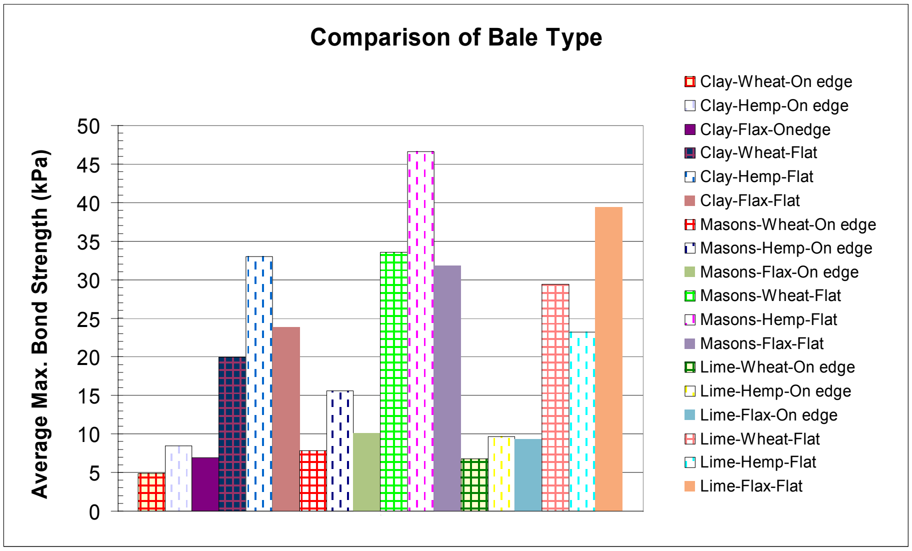

Figure 12: Comparison of Bale types.

When examining the data on a comparative test specific basis, most tests show no statistical difference between the bond strength developed by different bale types. When comparing bale types for clay-on edge bales it can be concluded within 95% confidence that the hemp bales where stronger than the wheat bales. Additionally, in the clay-flat bale case, the hemp bales were stronger than the wheat bales within 99% confidence. Since, for the large majority of tests, there is no statistical difference on an individual test level, it cannot be concluded that there is a valid relationship between the bale types tested and maximum bond strength overall. It appears that there may be difference in bond strength between hemp and wheat bales since hemp bales were found to be significantly stronger than wheat bales in 2 of 6 test types. However, since the relationship was not found to be valid in general, it is not possible to verify this relationship with the data collected in this experiment. The fact that valid differences appeared in some of the tests may indicate that if more trials were conducted to offset the variability of the trials, more relationships between bale types and bond strength may be able to be determined.

4.5 Comparison of Plaster Types

These results also allow for a direct comparison of the plaster to straw bond strength between clay, cement lime and mason's cement plasters. Table 5 shows the mean bond strength and standard deviation for each plaster type.

Table 5: Comparing plaster types across all tests.

Test	Average Bond Strength (kPa)	Standard Deviation (kPa)	Number of Trials
Clay	17.1	12.0	41
lime	20.0	15.4	41
Masons	25.1	19.9	44

Figure 13 shows a comparison of the bond strength developed by different plaster types across all tests completed during this experiment.

