Compressive testing and analysis of plastered straw bales

Stephen Vardy[1], Colin MacDougall[2]

Abstract: The structural performance of plastered straw bales under compressive loading is extremely important when considering the suitability of plastered straw bales as a construction material. Most currently available results do not investigate how different construction methods and practices can affect the strength of a plastered bale. The experiments discussed in this paper illustrate how the strength of the plaster, the thickness of the plaster and the orientation of the bale itself can affect the strength of the plastered bale. It was found that the bales plastered flat were 36% stronger than those plastered on edge. In addition it was found that although the plaster strength does affect the strength of the plastered bale, it does not have as significant an impact as the plaster thickness. It was also found that nearly all plastered bales tested had higher strengths than would be required in typical residential construction. The strengths were found to be in the same range as the values reported in the existing literature. The plastered bale modulus was found to be highly variable and un-predictable.

[1] Master's of Science Candidate, Department of Civil Engineering, Queen's University
[2] Assistant Professor, Department of Civil Engineering, Queen's University

Contact Information:
Department of Civil Engineering
Ellis Hall
Queen's University
Kingston, Ontario, Canada
K7L 3N6
Tel: (613) 533-2122
Fax: (613) 533-2128

Introduction

The use of plastered straw bales as a residential construction building material has recently been gaining popularity in North American and throughout the world (Lerner et al. 2000). One of the main reasons for this is an increasing awareness of the negative impacts that logging has on our environment, and a recognition that there is enough straw produced in North America to meet all residential building needs (Magwood and Mack 2000). Furthermore, because straw is an agricultural bi-product, it is considered waste and burning is often chosen as the easiest disposal method. These issues, coupled with the excellent insulation properties of straw bales, makes straw bale construction an environmentally friendly option to typical residential construction. Figure 1 shows a simplified detail of a typical wall. The bales are stacked up like building blocks to form the exterior walls of the structure. The straw is then compressed with a wooden box beam, and plaster or stucco is applied to both sides of the wall. In some cases, a wire mesh is attached to the straw before the plaster is applied (Magwood and Walker 2001). Not only do the straw bales provide excellent insulation, but they also act to laterally support the plaster skins and tie the plaster skins together, allowing the wall to act as a composite sandwich panel.
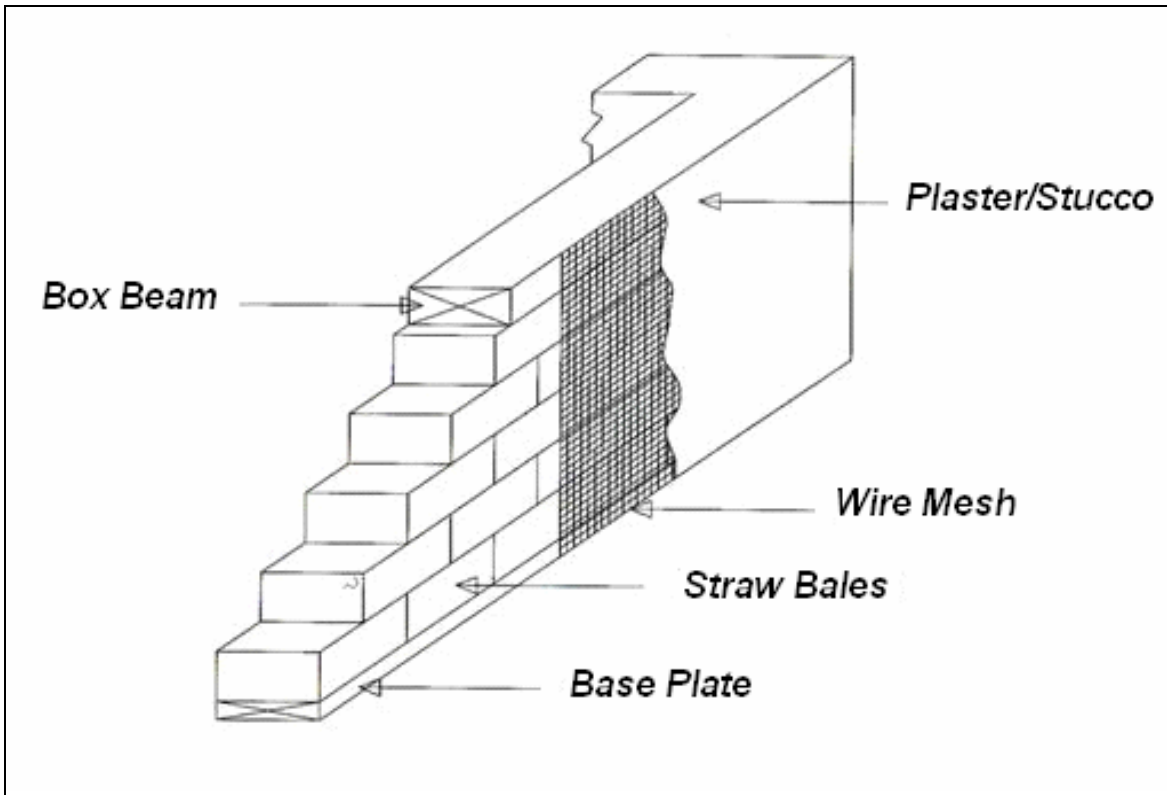
Figure 1: Simplified typical wall details.

Plastered straw bale walls have been around for at least a century (Magwood and Mack 2000), but are gaining new interest due to increased environmental awareness. Unfortunately, there are a number of issues facing the use of straw bales as a construction material. Fire resistance, moisture penetration and resulting rotting, insects and other pests, and questions regarding the structural performance of the walls are all issues that make it difficult to obtain permits to build a straw bale structure. Many of these issues have previously been addressed through various research projects and it has been found that straw bale walls perform as well as, and often better than, a typical stud framed wall. Despite this, a lack of knowledge of more specific structural properties of straw walls has significantly deterred the positive impact that straw bale construction could have on the construction industry. Because of this, many straw bale structures are built with wood framing, where the straw bales essentially only act as

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insulation.

There are currently no standards for testing related to straw bale construction. This creates a lack of consistency in test methods, and a wide range of reported test results. Few of the results have been published in peer reviewed journals. Furthermore, because of the limited data available it is difficult to assess the effect of changes in wall designs (bale orientation, etc.) on the structural performance of plastered straw bale walls.

Dreger (2002), Platts (1996), Grandsaert (1999), Carrick and Glassford (1998), and Faine and Zhang (2002) tested plastered straw bale walls in compression. There is little consistency noted in key parameters such as wall dimensions and plaster mix among these experiments, leading to highly variable results. The results obtained for ultimate compressive strength on plastered bale walls varied significantly from 28 kN/m to 90 kN/m for various tests conducted using a wide range of wall dimensions, plaster proportions and thicknesses, reinforcement schemes and bale types and sizes. Generally, the wall dimensions, plaster proportions, bale type and bale size are all reported, but the plaster thickness and the plaster strength are often omitted from the results. Bou-Ali (1993) tested un-plastered three-string bales and bale walls, however the results may not be applicable to the many projects that utilize the smaller two-string bales (Magwood and Mack 2000).

Typical straw-bale construction has the bales laid flat, but builders of straw bale homes are now experimenting with stacking the bales on edge as shown in Figure 2. This design decreases the number of bales required and the thickness of the wall, resulting in more interior space. In addition, the width of the box beam is also reduced resulting in a more efficient use of lumber in the construction.

Figure 2: Bales laid flat and on edge.

The objective of this paper is to investigate the effect of bale orientation on the strength and stiffness of plastered straw bales. Single straw bales, both flat and on edge, were plastered on each side and tested in compression. In addition, the effect of the thickness and strength of the plaster on the strength and elastic modulus of both flat and on-edge plastered bales will be examined. To reduce variability in the test results and to facilitate a meaningful comparison between the data, the design of a test jig for producing consistent straw bale samples for testing is also described.

The results of these tests on individual plastered bales will provide information regarding the general trends that will occur not only for the individual plastered bales, but also for full scale walls. Currently, there is no consensus on the relationship between the strength of an individual

plastered straw bale and the strength of a full-scale plastered straw bale wall. Clearly there are additional failure modes such as buckling that can affect the strength of the wall. However, testing of full-scale walls is expensive and time consuming. Tests on individual plastered straw bales permit a number of parameters to be investigated, so that the most critical ones can be identified. The data obtained in this study will provide a basis for future work focused on larger-scale experiments and creating an analytical model to predict the compressive strength of plastered straw bale walls.

Experimental Procedure

Bale Preparation

The straw bales used in the experiments were two-string wheat bales. They were obtained from a local farmer where they had been stored in a barn and were dry when purchased. The bales varied in mass and dimensions but were all approximately 12 kg with dimensions of 350 mm in height, 500 mm in width and 800 mm in length. This corresponds to a density of approximately 85 kg/m^3 which is consistent with values presented in the literature (Watts et al. 1995). Prior to testing, the bales were stored indoors in a room-temperature environment with a constant humidity. The bales were less than a year old when tested and, except where specifically noted, they were dry and in good condition at that time.

In order to produce specimens that had a consistent plaster thickness and reliable dimensions the wooden jig shown in Figure 3 was designed. The jig was placed over the bales and nuts were tightened to compress the bale to the required bale height as shown in Figure 3(a). Once the bale was compressed, the jig was used as a guide to trim the sides of the bale to exact
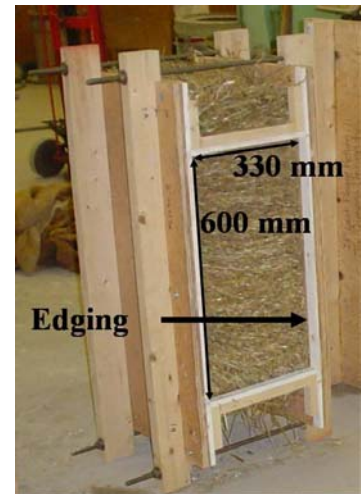
dimensions as shown in Figure 3(b). Plastic formwork, termed "edging" in the remainder of the paper, was attached to the jig, as shown in Figure 3(c). Note the edging is attached to each side of the jig, although only one side is shown in Figure 3(c). The edging has a length of 600 mm, a height of 330 mm, and a depth of 12.7 mm, 25.4 mm, or 38.1 mm. The edging ensures that the plaster skins on the sides of each plastered bale have consistent dimensions.

