

LOAD CARRYING CHARACTERISTICS OF A SINGLE STRAW BALE UNDER COMPRESSION

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ABSTRACT

In this paper, studies were carried out on the effect of compressibility on the engineering properties of straw bales, in particular strength and stiffness. The objective was to establish the load-carrying characteristic of a single bale with or without render.

Test results show that there are generally 4 distinct stages in the loading response of an unrendered bale. A linear trendline can be established accurately for each of the stages. The model developed here also provides the theoretical basis regarding the optimum amount of pre-compaction to be adopted in the practical wall erection. A typical value of 3-4% would be sufficient to improve the performance of the wall significantly.

From the test results it can be concluded that straw bales have excellent properties under low frequency cyclic loading, even at relatively high amplitude. Test results show that straw bales, regardless of whether it is rendered or not, do have a distinct failure point (at the end of Stage 2) indicated by the significant plateau in the stress strain curve. However, different from the common familiar plastic flow as seen in steel after yielding, straw bales can further develop significant amount of strength after the 'yielding' (Stage 3).

Comparing with unrendered bale, rendered straw bales provide a reasonable amount of increase in strength and in stiffness. Cement render has no significant difference in strength gain when compared with earth render, though cement render does appear to defer the occurrence of cracks longer than the earth render. Different loading regimes for the rendered test do not make a significant difference in the load resistance behaviour.

Keywords: cement render, compression, cyclic load, earth render, precompaction, strawbale, strawbale wall, strength, sustainability

1. INTRODUCTION

Resurgence of straw bale building in recent years derives largely from our concerns for the degradation of the environment and sustainability of human activities on earth, in particular the impact of the unsustainable nature of current building practices. The building technology and practice are nothing new and there have been a number of well-known texts covering the straw bale building techniques.

Straws are waste products resulting from human race's needs for food consumption. Unlike timbers, which grow from trees, which have a regeneration cycle of, typically, 20 years or longer, straws are regenerated yearly or twice every year at the time of harvesting crops. Therefore their production is definitely sustainable, as long as humans need to produce grains for food, straws will be produced as a waste/by product at the same time. Logging of native forest for building products has had a well-recognized devastating effect on the natural environment.

As a natural material that is difficult to be associated with building, our understanding of straw bale's building properties is rather limited. To date, it has been recognized without dispute that straw bales offer excellent thermal insulation property, far exceeding any other building materials and even far exceeding our expectation in term of energy efficiency (Canadian Society of Agricultural Engineering, 1995).

Advantages aside, there are some major drawbacks for straws to be used as a building material. Of all the influencing factors, people's perception and conventional wisdom proved to be the number one obstacle. The lack of understanding of the material often scares the so-called building professional away, needless to say the bewildered reaction of layman when straw bale house building is mentioned. The dramatization of 'the big bad wolf and the three little pigs' has planted deeply into people's mind that one cannot build houses with straw. The lack of understanding on how straw bales behave in a built environment when exposed to various natural effects is another factor that deters its wider application. These natural effects could be in the form of load, fire, degradation and so on. These uncertainties can be addressed by research.

In recent years there has been a persistent, albeit limited, research effort to increase our understanding of straw bale as a building material (Bou-Ali, 1993; Faine and Zhang, 2001 and 2002). Pioneer attempt has been made to rationalize the structural design aspect of straw bale building (King, 1996). It can be said that the research development of straw-based building materials follows a similar path to that of wood-based building materials a number of decades ago. Eventually straw-based building material will become a major player in the building product industry.

In this paper, results were presented on the structural behaviour of individual straw bales. The investigation was performed under laboratory conditions. Commercially available straw bales were compressed to a different degree under different loading conditions. Some were loaded under a number of loading cycles, whilst others were loaded to failure in one single loading session. Unrendered bales were used as basis of comparison to bales either rendered with cement render or earth render. The effect of compressibility on the engineering properties of straw bales, in particular strength and stiffness was addressed in detail. The objective was to establish the load carrying characteristic of a single bale with or without render.