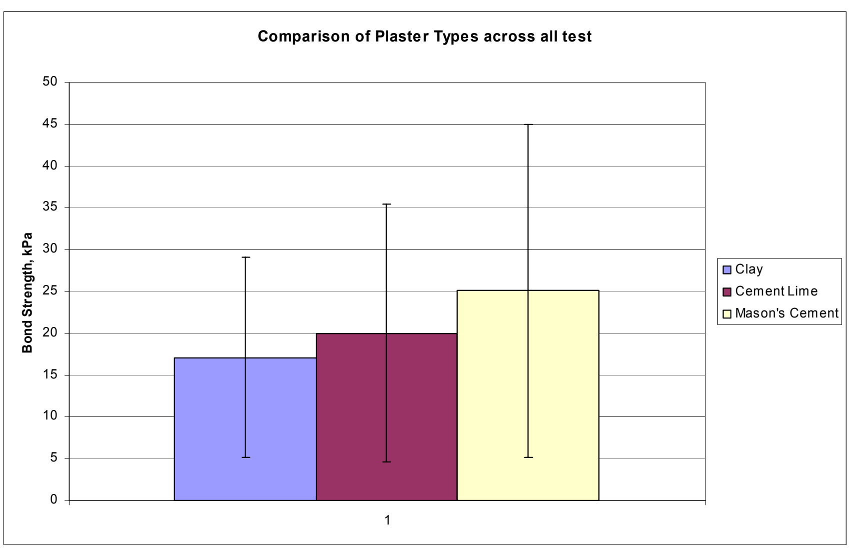

Figure 13: Comparison of plaster types across all trials

Figure 12 illustrates the difference in mean bond strength between the three plaster types. However, large variability is again present in the data and these results must be checked for statistical validity. Using the individual t-Test, it can be determined that there is no statistical difference between clay and cement lime and cement lime and masons cement plasters. The difference between masons cement and clay plaster can be considered accurate with 95% confidence. This analysis allows for the conclusion to be made that mason's cement plaster develops higher bond strength than clay plaster on average across the tests in this experiment. Mason's cement produced an average bond strength of 25.1kPa while the clay plaster had an average bond strength of 17.1kPa. The cause of this difference could be related to plaster cube strength or other properties specific to each type of plaster mix. These differences are discussed in section 4.6.

Similar to the comparison of bale types, when looking at individual tests, conclusions may be able to be developed on a more specific basis. Figure 13 shows the results of each test with a comparison of bale type.

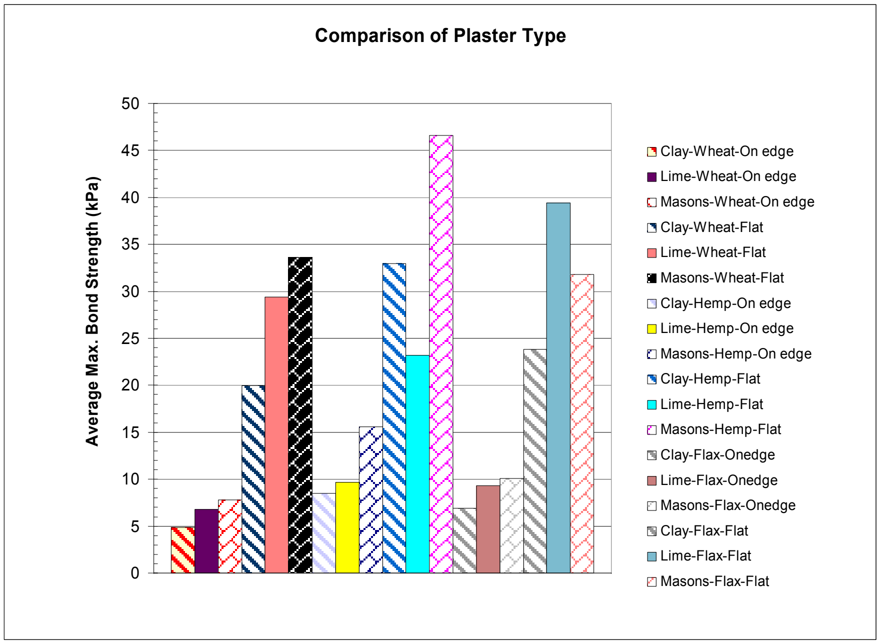

Figure 14: Comparison of plaster types

When examining the data on a test-specific basis, most tests show no statistical difference between the bond strength developed by different plaster types. When comparing plaster type for wheat – flat bales, it can be concluded within 97.5% confidence that the cement lime plaster and the masons cement plaster develop higher bond strengths than the clay plaster. When examining hemp flat bales, it can be stated that masons cement plaster has a higher bond strength than cement lime plaster within 95% confidence. In flax – flat bales, the cement lime plaster has higher bond strength than clay plaster within 95% confidence. It appears that in addition to the difference between masons cement and clay plaster, there may be difference in bond strength between cement lime and clay plasters. This relationship is valid in 2 of 6 tests. However, since the relationship was not found in general across all tests, it is not possible to verify this relationship with the data collected in this experiment. The fact that valid differences appeared in some of the tests may indicate that if more trials were conducted to offset the variability of the trials, more relationships between plaster types and bond strength may be able to be determined.

4.6 Best Performing Combinations

For construction purposes, it may be useful to examine the combination of variables that produced the best and worst bond strengths. Table 6 below shows the top 2 and bottom 2 tests based on average maximum bond strength.

Table 6: Best and Worst Combinations

Bale Type	Plaster Type	Bale Orientation	Average Bond Strength (kPa)
Top 2:			
Hemp	Masons	Flat	46.6
Flax	Cement - Lime	Flat	39.4
Bottom 2:			
Wheat	Clay	On edge	4.8
Wheat	Cement - Lime	On edge	6.8

The difference between the top 2 and the bottom 2 combinations was checked using the individual t-Test. The top mean performing combination was hemp bales plastered flat with masons cement. The worst performing combination was wheat plastered on edge with clay plaster.