(a) Bale compressed in jig.   (b) Trimming bale in jig.   (c) Trimmed bale with edging.

Figure 3: Bale preparation.

Once the bales and formwork were prepared, each bale was plastered completely on one side, then covered with moist burlap and allowed to cure for 12-24 hours. The bales were then plastered on the second side. The plastering was done by pouring wet plaster into the edging, ensuring the forms were completely filled, then using a trowel to ensure a flat outer surface. The plastered bales were again covered with burlap and allowed to cure for 12-24 hours. Finally, the plastered bales were stood on end, covered with moist burlap, and allowed to cure for an additional three days before being removed from the jigs. This curing scheme was chosen to simulate typical straw bale construction during which the plaster skins are cured using moisture

for only a short period of time (Magwood and Mack 2000). The plaster was applied directly to the bales without the inclusion of any additional reinforcement such as the wire mesh shown in Figure 1. The jig ensured that plastered bales with consistent and repeatable dimensions could be produced. Figure 4 shows typical plastered bales, both flat and on-edge, after fabrication.

Figure 4: Completed plastered bales.

For the bales plastered flat, the width of the bale is controlled by trimming the straw to approximately 405 mm. The height is controlled by compressing the bale to approximately 330 mm. When the bales were released from the jig, the straw rebounded, but the plaster height remained at 330 mm. This may have induced small tensile stresses in the plaster, but no cracking resulted and thus it was assumed that the stresses were not significant. The length of the plaster was determined by the location of the edging and was set at 600 mm for all experiments. The thickness of the plaster was also determined by the edging and was varied for different tests as discussed below. The length of the bale itself was variable depending on the

bale used, but is not a factor in the experiments because it was found that the contribution of the straw to the ultimate load of the plastered bale is very low.

The bales plastered on edge were prepared in a very similar manner to those plastered flat. The bales were trimmed in the same jig as the flat bales. The bales were then turned on edge and placed in a new jig to which the edging was attached. The height of the bales was set by trimming the bales to 405 mm. The width of the bales was set at 330 mm and was controlled by compression in the first jig while trimming took place. The length of the plaster was controlled by the formwork and was set at 600 mm. The thickness of the plaster was set by the edging and was varied for different tests. Because the width of the on-edge bales was determined by pre-compression, the bales tended to bulge when released before plastering and it was found that the bulging reduced the plaster thickness by about 12.7 mm in the centre of the bale. This value would have been different from bale to bale and could have led to inconsistencies in the results for the on-edge plastered bales. As with the bales plastered flat, the bale length was variable, but again, this was not an issue because the straw contribution to the plastered bale strength was found to be minimal.

Note that there is currently no standard for plaster mixtures for straw bale construction. It was determined through discussions with a local straw bale builder that a typical wall consists of two separate structural layers of plaster. The first layer is a cement-lime plaster with proportions of 3 : 0.75 : 0.25 of sand, lime and cement. This layer is typically applied to a thickness of approximately 16 mm. The second layer is a lime plaster with proportions of 3 : 1 of sand and lime. This layer is typically applied to a thickness of 9 mm. In the current study, a single mix with proportions of 4.5 : 1.25 : 0.25 of sand, lime and cement respectively was applied in one coat to a total thickness of 25.4 mm. This mix represents a weighted average of the two layers

and is justified if the plaster fails in pure axial compression.

In order to vary the plaster strengths for the experiments, different amounts of water were used in the mixes. Not only did this provide a means of understanding how plaster strength can affect the strength of a plastered straw bale, but it also provided insight into how the amount of water used in a mix can affect the strength of the plaster. This has important implications for straw bale builders as common practice when plastering is to proportion the water in the mix based on the consistency desired, rather than the required strength. Three plasters were created with cube strengths of 0.69 MPa, 1.20 MPa and 1.72 MPa as determined using the mean strengths of three 50 mm cubes cured in the same manner as the plastered bales and tested after 28 days. These strengths represent water proportions for a dry, average and wet mix. Vardy et al. (2005) discusses the properties of these plasters in greater detail, as well as the implications that these properties have in the straw bale construction industry.

Testing Apparatus

A trial apparatus was constructed to determine the best method to test the plastered bales. Figure 5 shows the loading apparatus which consists of a steel box-beam, two steel I-sections, a 19 mm thick plywood board and a wooden brace. The box beam transfers the load to the steel sections which in turn transfer the load to the plaster skins. The plywood is used to ensure even compression of the straw.   During initial tests it was found that the plywood deflected significantly at higher loads as the force in the straw increased.   In order to prevent this, the wood brace was installed in the middle of the loading apparatus as can be seen in Figure 5.
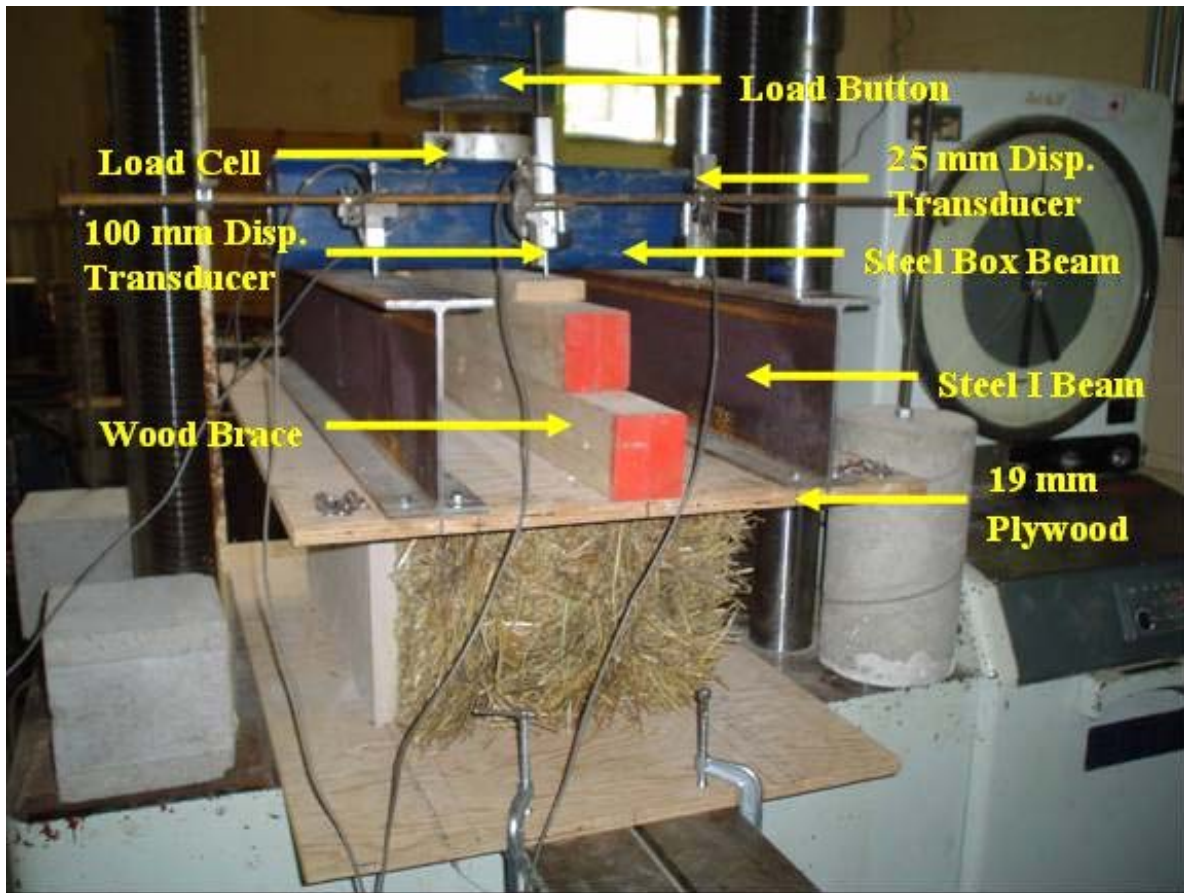
Figure 5: Loading apparatus.

In order to record the data from the experiments, a load cell, two 100 mm extensometers and four 25 mm extensometers were connected to a data acquisition system. The load cell was located beneath the loading button as indicated in Figure 5. The two 100 mm extensometers were located at either end of the bale, while the 25 mm extensometers were located at the four corners of the bale. The bales were loaded at approximately 1 mm/min until the ultimate load was reached. Once a bale had passed its ultimate load, the loading rate was increased to about 2 mm/min. When the four 25 mm extensometers had reached their limits the loading rate was increased to 3 mm/min until the test was stopped when the two 100 mm extensometers exceeded their range.

Test Parameters

Experiments were conducted on thirty plastered bales in order to compare the compressive strength of bales plastered flat to those plastered on edge. In addition, plaster strength and thickness were varied in order to determine their affects on the strength and elastic modulus of the individual plastered bales in compression. Each test was repeated three times in order to acquire an understanding of the variability of the results. Experiments were also conducted on an un-plastered bale on edge and an un-plastered bale flat in order to determine how the straw alone behaves when loaded. Table 1 summarizes the parameters for the tests. Tests 19-24 were excluded from the results as the bales were damaged by flood water during curing and the straw was wet and moldy when the bales were tested. Tests 28-30 were a repeat of tests 19-21, while tests 22-24 were not repeated.

Table 1: Plastered bale test parameters.

