An Investigation of Bond Strength in Straw Bale Construction

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Abstract
The strength of the bond between plaster and fibre bales is an important factor that impacts the structural performance of straw bale construction. As straw bale construction enters the mainstream, there is increasing need by engineers for data on the performance of various plasters with various types of fibre bales. This paper investigates the effect of fibre type, plaster type and fibre bale orientation on the bond strength of a plastered straw bale. It was found that bale orientation is by far the parameter that has the greatest impact on bond strength. Bales plastered flat have bond strengths that are 2.4 to 4.4 times higher than bales plastered on-edge for a wide variety of plaster and fibre types at the 95% confidence level. It was also shown that there are no significant differences in bond strength between wheat, hemp, and flax bales. For bales plastered flat, mason's cement will produce a significantly higher bond strength (47% higher on average) than clay plaster at the 95% confidence level. However, there are no significant differences between lime and mason's cement, or between lime and clay plasters.

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. Fig. 1 shows typical straw bales with plaster applied in both the flat and on-edge positions.

Fig. 10. Straw bales plastered on-edge (left) and flat (right).

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 [3] and load capacity comparable to conventional construction [5].

There is little available literature regarding the bond strength of plaster to straw fibers. Parker et al. [4] 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. Lack of proper bond between fibre and plaster can lead to local buckling failure and premature failure of a straw bale wall. This paper compares the bond strength developed while varying plaster type, fibre type and bale orientation.

MATERIALS

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 dimensions 375 ± 10 mm x 475 ± 10 mm x 875 ± 25 mm and dry bulk densities ranging between 84 and 123 kg/m^3.

The mixes for the three plasters used are outlined in Table 1. The “clay” plaster was prepared using a commercially available clay, Turface Professional Mound Clay, sand and water. The “mason’s cement” plaster was prepared using St. Lawrence Type N Mason’s Cement, sand and water. The “cement-lime” plaster was prepared using St. Lawrence Type N Mason’s Cement, Graymont Bondcrete stucco lime (meeting ASTM C207 [2] for hydrated lime), sand and water. These represent the range of plasters used for straw bale construction.

Table 4. Plaster Mix Properties by mass ratio.

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

BALE PREPARATION

The as-received bales were placed in a jig, Fig. 2, to ensure they had consistent dimensions and surfaces [5]. Edging extends 25 mm from the face of the bale on each side of the jig so that a rectangular area for the plaster to be applied on each side with dimensions of 600 mm by 330 mm is available.

Fig. 2. Bale installed in jig.

Fig. 3 shows the bales with plaster applied. For the bales plastered flat, the fibres of the bale are perpendicular to the plaster, and the ends of the fibres protrude into and bond with the plaster. For the bales plastered on-edge, the fibres are parallel to the plaster skin.

The plaster was applied first by hand, pressing the plaster into the 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. The plaster strength for each batch was measured using a set of 3 cubes in accordance with ASTM C 109/C 109M [1]

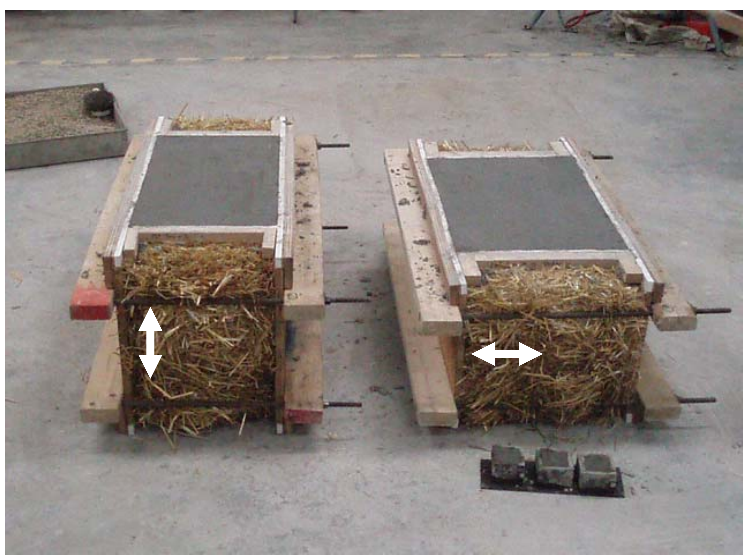


Fig. 3: Plastered bales. Bale plastered flat (left); bale plastered on-edge (right). Fibre orientation is indicated by the white arrows.

BOND TESTING PROCEDURE

The testing was performed using a modified DYNA Proceq pull-off testing device manufactured by Hoskin Scientific as shown in Figure 4. This device is commonly used to perform bond tests for reinforced concrete structures, but was modified for testing straw bales. A disc of 101.6 mm diameter circle was cut in the plaster using a handheld hole saw. A circular steel disc of the same diameter was then glued to the plaster disc using LePage 5 minute adhesive epoxy. The frame of the Proceq pull-off device was then placed over the disc, the disc connected to the frame, and then slowly pulled off the fibre while recording load and displacement values. Load was measured using a load cell accurate to 5 N, and displacement was measured using a dial gauge accurate to 0.01 mm.