4.7 Plaster Cube Strength

Each plaster mix was tested for compressive strength using the cube test. The plaster strengths were compared between bales to ensure that the plaster applied to each trial had similar strength values. The average plaster strengths are shown in Table 7 below.

Table 7: Average plaster strengths / deviation

Plaster	Average Plaster Cube 28 Day Strength (MPa)	Standard Deviation (MPa)
Clay	1.11	0.22
Mason's Cement	6.9	0.59
Cement Lime	1.19	0.42

The cube strengths found show an acceptable level of variability between tests. The standard deviation of the plasters between bales is within an acceptable range that would not be expected to have a significant effect on the bond strength testing. These results show that the cube strength of the clay and cement lime can be considered, on average, equal and masons cement was found to be considerably (6x) stronger. These results allow for the investigation of the direct relationship between bond strength and plaster strength. Figure 15 below shows this relationship for each bale type and orientation.

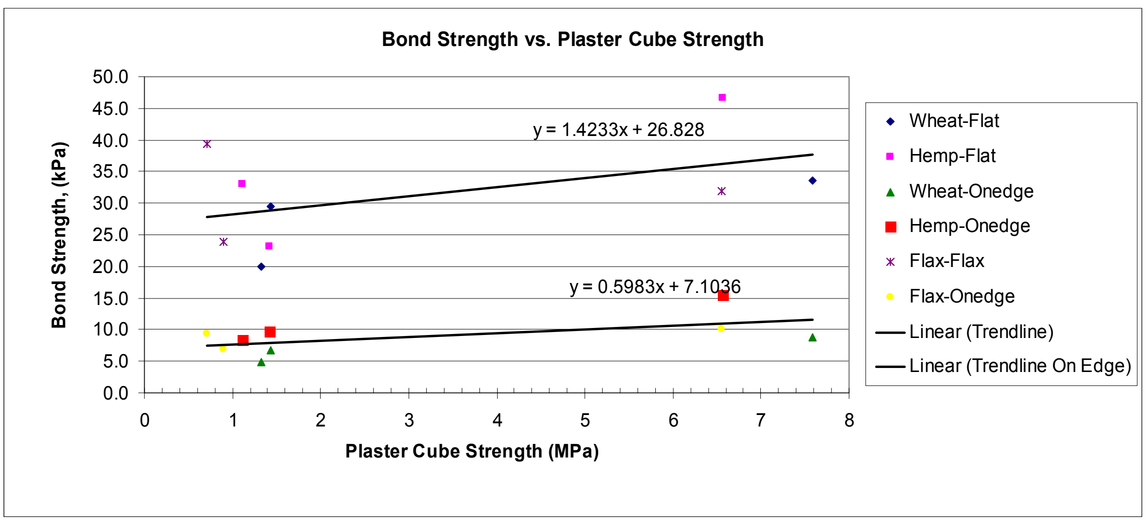

Figure 15: Plot of bond strength vs. plaster cube strength

Both the flat and on edge bales have been fitted with a trend line that represents the relationship between bond strength and plaster cube strength. These trend lines both show a weak relationship between bond strength and plaster cube strength. Separate trend lines were developed for flat and on edge bales because of conclusion that bale orientation is by far the strongest factor effecting bond strength in this experiment. These results show that there may be a small relationship between the cube strength and bond strength in these tests. This indicates that bond strength may instead be governed by the pull out resistance of the straw fibers rather than the strength of the plaster. This would result in a weak relationship between plaster strength and bond strength, as is found in these results. It is apparent that there may also be other properties in the plaster mixes other than plaster cube strength that have a significant effect on the bond strength. All tests experienced a significant change in bond strength between clay and cement lime plasters, despite the relatively small difference in plaster cube strength. The differences in plaster mix composition may have an effect on the bond strength of a given plaster. In general, the plaster mixes that included cement in the mix have higher bond strengths, regardless of cube strength.

4.8 Sources of Variability

Since the results of this experiment are dominated by large variability some possible causes of this variability were examined. The load cell on the pull-off testing device could record load values in 2.4 kPa intervals. This level of accuracy may have affected the recording of the maximum bond strengths, especially for those tests that did not reach high strength levels. The straw bales used in the experiment were farm produced and there is a factor of variability in the number and length of the straw fiber per unit of surface area of the bales. Areas with longer fibers bunched closer together would have generated higher bond strength. The plaster mixes used in this experiment, although found to be fairly consistent, varied slightly between mixes. This variability could have affected the bond strength differences recorded between tests. Another possible source of variability is the depth of plaster in the testing areas. Although the desired plaster depth was 1”, small variations in depth occurred between trials. The depth of plaster in the tests ranged from approximately ¾” to 1 ¼”. Additionally, the method of plastering the bales may have resulted in some variation in the plasters penetration into the bales. Plaster that was pressed further into the bale during application may result in higher bond strength.