Test Number	Plaster Strength (MPa)	Plaster Thickness (mm)	Actual Thickness (mm)	Bale Orientation	Additional Comments
1,2,3	1.72	25.4	25.4	Flat	
4,5,6	1.72	25.4	12.7	Edge	
7,8,9	1.20	25.4	25.4	Flat	
10,11,12	1.20	25.4	12.7	Edge	
13,14,15	0.69	25.4	25.4	Flat	
16,17,18	0.69	25.4	12.7	Edge	
19,20,21	1.72	38.1	38.1	Flat	Water Damage
22,23,24	1.72	38.1	25.4	Edge	Water Damage
25,26,27	1.72	12.7	12.7	Flat	
28,29,30	1.72	38.1	38.1	Flat	Redone
31	N/A	N/A	N/A	Flat	Un-Plastered
32	N/A	N/A	N/A	Edge	Un-Plastered

Results

The theoretical strength of plastered straw bales was calculated assuming a pure compression failure of the plaster and perfect bond between the plaster and straw. Figure 6(a) is

a schematic of a typical test and Figure 6(b) is a free-body diagram of the loading plate. The thickness of the plaster (t) is 12.7 mm, 25.4 mm or 38.1 mm depending on the test, and the plaster length (L) is 600 mm for all tests. Assuming the loading plate to be rigid implies equal compression of the plaster and straw. If the plastered bale fails when the plaster reaches its cube strength f_c', the plastered bale strength per unit length, w_{bale} is:

$$w_{Bale} = \frac{\left(f_c' \times 2t \times L + F_{Straw}\right)}{L}$$

[1]

where F_{straw} is the total force in the straw at failure.

(a) Schematic of Test Setup

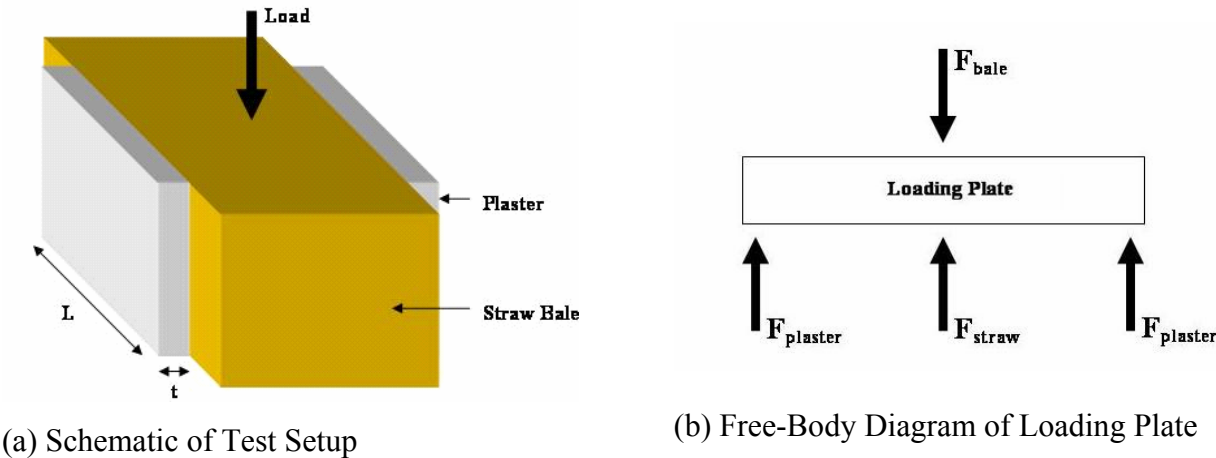(b) Free-Body Diagram of Loading Plate

Figure 6: Loading diagrams.

Figure 7 gives the axial load versus axial displacement response for an un-plastered straw bale tested flat. The curve indicates an increase in stiffness as the bale is loaded. This behaviour has been noted in other experiments on three string bales (Bou-Ali 1993) and two string bales

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(Watts et al. 1995).   The test was ended when the maximum axial deflection reached

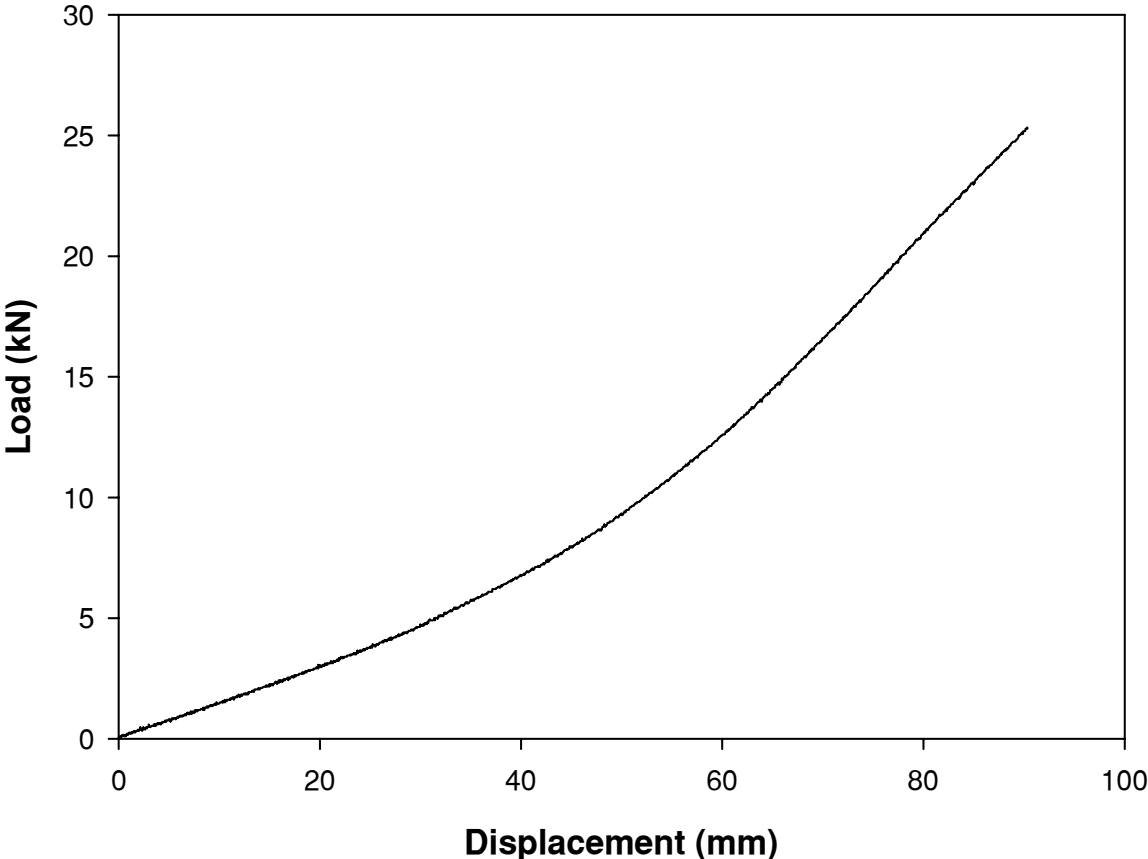approximately 90 mm, although the bale had not undergone failure at this point.

Figure 7: Load-displacement response of flat, un-plastered straw bale.

The axial load versus axial displacement response for a bale tested on edge is given in

Figure 8.   The curve indicates that the relationship between load and displacement is nearly

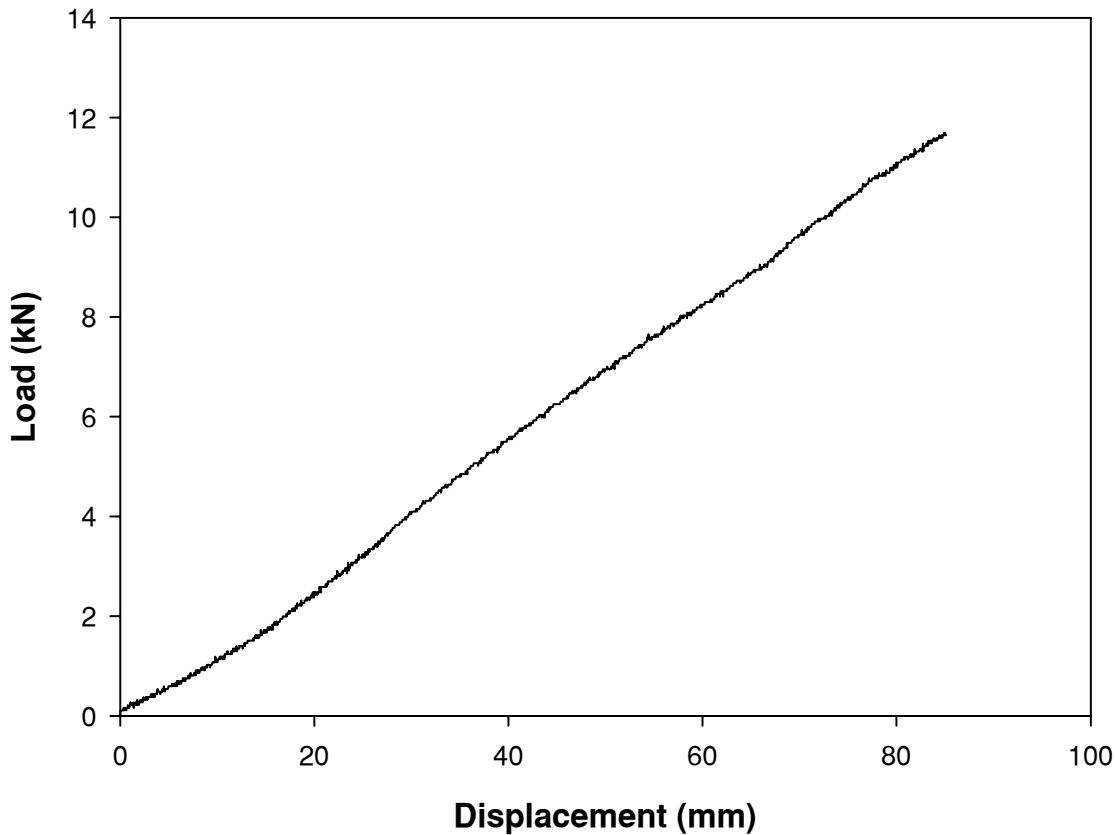linear for a bale loaded on edge and is similar to the response noted by others (Bou-Ali 1993).

Figure 8: Load-displacement response for on-edge, un-plastered straw bale.