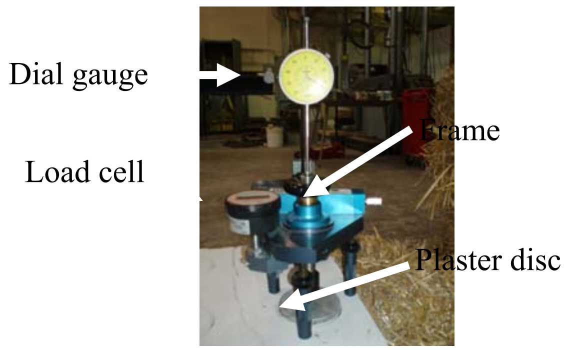


Fig. 4: Pull-off testing apparatus.

After the pull-off device was extended though its full range (50 mm), 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.

RESULTS AND DISCUSSION

Pull-off Failure Behavior

An example of typical pull-off results is shown in Figure 5, in this case for wheat bales plastered with clay plaster. Other bale/plaster combinations showed similar force-displacement behavior to the results shown in this figure. It was observed that the force increased roughly linearly with displacement until a maximum force was reached. A plateau was observed whereby the displacement increased but the load remained constant. The plateau is indicative of the breakdown in the bond between the plaster and fibre. The maximum load from this plateau was used to calculate the bond strengths reported herein by dividing by the cross-sectional area of the 101.6 mm diameter disc.

The slope of the linear portion of the curve is clearly much steeper for the bales plastered flat than for the bales plastered on-edge. For these two particular tests, the strength of the bond for the bales plastered flat is 3.5 times higher than for the bales plastered on-edge.

There were two modes of bond failure observed, as shown in Fig. 6. Typical discs showing the plaster and fibre following failure are shown. For bales plastered flat, the failure was due to fracture of the fibres, rather than pulling out of the fibres from the plaster. Long strands of fibre can be seen for the flat specimen in Fig. 6. On the other hand, for the bales plastered on-edge, failure was characterized by the fibres pulling away from the plaster, leaving a few short strands of fibre remaining. Note that for the bales plastered flat, good use is being made of the strength of the fibres as they are being loaded in tension. For the bales plastered on-edge, the fibres, which have little flexural stiffness, undergo bending as they are pulled by the plaster.

Summary of Bond Strengths

Table 2 is a summary of the bond strengths from the tests conducted. 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 has an accuracy of 2.4 kPa.

The results show that there is a wide variation in bond strength for plastered bales. Average bond strengths range from 4.8 kPa to 46.6 kPa. As will be discussed in the following discussion, some of this variation can be explained by differences in bale orientation, type of fibre, or type of plaster. However, even within a given set of parameters, the standard deviation of the bond strengths is high. The standard deviation values range from 20% to 70% of the average bond strength.

Effect of Bale Orientation

The results in Fig. 5 indicate that there is a significant difference between the bond strength for bales plastered flat versus on-edge.

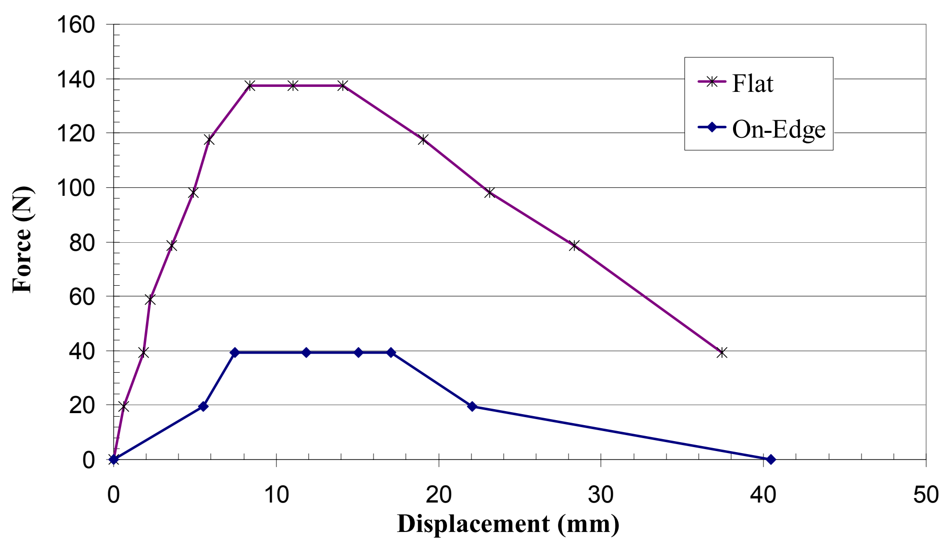


Fig. 5: Pull-off tests for wheat bale with clay plaster.