5.0 Conclusions

The results of the tests conducted on individual straw bales in this experiment lead to the conclusions on the effect of different variables on bond strength presented herein:

1. The behavior of bond failure follows a linear response pattern until reaching a load plateau. At this plateau, displacement increases until a sudden failure of the bond occurs and load quickly decreases to zero.
2. Average displacement to the maximum bond force was 10.37 mm for flat bales and 5.67 mm for bales on edge. There were no other significant differences in average displacement to maximum force when examining other variables.
3. Bales plastered flat developed higher average bond strengths (28.1kPa) than bales plastered on edge (9.2kPa) across all tests. This

conclusion is valid within 95.5% confidence. Bales plastered flat also developed statistically valid higher bond strengths than bales plastered flat in all individual comparative tests.

4. Through analysis, it was determined that there were no significant differences in the average bond strength developed by different bale types across all tests. In examination of individual comparative tests, 2 of 6 tests showed a valid difference between hemp (higher bond strength) and wheat (lower bond strength) bales. Completion of more trials to offset variability may reveal a significant difference in general between hemp and wheat bales.

5. Mason's cement plaster developed higher average bond strength across all tests (25.1kPa) than clay plaster (17.1kPa). This conclusion is valid within 95% confidence. No significant difference was found between cement lime and the other plasters across all tests in this experiment. In examination of individual comparative tests, clay plaster was found to have lower bond strength than cement lime in 2 of 6 tests. Additionally, cement lime was found to have lower bond strength than mason's cement in 1 of 6 tests. Based on these findings, completion of more trials may reveal cement lime to have a bond strength between those of clay plaster and mason's cement.

6. The combination of variables with the highest mean bond strength was hemp bales plastered flat with mason's cement. The lowest mean

bond strength was generated by wheat bales plastered on edge with clay plaster.

7. There is a positive relationship between plaster cube strength and bond strength for flat and on edge plastered bales.

These results provide insight into the factors effecting bond strength in straw bale construction. They also provide a sound basis for further examination of bond strength and other aspects of straw bale construction.

6.0 References

Grepo, S.V. 1996: Houses of Straw. *Technology Review* v.99, pp.18

Parker A, et Al. 2006: Recommended Mesh Anchorage Details for Straw Bale Walls. *Journal of Green Building* v.1 No. 4, pg. 141-151.

Vardy, S., MacDougall, C. 2006: Compressive Testing Analysis of Plastered Straw Bales. *Journal of Green Building* v.1 No. 1 pg.65 – 79.

Appendix 1

Submitted Electronically

Appendix 2

Bale Orientation T-Tests

Flat vs. On Edge over all trials

	Flat	On Edge
n	66	60
x	31.43	9.19
s	15.83	5.63

t= (x1-x2)/(sqrt(A*B)

x1 - x2	22.24	
A	0.031818182	A=(n1+n2)/(n1*n2)
B	146.4386742	B=((n1-1)*s1^2+(n2-1)*(s2^2)/(n1+n2-2

t=	**10.3031307**	**>**	**2.81**	@	D.O.F	124

p= 0.005

Summary of results from individual comparative tests

Test	Comparing	t value	t required	p value
Clay-Wheat	Flat vs. On edge	6.74	3.58	0.005
Masons-Wheat	Flat vs. On edge	4.81	3.33	0.005
Lime-Wheat	Flat vs. On edge	5.21	3.58	0.005
Clay-Hemp	Flat vs. On edge	6.09	3.33	0.005
Masons-Hemp	Flat vs. On edge	3.18	3.01	0.01
Lime-Hemp	Flat vs. On edge	2.27	2.16	0.05
Clay-Flax	Flat vs. On edge	4.68	3.5	0.005
Masons-Flax	Flat vs. On edge	2.77	2.59	0.025
Lime-Flax	Flat vs. On edge	5.17	3.43	0.005

Bale types over all trials

	wheat	hemp	flax
n	40	46	40
x	18.94	22.89	20.39
s	13.42	18.85	16.29

Wheat vs. hemp

t= (x1-x2)/(sqrt(A*B)

x1 - x2	3.95
A	0.04673913
B	273.967525

t=	**1.103842823**	**<**	**2.23**	@	D.O.F	84
p=	**0.05**					

Wheat vs. flax
t= (x1-x2)/(sqrt(A*B)

x1 - x2	1.45		A=(n1+n2)/(n1*n2)			
A	0.05		B=((n1-1)*s1^2+(n2-1)*(s2^2)/(n1+n2-2			
B	222.73025					
t=	**0.434503619**	**<**	**2.26**	@	D.O.F	78
p=	**N/A**					