The axial load versus axial deflection response for a typical plastered bale tested flat is shown in Figure 9. The curves labeled DISP 1 through DISP 6 represent the load displacement curves for the plastered bale as measured at six points on the top of the bale. The plaster was 25.4 mm thick with $f_c' = 1.72$ MPa. The response of the plastered bale is non-linear up to about 3 mm axial deflection. The straw bale bulged above the plaster skins for the flat plastered bales, and this represents the deflection of this straw until the loading plate made contact with the plaster skins. Beyond this point, the load-displacement response is linear until the maximum load is attained at 35 kN. The deflections obtained by the six displacement transducers at each load level differ by less than 10% prior to reaching the ultimate load. This indicates that the loading applied to the plastered bale was essentially uniform up to this point.
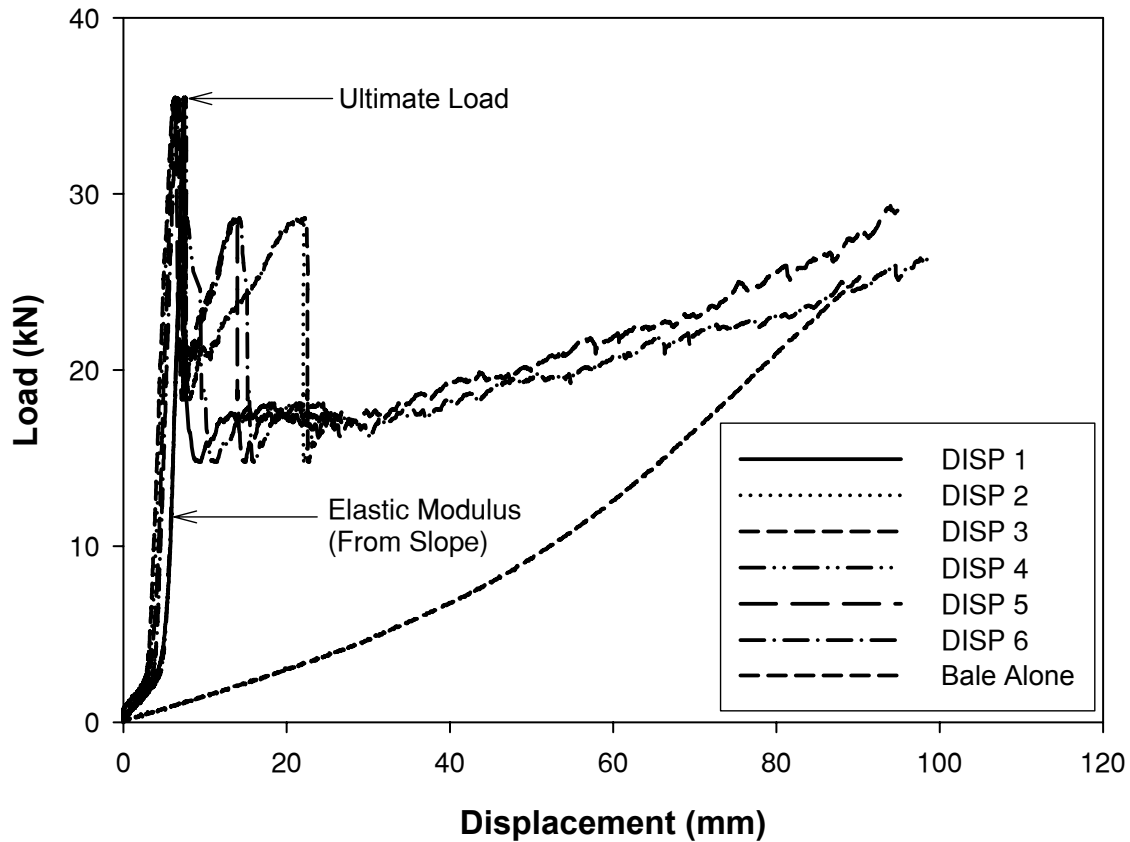
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Figure 9: Typical load-displacement response for flat, plastered straw bale.

Also included in Figure 9 is the load-displacement curve for a flat un-plastered bale, labeled "Bale Alone". It was found that the plastered bales tested flat typically failed at a deflection of 5 to 10 mm. It can be seen that the bale alone will only contribute about 2 kN to the total load in this deflection range. The response curves of the cracked plastered bale and the un-plastered bale begin to converge at about 75 mm axial deflection, indicating that the straw is essentially carrying the applied load at this point. The test was ended at approximately 90 mm axial deflection.

Upon reaching the ultimate load, the plaster was observed to crack as indicated in Figure 10. This corresponded to a sudden drop in load from about 35 kN to about 18 kN. The post-

cracking behavior was ductile, as the load was transferred from the plaster to the straw bale. Note that the cracked plastered bale continued to carry about 18 kN, and beyond about 20 mm axial deflection, the load increases gradually. Most failures of the flat plastered bales occurred at the top of the plaster as seen in Figure 10. This indicates that the failures may have occurred somewhat pre-maturely, possibly as a result of minor un-evenness at the top of the plaster where the load was applied. However, this behaviour does indicate compression failure, which shows that the bond between the plaster and straw was adequate to prevent buckling of the plaster skins.

Figure 10: Typical failure of a flat, plastered straw bale.

Figure 11 gives the axial load versus axial deflection response for a typical bale plastered on edge. The plaster was 12.7 mm thick (after straw bulging) with $f_c' = 1.72$ MPa. Because the

top and bottom of the on-edge bales are cut flat, the loading apparatus is in immediate contact with the plaster skins. There is no initial non-linearity in the response as there was with the flat plastered bales. The load-displacement is linear until the ultimate load is reached at 13 kN. As with the plastered bales tested flat, the load-displacement response is nearly identical for all six displacement transducers prior to the ultimate load being reached.
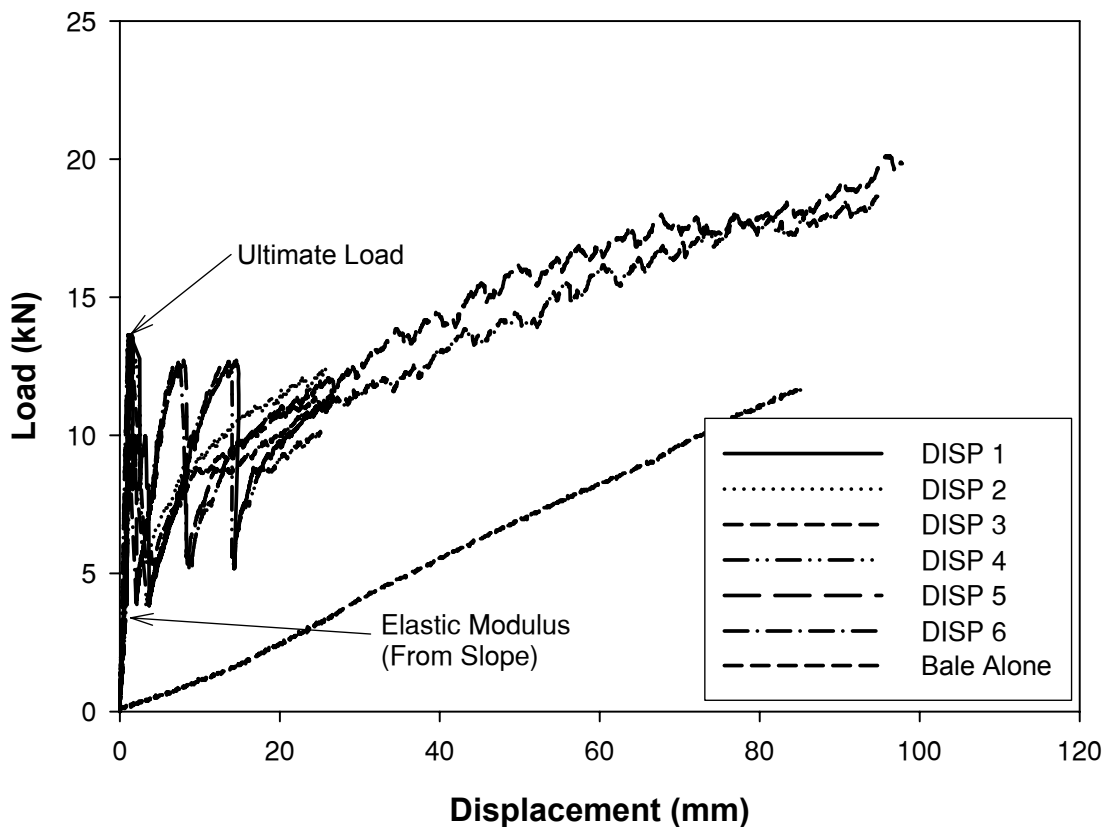

Figure 11: Typical load-displacement response for on-edge, plastered straw bale.

The load-displacement response for the bale plastered on edge followed similar trends to that of the bale plastered flat. There was a linear portion to the relationship prior to failure at 13 kN, at which point failure occurred with a sudden crack as shown in Figure 12. This caused the load to drop to about 3 kN. Following failure, the plastered bale behaved in a ductile manner, as

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it continued to take load immediately after the initial cracking. Figure 11 indicates that the failed plastered bale tended to behave more like an un-plastered bale as the deflections increase and the damage to the plaster skins increases. It appears that with the plastered bale tested on edge, greater displacements are required for the plaster to become non-functional and for the plastered bale to perform as an un-plastered bale. In fact, it can be seen that with the flat plastered bales, the contribution of the plaster becomes insignificant at about 85 mm deflection while with the plastered bales on edge, the plaster continues to contribute even up to the termination of the experiment at 100 mm deflection. When comparing the load-deflection curve of the un-plastered bale with that of the plastered bale it can also be seen that when the plastered bales failed at a typical deflection of 5 mm, the contribution from the straw was 0.75 kN.

Figure 12: Typical failure of on-edge, plastered straw bale.

The failure mode of the plastered bale tested on edge was different than for the flat plastered bale. The flat plastered bale clearly failed as a result of crushing of the plaster while the failure of the on-edge plastered bale was a result of buckling of the plaster skins. The horizontal crack in the middle of the plaster which is evident in Figure 12 indicates that as buckling occurred, the outside edge of the plaster was put into tension causing the crack to form. This caused the subsequent failure of the plastered bale. Such a failure is a sign that the bond between the plaster and the straw for the on-edge plastered bales is not as strong as for the flat plastered bales.