Fig. 6: Example of pull off disc from flat (left) and on-edge (right) wheat bales.

Table 5: 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	5	5	5	0.0
		Flat	8	27	15	20	4
	Cement-Lime	On edge	5	10	5	7	3
		Flat	8	46	17	29	9
	Mason's Cement	On edge	8	19	5	9	5
		Flat	8	58	15	34	14
Hemp	Clay	On edge	8	12	5	9	3
		Flat	8	56	22	33	11
	Cement-Lime	On edge	8	19	5	10	4
		Flat	7	53	10	23	16
	Mason's Cement	On edge	7	32	5	16	11
		Flat	8	85	27	47	24
Flax	Clay	On edge	7	15	2	7	4
		Flat	6	34	15	24	8
	Cement-Lime	On edge	7	17	5	9	4
		Flat	7	61	15	39	15
	Mason's Cement	On edge	6	17	5	10	6
		Flat	7	68	12	32	18

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

Figure 7 shows a comparison of flat and on edge bond strength across all tests.

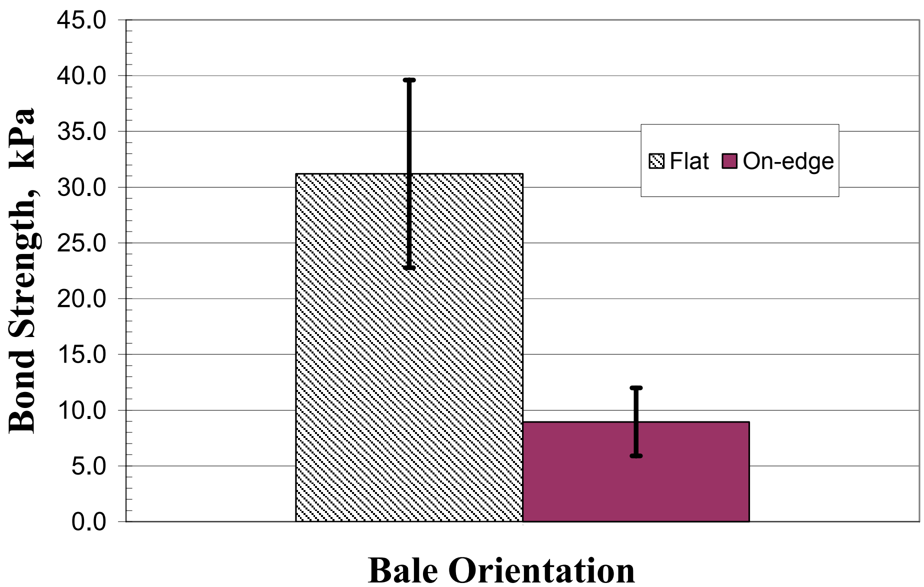


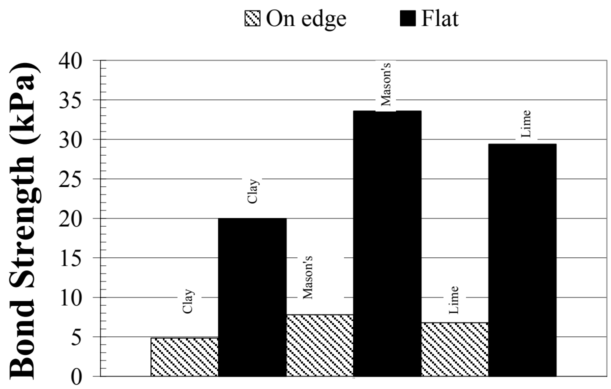
Fig. 7: Comparison of bond strengths for bales oriented flat and on-edge.

The error bars on Figure 7 represent one standard deviation. A t-test of the data showed that the strength of the bales plastered flat was significantly larger than the bond strength of bales plastered on-edge at the 99.5% confidence level. The difference may be attributed to the bonding 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. On the other hand, when plastered on edge, the fibers attached to the plaster run along the surface of the bale.