Hemp vs. Flax
t= (x1-x2)/(sqrt(A*B)

x1 - x2	2.5					
A	0.04673913					
B	313.5561					
t=	**0.653043434**	**<**	**2.16**	@	D.O.F	84
p=	**N/A**					

Summary of results from individual comparative tests

Test	Comparing	t value	t required	p value
Clay- On edge	wheat vs. hemp	2.49	2.23	0.05
Clay- On edge	wheat vs. flax	0.95	2.26	N/A
Clay- On edge	flax vs. hemp	0.86	2.16	N/A
Clay- Flat	wheat vs. hemp	3.1	2.98	0.01
Clay- Flat	wheat vs. flax	1.1	2.18	N/A
Clay- Flat	flax vs. hemp	1.7	2.18	N/A
Masons- On edge	wheat vs. hemp	1.63	2.16	N/A
Masons- On edge	wheat vs. flax	0.47	2.18	N/A
Masons- On edge	flax vs. hemp	1.13	2.2	N/A
Masons- Flat	wheat vs. hemp	1.34	2.14	N/A
Masons- Flat	wheat vs. flax	0.22	2.16	N/A
Masons- Flat	flax vs. hemp	1.34	2.16	N/A
Lime- On edge	wheat vs. hemp	1.34	2.2	N/A
Lime- On edge	wheat vs. flax	1.14	2.23	N/A
Lime- On edge	flax vs. hemp	0.18	2.16	N/A
Lime- Flat	wheat vs. hemp	0.87	2.18	N/A
Lime- Flat	wheat vs. flax	1.51	2.18	N/A
Lime- Flat	flax vs. hemp	1.95	2.18	N/A

Plaster types over all trials
All Trials

	Clay	Cement lime	Masons			
n	41	41	44			
x	17.12219024	20.01525	25.08749754			
s	12.02334912	15.44361	19.88032875			
Clay vs Cement lime						
t= (x1-x2)/(sqrt(A*B)						
x1 - x2	2.89305973					
A	0.048780488					
B	191.533041					
t=	**0.946482261**	**<**	**1.98**	@	D.O.F	80
p=	**N/A**					
Clay vs. masons						
t= (x1-x2)/(sqrt(A*B)						
x1 - x2	7.965307307		A=(n1+n2)/(n1*n2)			
A	0.047117517		B=((n1-1)*s1^2+(n2-1)*(s2^2)/(n1+n2-2			
B	274.4243159					
t=	**2.215134211**	**>**	**1.98**	@	D.O.F	83
p=	**0.05**					
Cement Lime vs. Masons						
t= (x1-x2)/(sqrt(A*B)						
x1 - x2	5.072247578					
A	0.047117517					
B	319.6986455					
t=	**1.306889441**	**<**	**1.98**	@	D.O.F	83
p=	**N/A**					

Summary of results from individual comparative tests

Test	Comparing	t value	t required	p value
Wheat- On edge	Clay vs. Cement Lime	1.46	2.36	N/A
Wheat- On edge	Clay vs. Mason's Cement	1.66	2.23	N/A
Wheat- On edge	Lime vs. Mason's Cement	0.86	2.2	N/A
Wheat- Flat	Clay vs. Cement Lime	2.56	2.53	0.025
Wheat- Flat	Clay vs. Mason's Cement	2.66	2.51	0.025
Wheat- Flat	Lime vs. Mason's Cement	0.68	2.16	N/A
Hemp- on edge	Clay vs. Cement Lime	0.65	2.14	N/A
Hemp- on edge	Clay vs. Mason's Cement	1.81	2.16	N/A
Hemp- on edge	Lime vs. Mason's	1.44	2.16	N/A

	Cement			
Hemp- Flat	Clay vs. Cement Lime	1.38	2.16	N/A
Hemp- Flat	Clay vs. Mason's Cement	1.47	2.14	N/A
Hemp- Flat	Lime vs. Mason's Cement	2.19	2.16	0.05
Flax- on edge	Clay vs. Cement Lime	1.04	2.18	N/A
Flax- on edge	Clay vs. Mason's Cement	1.17	2.2	N/A
Flax- on edge	Lime vs. Mason's Cement	0.29	2.2	N/A
Flax- Flat	Clay vs. Cement Lime	2.28	2.2	0.05
Flax- Flat	Clay vs. Mason's Cement	0.98	2.2	N/A
Flax- Flat	Lime vs. Mason's Cement	0.85	2.18	N/A