In order to estimate the plastered bale axial stiffness, the readings from the six displacement transducers at each load level were averaged. The response up to the ultimate load for a typical flat and on edge plastered bale is indicated in Figure 13. The slope of the figures from a point when the graph first becomes linear, to the point just below the ultimate load was used to determine the plastered bale modulus (E_{PB}) for each test. The data for that portion of the graph was isolated and a trendline was created. The linear equation of the trendline yielded the slope of the graph. The slope represents the stiffness of the plastered bale in kN/mm. This value was divided by the area of the plastered bale (600mm x width), then multiplied by the height of the plaster in order to determine the plastered bale modulus.
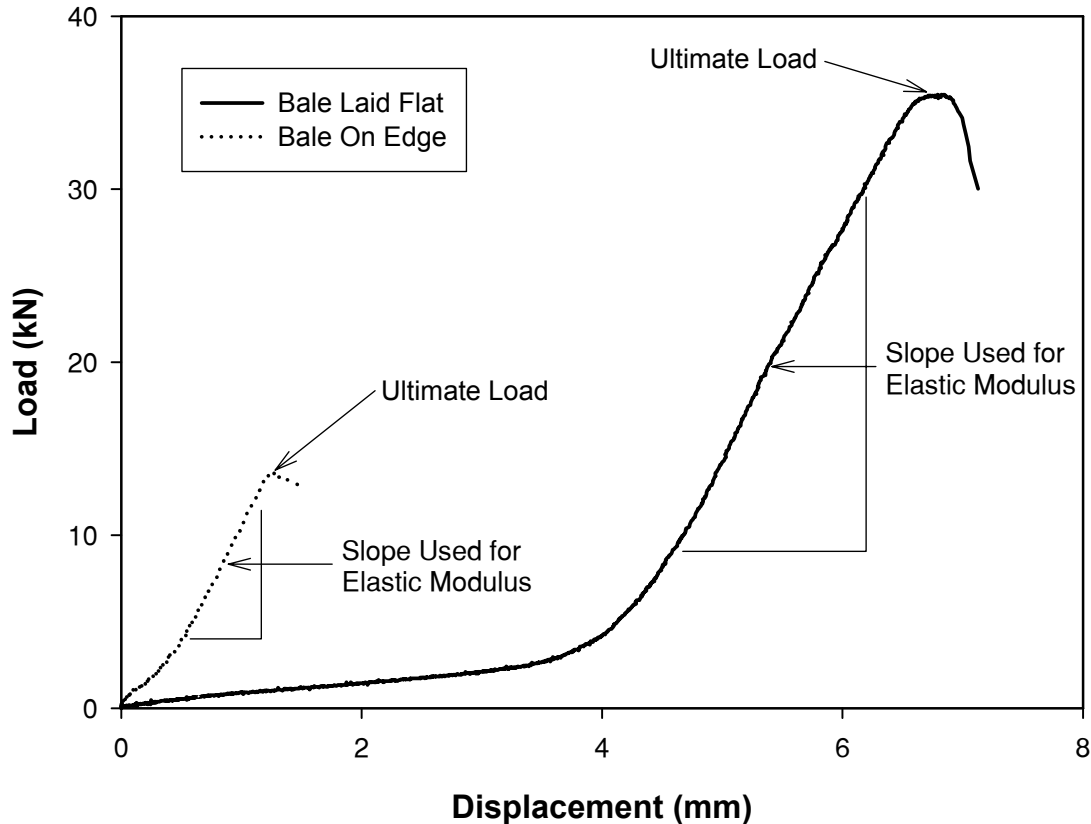
Figure 13: Averaged load-displacement responses for plastered straw bales.

One of the primary objectives of the plastered bale experiments was to determine how the orientation of the bale affects the strength of the plastered bale. This effect can be seen by comparing the ultimate strength of plastered bales in different orientations tested with the same strength and dimensions of plaster. Table 2 gives the results for flat and on-edge plastered bales tested with 12.7 mm plaster thickness and plaster strength of 1.72 MPa. It is evident that the bales plastered flat are stronger than those plastered on edge. All three plastered bales tested flat were found to have a greater ultimate load than the plastered bales tested on edge. The average strength of the plastered bales tested flat was found to be 35.34 kN/m, which is approximately 10 kN/m stronger than the average of 25.96 kN/m found for the plastered bales tested on edge. This difference of 36% can be attributed to the difference in failure modes discussed for Figures 10 and 12.

Table 2: Comparison of flat and on-edge plastered bale strengths for plaster with f_c' = 1.72 MPa and t = 12.7 mm.

Bale Orientation	Plastered Bale Strength (kN/m)			
	First Test	Second Test	Third Test	Average
Flat	34.68	38.18	33.15	35.34
On Edge	22.73	23.00	32.16	25.96

Figure 14 is a comparison of the plastered bale strength and the plaster cube strength for flat plastered bales with plaster thickness of 25.4 mm. The experimental strength was obtained by dividing the measured ultimate plastered bale load by the length of the plaster skins. A linear regression trendline fit to the data is indicated. Also shown in Figure 5 is the plastered bale strength obtained using Eq. [1]. The value of F_{straw} used for Eq. [1] was 2 kN, as described in the discussion of Figure 9.
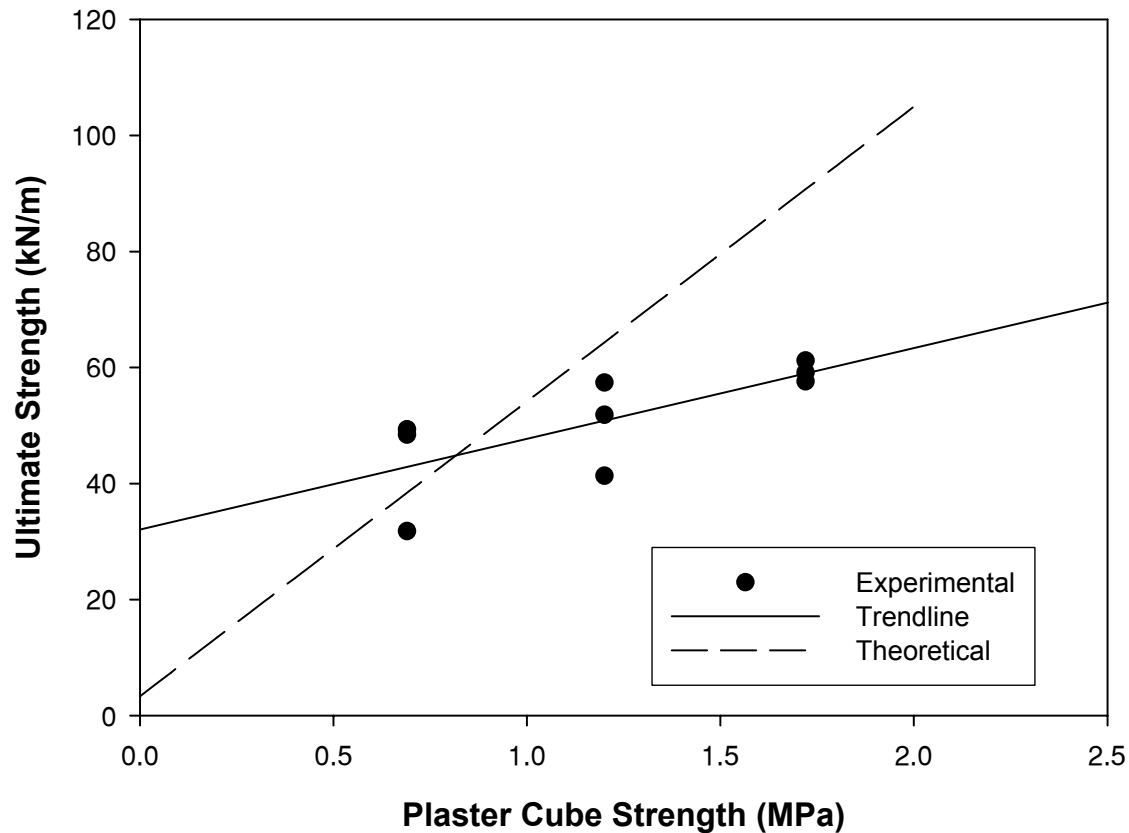
Figure 14: Plastered bale strength versus plaster cube strength for flat bales with plaster *t* = 25.4 mm.

The R^2 value for this data was determined to be 0.54, which indicates that there is not a strong linear relationship between plaster cube strength and plastered bale strength, and that there is significant scatter in the data. Comparison of the experimental results with the theoretical line indicates that the plaster cube strength does not have as large an impact on the plastered bale strength as would be expected if a purely axial compressive failure of the plaster took place. This is further emphasized in Table 3, where the average plastered bale strengths are compared with the plaster cube strengths. As the plaster strength is increased 149% from 0.69 MPa to 1.72 MPa, the average plastered bale strength increases only 37%, from 43.18 kN/m to 59.29 kN/m.

A comparison of the plastered bale strength and the plaster cube strength for a bale plastered on edge with 12.7 mm of plaster is given in Figure 15. Note that a direct comparison