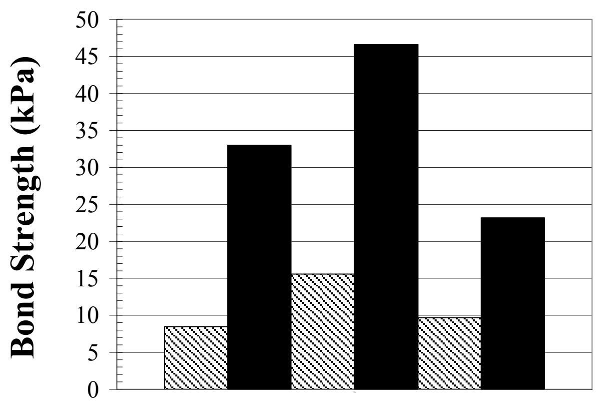
Figure 8 shows a comparison of flat and on edge bond strength for each bale type / plaster type combination tested. The difference in the mean value of bales oriented flat and on-edge was validated using the t-test at the 95% confidence level. The consistency of this trend across all tests further strengthens the conclusion that flat bales produce a higher bond strength than on edge bales. The strength of the bales plastered flat ranges from 2.5 to 4.4 times higher than the bales plastered on-edge.

Effect of Plaster and Fibre Type

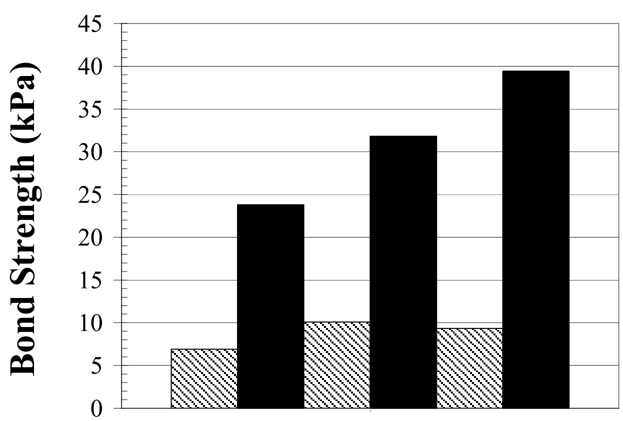
One-way analysis of variance (ANOVA) was carried out to determine the significance of plaster and fibre type on the bond strength. The results of the cube tests for the three types of plaster are provided in Table 3. The results indicate that the clay and lime plasters have similar strengths, while the mason's cement plaster is approximately 6 times stronger than the other two plasters.



(a-wheat)



(b-hemp)



(c-flax)

Figure 8: Affect of bale orientation on bond strength: (a) wheat; (b) hemp; (c) flax.

Table 3: Summary of plaster cube strength tests.

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

Also note that the standard deviation of the plaster strengths ranges between 9% and 18% of the average value. This is much less than the variation observed for the bond strength values, and indicates that the variation in plaster strength alone cannot account for bond strength variation.

Table 4 is the summary of the one-way ANOVA analysis of the significance of plaster type on bond strength. For this analysis, tests on wheat, hemp, and flax bales were combined. The null hypothesis was that the average bond strength of bales plastered with clay, lime, or mason's cement plaster are not significantly different at the 95% confidence level. Table 4 indicates that the null hypothesis is validated for bales plastered on-edge. However, for bales plastered flat, the results indicate that there is a significant effect of plaster type on bond strength. Further t-tests were conducted to compare clay, lime, and mason's cement plasters, with the results summarized in Table 5.

Table 4: One-way ANOVA test results for the significance of clay, lime, and mason's cement plaster on bond strength.

	F-value	*F-critical*
On-Edge	*3.15*	*3.16*
Flat	*3.41*	*3.14*

Table 5: T-test results for the significance of clay, lime, and mason's cement plaster on bond strength for bales plastered flat.

	P-value
Clay/Mason's cement	*0.0071*
Clay/Lime	*0.1024*
Mason's Cement/Lime	*0.0972*

The t-test analysis indicates that there is a significant difference in the bond strength of bales plastered flat with clay versus mason's cement at the 95% confidence level.

Table 6 is the summary of the one-way ANOVA analysis of the significance of fibre type on bond strength. For this analysis, tests with clay, lime, and mason's cement plaster were combined. The null hypothesis was that the average bond strength of bales plastered with wheat, hemp, or flax bales are not significantly different at the 95% confidence level. Table 6 indicates that the null hypothesis is verified for both bales plastered on-edge and flat. Fibre type does not have a statistically significant effect on the bond strength of plastered bales.

Table 6: One-way ANOVA test results for the significance of wheat, hemp, and flax bales on bond strength.

	F-value	*F-critical*
On-Edge	*2.43*	*3.16*
Flat	*1.21*	*3.14*

CONCLUSIONS

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

1. The behavior of bond failure follows a linear response 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. Bales plastered flat developed higher average bond strengths (28.1kPa) than bales plastered on edge (9.2kPa) across all tests. This conclusion is valid at the 99.5% confidence level. Bales plastered flat also developed statistically valid higher bond strengths than bales plastered flat in all individual comparative tests for clay, mason's cement, and lime plasters with wheat, hemp, and flax bales.
3. There is no significant difference in the average bond strength developed by different bale types (wheat, flax, hemp) 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.
4. 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.

These results provide insight into the factors affecting 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.

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