The project forms part of a major research effort at University of Western Sydney to assess straw bales as a building material, in particular their mechanical and physical properties.

2. EXPERIMENTAL PROGRAM

11 individual bales were tested as part of the investigation. Of these, five were unrendered with three being tested on flat and two on edge. A number of these were also tested under a number of loading cycles, i.e., loading and unloading and loading again. The remaining six was rendered with either earth render or cement render.

Individual straw bale was sourced from a commercial source. Because of the off-season and the current drought, straw bale is relatively hard and more expensive to obtain.

Compressive tests were carried out using the *Universal Testing Machine (UTM)* in the Construction Laboratory at the University of Western Sydney. A rigid loading spread platform was constructed out of *Formply* reinforced with timber ribs to apply the load from the top platens of the *UTM* to the specimen uniformly (Figure 1). A digital deformation device was fitted onto the machine to give the readout of the deformation during the test. Load readings were provided by both the analogue dial indicator and the digital indicator. For the unrendered specimens, load was applied with either straw bale placed flat or on edge. For rendered specimens all straw bales were tested on flat.

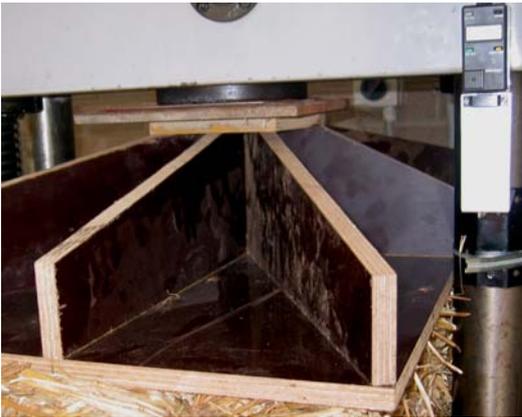


Figure 1 Loading spread platform and digital metre

In every test, the specimen was tested to the maximum deformation that the deflection device can record, i.e. in the order of 100 –150 mm. For each specimen, the physical dimensions and the weight were recorded. Load was applied at an increment of 0.5 to 2 kN, and for each load increment a deformation reading was taken from the digital metre. The data recorded was then processed to produce various curves of load versus deformation. The test programs are described in detail below.

The information for each of the specimen is listed in the Table 1 below

Table 1 Specimen parameter

Spec.	Length (mm)	Width (mm)	Height (mm)	Weight (kg)	Render	Note

1	820	460	350	12.89	-	on flat, 3 cycles
2	820	470	360	13.21	-	on edge, 3 cycles
3	800	460	350	13.27	-	on flat, 3 cycles
4	830	460	350	15.42	-	On flat
5	820	460	350	13.5	-	on edge
6	720	490	350	-	40	earth render 10 mm top and 40 mm bottom, loaded on bale only top and bottom using frame
7	820	500	350	44.47	50	earth render 40 mm mean, load on bale only at top, bottom sits flat on UTM
8	750	500	350	-	50	earth render, loading both bale and render
9	780	500	350	-	50	cement render, two major central cracks before testing, load on bale only both top and bottom
10	750	500	350	-	50	loading same as for No. 7
11	760	500	350	42	50	load as for No 8

3. TESTS OF UN-RENDERED STRAWBALE

3.1 Test set-up

Tests on un-rendered straw bales are straightforward. The load was applied through the top spreading platform (Figure 2). Of five unrendered bales, three were tested on flat and two on edge to study the effect of bale orientation on the loading behaviour. A low frequency three cycles cyclic loading is also applied to study the response of the bales under such loading condition.



Figure 2 Test set-ups for unrendered strawbale test

3.2 Test observation and result discussion

The test results in the way of stress vs. strain (shortening) are presented as graphs and two typical curves are given in Figure 3. The graph reveals some interesting insight regarding the load carrying behaviour of straw bales. It shows that there are four distinct stages in the whole process of loading.