with the results of Figure 14 is not appropriate due to the difference in plaster thickness. Again, the experimental strength was taken as a normalized strength where the ultimate load was divided by the length of the plaster skins. As with the bale plastered flat, a linear regression trendline was fit to the data. The theoretical relationship is also given in Figure 15. The strengths used for this relationship were determined using Eq. [1], where the value of F_{straw} was 0.75 kN as determined in the discussion of Figure 11.
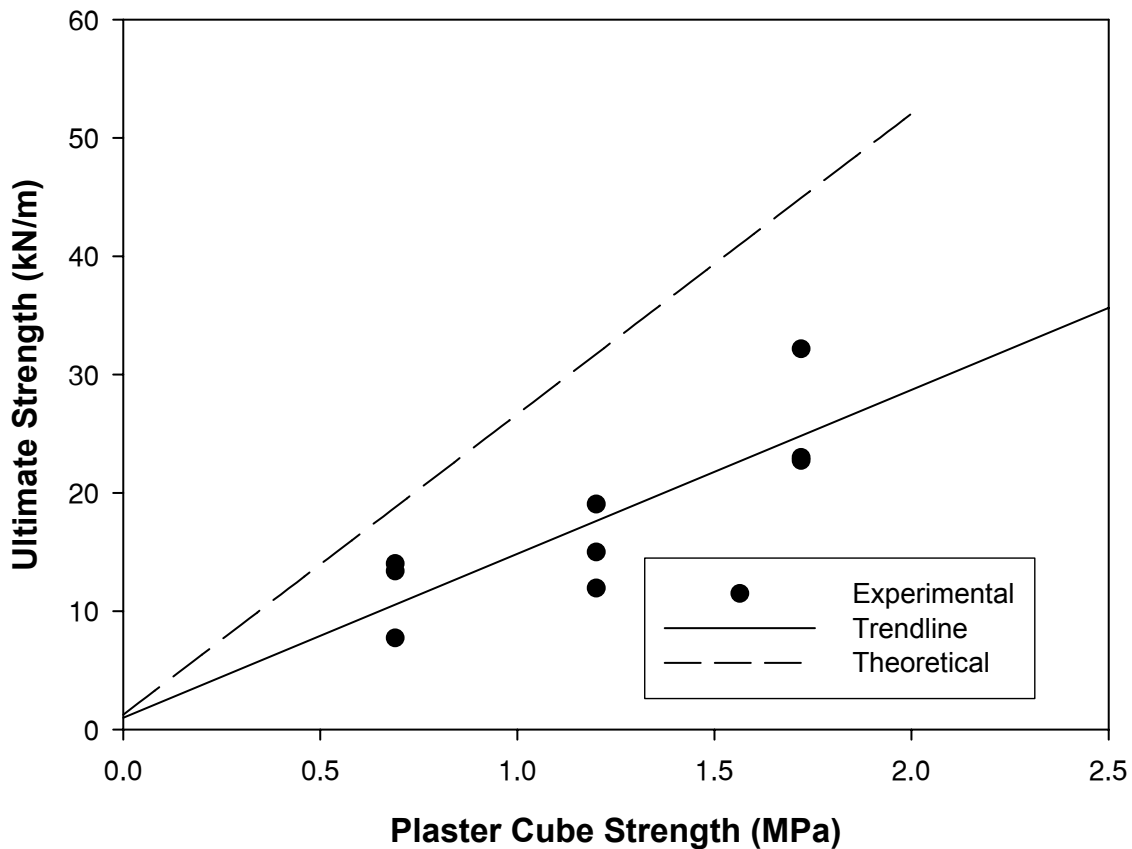

Figure 15: Plastered bale strength versus plaster cube strength for on-edge bales with t = 12.7 mm.

The R^2 value for the trendline was determined to be 0.70, which indicates a better fit than for the plastered bale tested flat. The theoretical line on Figure 15 indicates that the expected

increase in plastered bale strength with plaster cube strength was not observed in the experimental results. The theoretical plot over-estimates the ultimate strength, but does not over-estimate the impact that the plaster strength has on the ultimate strength of the plastered bale as much as was seen for the flat plastered bale. Table 3 further highlights these facts as it can be seen that the average values of the experimental ultimate strength are significantly smaller than the theoretical values. On the other hand, it can be seen that as the plaster cube strength was increased 149% from 0.69 MPa to 1.72 MPa, the average plastered bale strength increased 121% from 11.71 kN/m to 25.96 kN/m, indicating that the plaster strength did have a significant impact on the ultimate strength of the on-edge plastered bale.

Table 3: Comparison of plastered bale ultimate strength and plaster cube strength for flat bales with t = 25.4 mm and on-edge bales with t = 12.7 mm.

Bale Orientation	Plaster Strength (MPa)	Plastered Bale Strength (kN/m)				
		First Test	Second Test	Third Test	Average	Theoretical
Flat	0.69	49.32	48.42	31.80	43.18	38.39
	1.20	51.83	41.32	57.40	50.18	64.29
	1.72	59.11	57.58	61.18	59.29	90.71
On Edge	0.69	7.73	13.39	14.01	11.71	18.78
	1.20	11.95	15.00	19.04	15.33	31.73
	1.72	22.73	23.00	32.16	25.96	44.94

Figure 16 gives the relationship between the plaster thickness and the plastered bale strength for plaster with $f_c^{'}$ = 1.72 MPa and bales plastered flat. The experimental strength is determined by normalizing the ultimate plastered bale load with the length of the plaster skins. The appropriateness of a linear model is determined by considering a linear regression trendline which is fit to the data. This trendline is shown in Figure 16 along with a theoretical line which is found using Eq. [1]. The value of F_{straw} used in Eq. [1] was taken as 2 kN.
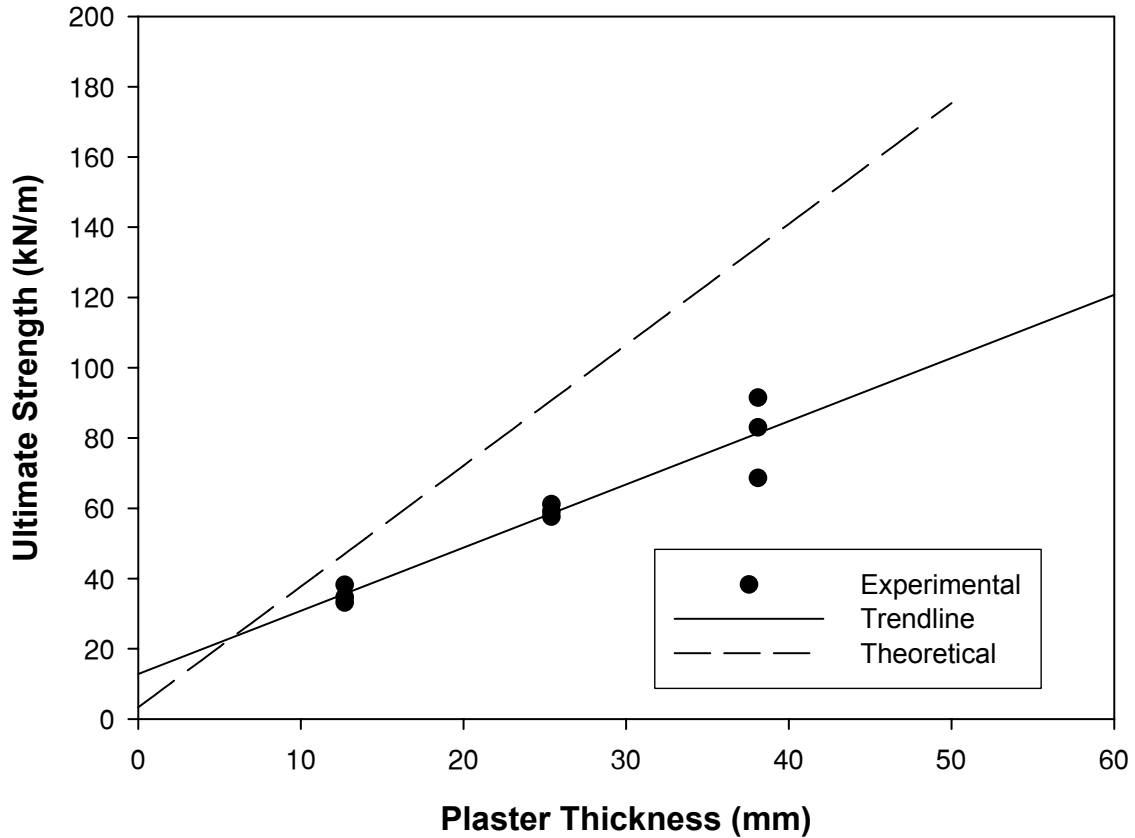
Figure 16: Plastered bale strength versus plaster thickness for flat bales with $f_c' = 1.72$ MPa.

Figure 16 indicates that the plaster thickness has a significant impact on the ultimate strength of a plastered bale. There is significantly less scatter about the linear trendline than was seen in Figures 14 and 15 as reflected in the R^2 value of 0.92, which indicates a good fit. The theoretical equation over-estimates the strength of the plastered bales, as essentially all theoretical values are greater than the experimental values. As can be seen from the data in Table 4, as the plaster thickness was increased 200% from 12.7 mm to 38.1mm, the average plastered bale strength increased 129% from 35.34 kN/m to 81.03 kN/m. This indicates the significance of the plaster thickness on the strength of the plastered bale.

Table 4: Comparison of plastered bale ultimate strength and plaster thickness for flat bales with f_c' = 1.72 MPa.

Bale Orientation	Plaster Thickness (mm)	Plastered Bale Strength (kN/m)				
		First Test	Second Test	Third Test	Average	Theoretical
Flat	12.7	34.68	38.18	33.15	35.34	47.02
	25.4	59.11	57.58	61.18	59.29	90.71
	38.1	83.01	68.63	91.45	81.03	134.40

In addition to considering the thickness of the plaster, the aspect ratio of the plaster skin (ratio of the height to thickness) is also an important parameter. As the aspect ratio increases, there is an increased susceptibility to buckling. Buckling was only observed for the plastered bales on-edge. However, it should be noted that the plastered flat bales had smaller aspect ratios and were therefore less susceptible to buckling than the plastered on-edge bales. Further research should look at how significant differences in the aspect ratio of plastered straw bale walls can affect the strength of the wall, and at what aspect ratio buckling becomes an issue for flat plastered bales.

The plastered bale modulus is another important property that was studied in these experiments. Tests were conducted to determine how the plastered bale modulus varied with the orientation of the bales. Table 5 gives the results for bales tested flat and on edge with a plaster thickness of 12.7 mm and plaster cube strength of 1.72 MPa. Although the on-edge plastered bales do have a higher plastered bale modulus on average, there is a large variation in the results for both the flat and on-edge bales so that this difference may not be statistically significant. However, further test data would be needed to confirm this observation. Furthermore, it would be expected that the on-edge plastered bales are somewhat stiffer because although the minimum thickness of plaster is 12.7 mm, much of the plastered bale has a thicker plaster skin where bulging of the straw was prevented. The only significant conclusion that can be drawn with any certainty is that the plastered bale modulus for both the on-edge and flat plastered bales is highly

variable, and that the plastered bale modulus for both bale orientations is within a similar range.

Table 5: Comparison of flat and on-edge plastered bale modulus for $f_c' = 1.72$ MPa and $t = 12.7$ mm.

	Plastered Bale Modulus (MPa)			
Bale Orientation	First Test	Second Test	Third Test	Average
Flat	9.15	16.25	11.89	12.43
On Edge	23.43	19.15	12.71	18.43

The plastered bale modulus of the plastered straw bales was compared to the strength of the plaster used in numerous experiments to determine if there was a correlation between the two variables. Figure 17 shows the relationship between the strength of the plaster and the plastered bale modulus, for bales tested flat. For this comparison, a plaster thickness of 25.4 mm was used.
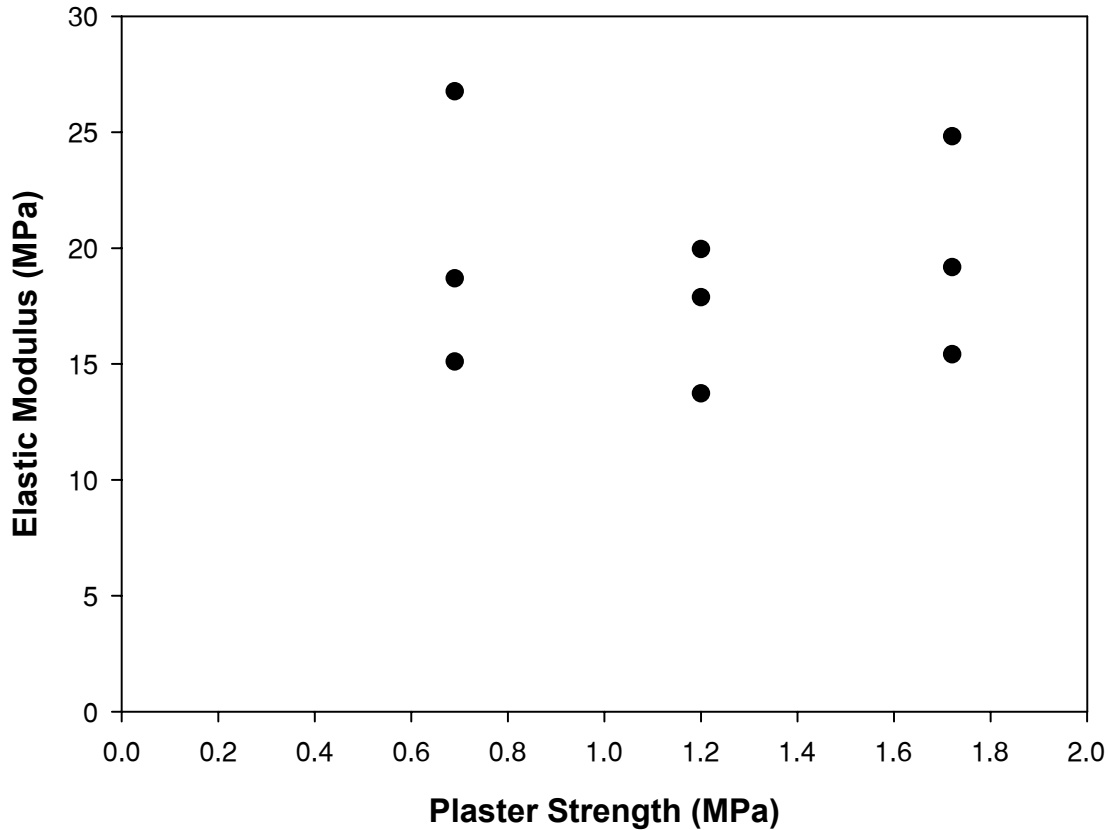
Figure 17: Plastered bale modulus versus plaster cube strength for flat bales with _t_ = 25.4 mm.

Figure 17 indicates that for a flat bale, the plaster strength does not affect the plastered bale modulus. For all three different plaster strengths, the plastered bale modulus varied between 14 and 27 MPa. The only noticeable trend was the fact that in all cases, the plastered bale modulus values exhibited large scatter.

Similar experiments were conducted to determine how the on-edge plastered bale modulus related to the strength of the plaster used. For these experiments the minimum plaster thickness was kept constant at 12.7 MPa. The relationship between the plastered bale modulus and the plaster strength for a plastered bale tested on edge is given in Figure 18.
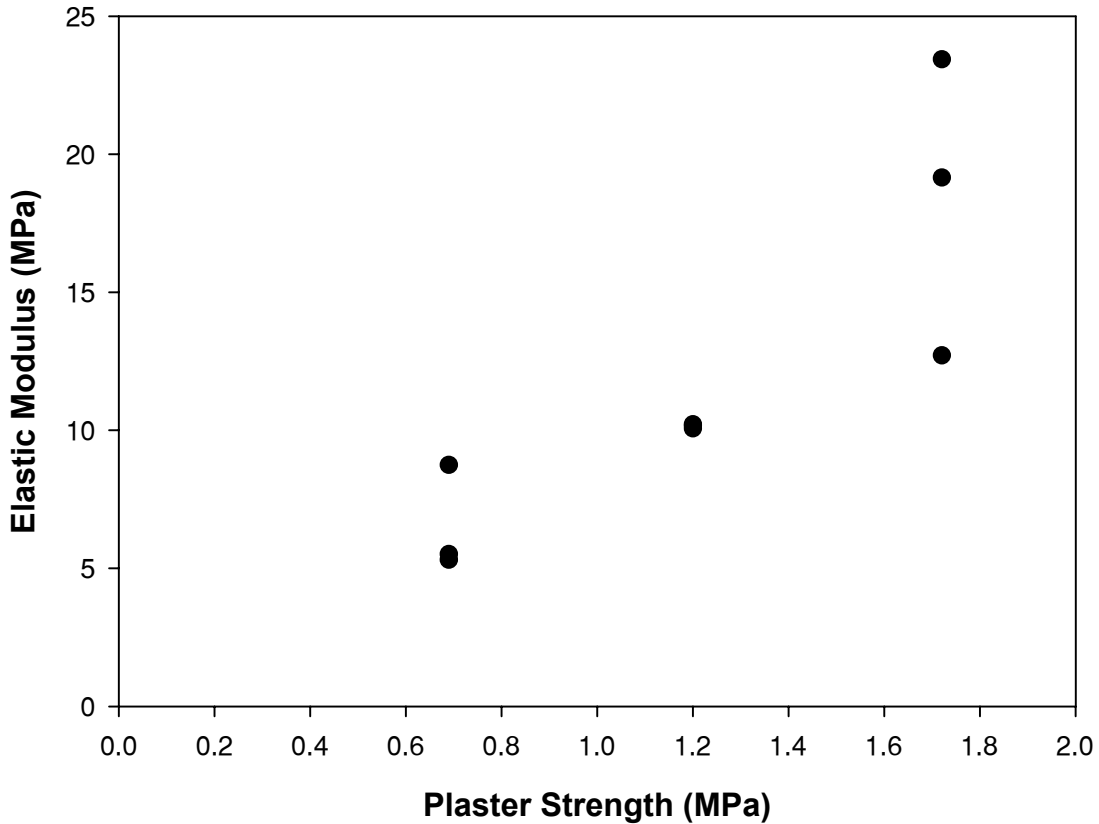
Figure 18: Plastered bale modulus versus plaster cube strength for on-edge bales with *t* = 12.7 mm.

Figure 18 indicates little difference in the plastered bale modulus for plaster cube strengths of 0.69 MPa and 1.20 MPa. It appears that there is a higher modulus at a plaster cube strength of 1.72 MPa. However, the results for this cube strength were widely scattered and so it cannot be stated conclusively that plastered bale modulus increases with plaster cube strength for the on-edge plastered bales. Furthermore, the inconsistencies that were evident in the thickness of the plaster for the on-edge bales could have significantly contributed to the large scatter in modulus.

The plastered bale modulus was also compared to the thickness of the plaster skins. As with the comparison between the plaster thickness and plastered bale strength, results are only presented for the plastered bales tested flat. Figure 19 gives the relationship between plaster

thickness and plastered bale modulus for bales tested flat with plaster strength of 1.72 MPa.
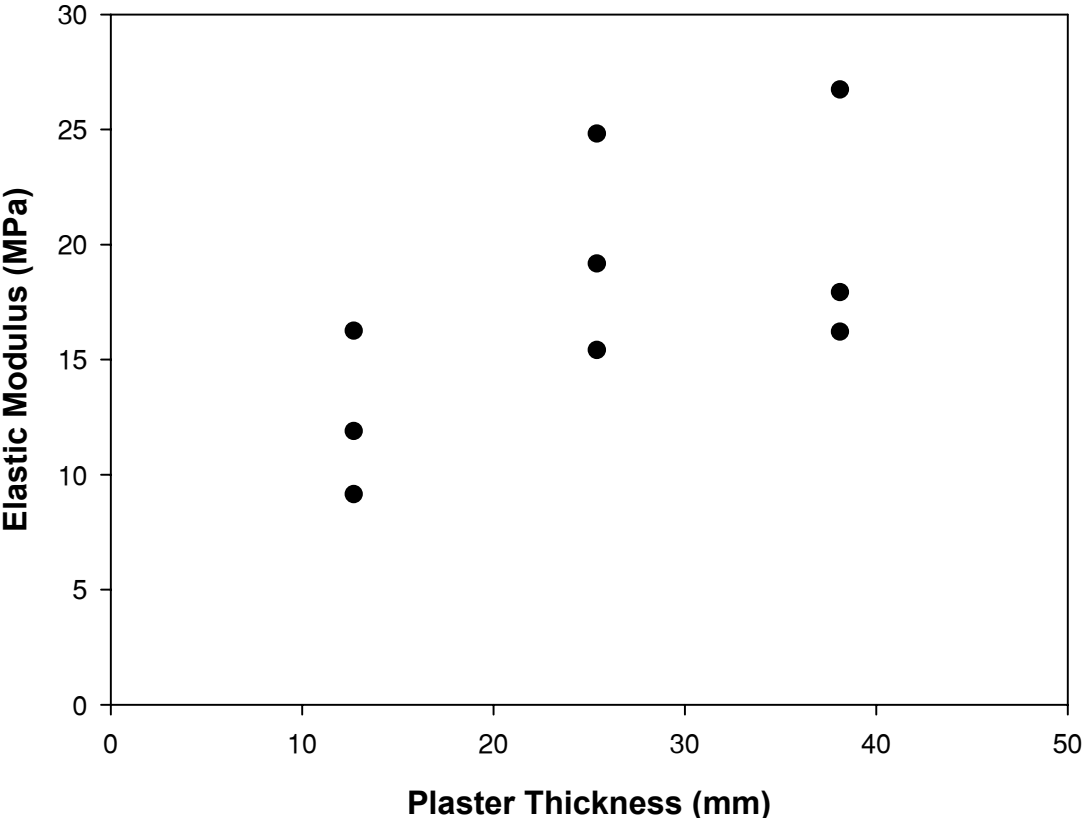

Figure 19: Plastered bale modulus versus plaster thickness for flat bales with f_c' = 1.72 MPa.