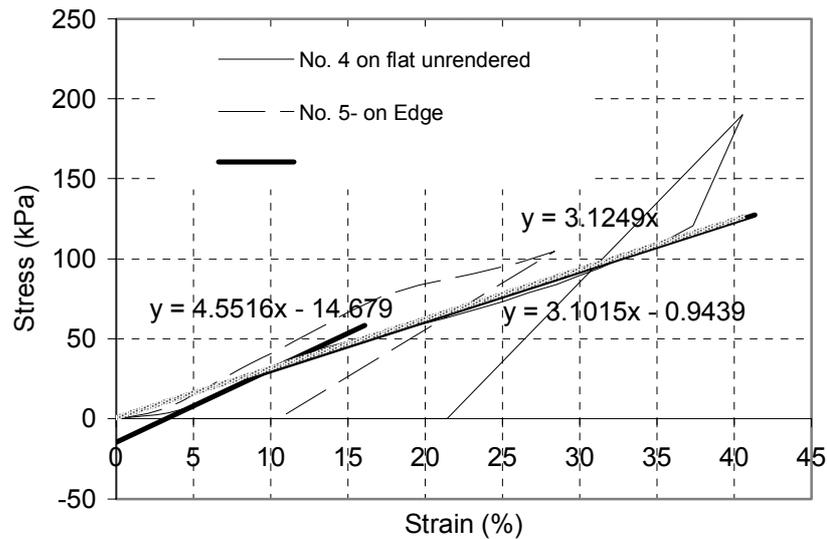


Figure 3 Stress strain curves of unrendered straw bales and the trendlines

At Stage 1 when the bale was first loaded, the material is ‘soft’ and the resistance is almost none because of the relatively unpacked nature of straw bale. This is indicated by the low inclination on the curve up until a strain value of 4%. This is the initial pre-compaction stage of the strawbale. It would be interesting to suggest that by studying the behaviour and the deformation level for this stage, the precompaction level can be quantified in the straw bale wall erection. After initial compaction, a significant increase in resistance is evident, indicated by the region of the steeper curve. This is Stage 2 from 4% to 12% of the strain. The behaviour of the straw bale in this region is similar to that of conventional building materials including timber or concrete, although with a lower stiffness. Load increases almost linearly with the increase of deformation. A linear trendline was added for the middle range of the curve by using linear regression analysis.

From this trend line one can assume that by precompressing the bale by 3-4% before loading one can effectively remove the early flat part of the curve and therefore improve the behaviour of the bale under compression. For 2700 mm high wall, 3-4% translates into 80-100 mm precompression. Based on the observation made on the full-scale wall test (Faine and Zhang, 2001 and 2002), this is the realistic precompaction level that has been achieved. Beyond this, the precompaction using the conventional tension wire method becomes difficult. From the curve above one can also conclude that any precompaction above this level is also unnecessary, as the bale already behaves as though it is properly compacted.

Beyond the 12% shortening (the load level of approximately 15 kN), the bale goes into Stage 3, where the material becomes slightly ‘soft’ because of the applied compression, yet it is still able to carry a significant amount of additional load. Deformation increases at a much faster pace than the load increase, indicating there is significant plastic flow within the material.

The plastic flow is similar to the yielding in steel. Here the plastic deformation occurs when the hollow straw tubes start to collapse. However the behaviour is different from steel in that the load continues to increase significantly. This unique behaviour is due to the progressive nature of the collapse of the hollow straw tubes under compression. The collapse probably propagates

from the surface in contact with the loading platforms into the inside of the bale as illustrated in Figure 4.