As would be expected, there appears to be a slight increase in the plastered bale modulus as the plaster thickness is increased. However, due to the wide scatter in the results, this cannot be stated conclusively.

Discussion

The experiments presented herein provide valuable insight into the structural behavior of plastered straw bales. The strength of the plastered bales was found to have a range of ultimate

strengths between 8 and 90 kN/m, depending on the plaster thickness and strength, and the bale orientation. Figure 20 is a comparison of the results obtained in this study with those available in the literature. Also shown is the range of typical wall strengths for residential construction using conventional 2 x 6 stud-wall construction (Riley and Palleroni 2001). Note that where multiple bars are shown for the same experiments, the experiment was conducted more than once.
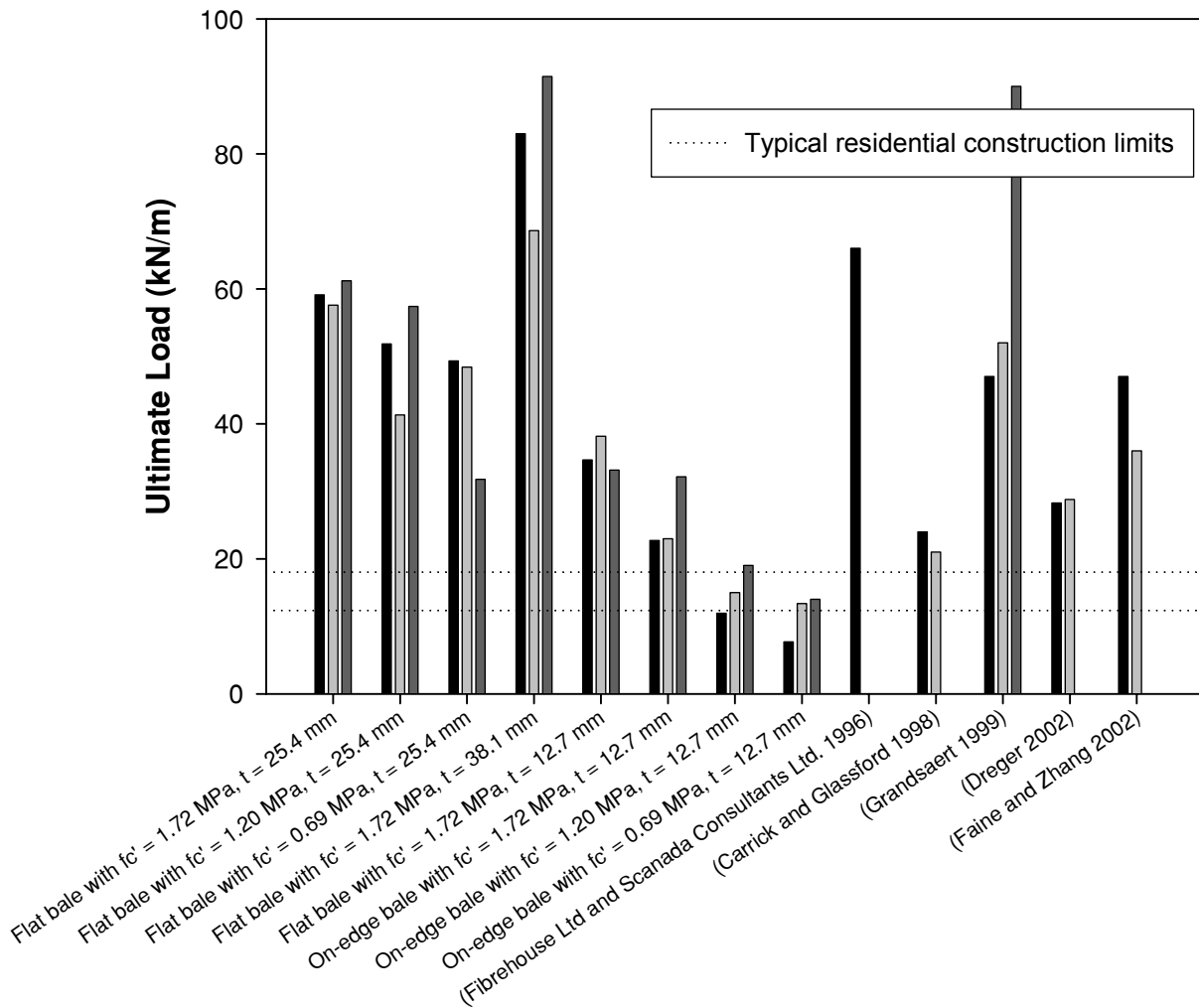

Figure 20: Comparison of experimental results with values in the literature.

Figure 20 indicates that the current results fall within a range of strengths comparable to those seen in the literature. An important advance with the current results is that parameters such

as plaster thickness and strength have been clearly identified and their effect on plastered bale strength has been systematically investigated. This is useful from a design perspective, since the optimal combination of parameters for a given design can be identified. In addition, the current results indicate that for the flat bales, the method of preparing the bales was successful in creating specimens that provided consistent results. The results for the flat plastered bales were likely somewhat conservative as it appeared there was possibly premature failure of these bales as a result of boundary effects. The plastered bales prepared on-edge did contain inconsistencies in the plaster thickness, but they were adequate enough to provide some significant results.

The strength values obtained in the current study exceed or fall within the range of strengths for residential construction using conventional materials. Thus, plastered straw bales are a very viable building material for residential construction. Note that the plastered bale that best approximates field practice was plastered flat with 25.4 mm of plaster that had cube strength of 1.72 MPa. These plastered bales were found to have an ultimate strength of around 60 kN/m, which is far superior to the strength of a typical residential wall.

The lowest strength values were for the plastered bales oriented on edge and with a plaster thickness of 12.7 mm. Note that typical straw bale construction has plaster skins with a thickness of 25.4 mm. Plastered bales on-edge were also tested with a plaster thickness of 25.4 mm, although these bales were damaged by water before testing. These bales achieved an ultimate strength of about 35 kN/m. With this thicker plaster, the strength comfortably exceeds the typical residential construction range of between 12.34 and 18.04 kN/m. Thus, it appears that walls with bales stacked on edge could have sufficient strength for residential construction, provided the plaster thickness is adequate. Further testing of full-scale walls with bales stacked on edge appears warranted.

These results have a number of implications for straw bale builders. Builders who have considered using the bales on edge to increase the square-footage of the structure and decrease the number of bales should consider strategies to prevent the buckling of the plaster skins noted during the testing. This could be done by improving the bond between the straw and the plaster and by providing an improved horizontal tie between the plaster skins. For all experiments in the current study, there was no wire mesh reinforcement attached to the bales prior to plastering. Often in straw bale construction a wire mesh is affixed to the sides of the wall in order to comply with current building codes (U.S. Department of Energy, 2004). This is done for a number of reasons, one of which is to improve the bond between the straw and the plaster (Magwood and Mack 2000). In addition, if the mesh is tied through the bales, there will be an improvement in the horizontal tie between the plaster skins. If this were done with the bales laid on edge, it may be adequate to prevent the buckling issues noted in the experiments.

Straw bale builders must also take into consideration the thickness and strength of the plaster used for the walls. The results indicate that ensuring an adequate plaster thickness is extremely important. Furthermore, maintaining appropriate mix proportions (including water content) is also important, but not as significant as the plaster thickness. For the plastered bales laid flat, the plaster thickness was found to have the most important impact on the strength as it was found that the percentage increase in plastered bale strength was 65% of the percentage increase in the plaster thickness. In other words, if the plaster thickness is doubled, the plastered bale strength is increased by about 1.65 times. On the other hand, the strength of the plaster was found to not have as significant an impact on the strength of the plastered bale. It was found that the percentage increase in the plastered bale strength was 25% of the percentage increase in the plaster strength for bales tested flat. This indicates that if the plaster strength is doubled, the

plastered bale strength increases by only 1.25 times.

It should be noted that although the results presented in this paper provide valuable information on a number of parameters that can affect the strength of individual plastered straw bales, caution should be exercised when applying the results to full-scale walls, since the effects of buckling and construction imperfections may be magnified. Therefore, these results should be used primarily to indicate trends and as a basis for further research on how these parameters affect full-scale walls.

Conclusions

The results of experiments conducted on individual plastered straw bales highlighted a number of important parameters that affect the structural properties of a plastered straw bale:

1) The strength of a plastered straw bale is highly dependent on the orientation of the bale. The strength of plastered bales orientated flat is 36% greater than those oriented on edge for a plaster thickness of 12.7 mm and plaster cube strength of 1.27 MPa.

2) The mode of failure is an important design consideration for plastered straw bales, as it is for any construction material. The failure mode for the bales plastered on edge was seen to be different than for the bales plastered flat. Buckling was observed as the main failure mechanism for the on-edge plastered bales, while the flat bales appeared to fail by crushing of the plaster. This explains the differences in strengths observed for the two bale orientations.

3) The plaster strength and thickness has a profound effect on the strength of a plastered bale. The plaster thickness was seen to have a greater effect on the plastered bale strength than the cube strength of the plaster. It was found that doubling the plaster thickness increased the average plastered bale strength 65%, while doubling the plaster strength increased the average

plastered bale strength 25%.

4) For nearly all experiments it was found that the plastered straw bales exceeded the strengths found in typical residential construction. The only plastered bales found to fall below the residential construction range were those tested on edge with only 12.7 mm plaster skins.

5) The plastered bale modulus was found to be highly variable, regardless of the test parameters. Values were found to range from 5.69 MPa to 26.76 MPa. Some general trends were noted, but due to the variability of the results, the reliability of these trends is questionable, indicating the need for further testing.

These results will serve to increase the general knowledge of how straw bale walls perform structurally. This in turn will help to increase the credibility of straw bale construction as a mainstream construction technique, and will provide an excellent foundation to future research regarding the structural performance of plastered straw bale walls.

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