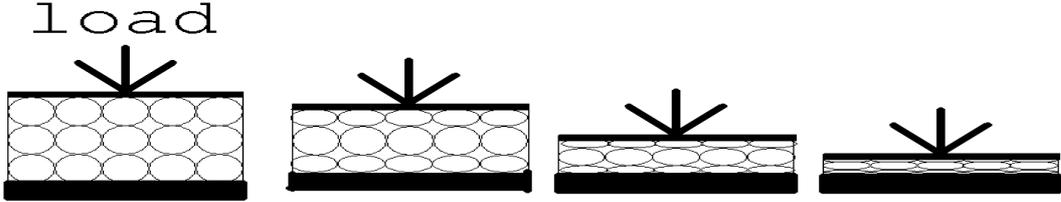


Figure 4 Progressive collapse of straw bale

Stage 3 is extensive until the strain reaches to about 37%. The behaviour in this segment is almost perfectly linear. A linear trendline is also drawn up to Stage 3. It can be seen that the behaviour can be represented by a linear response accurately up to Stage 3.

Finally in Stage 4 as the straws become more compact, the material displays the characteristic of a “hardening” material, where the more it is crushed, the harder it becomes to crush further. The hardening behaviour of the material is indicated by the curve curving towards the vertical axis in the graph. This hardening behaviour was also observed in the full-scale wall tests (Faine and Zhang, 2001; 2002). Although this hardening behaviour is well outside the useful deformation range, it still indicates that in extreme case it has the capacity to absorb a large amount of energy without total structural failure.

Most of the tests were stopped at the maximum deformation level of the measuring device. The specimen was then unloaded in a controlled manner and the residual deformation at the zero load level was recorded. For Specimen No. 4, the residual deformation was 75 mm (21%) at zero load level, the residual deformation when specimen completely rebound is 15 mm (Figure 6). The photograph in Figure 5 best illustrates the final compressed state of the strawbale.



Figure 5. Compressed state of the straw bale

For tests on edge, the behaviour at the initial stage (Stage 1) was almost identical to the test on flat. This was also followed by Stage 2, where the resistance begins to increase linearly with the deformation. A linear trendline could also be drawn accurately. Surprisingly, both strength and

stiffness were slightly higher because of the reduced surface area. However the interesting point was that Stage 2 is prolonged until the load was approximately 20 kN (strain value of 17%), then the curve exhibited significant softening (Stage 3). The final hardening stage (Stage 4) was not obvious.

In order to compare results of different bales which have slightly different physical dimensions, (in particular length) and bales tested in different ways, the above results were presented as stress and strain. Sometimes, it is easier to interpret the results on load deformation curves. Load can also be converted into load per linear metre of wall (kN/m). These results were presented in Figures 6, and 7, respectively.

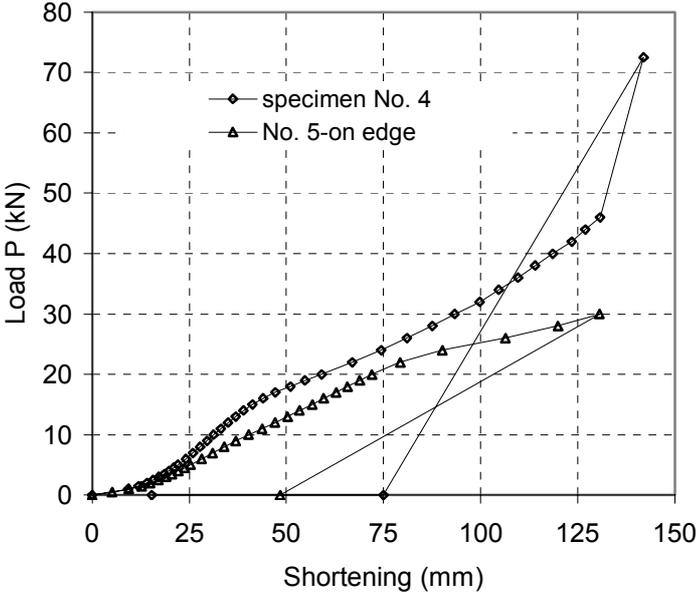


Figure 6 Load shortening curves

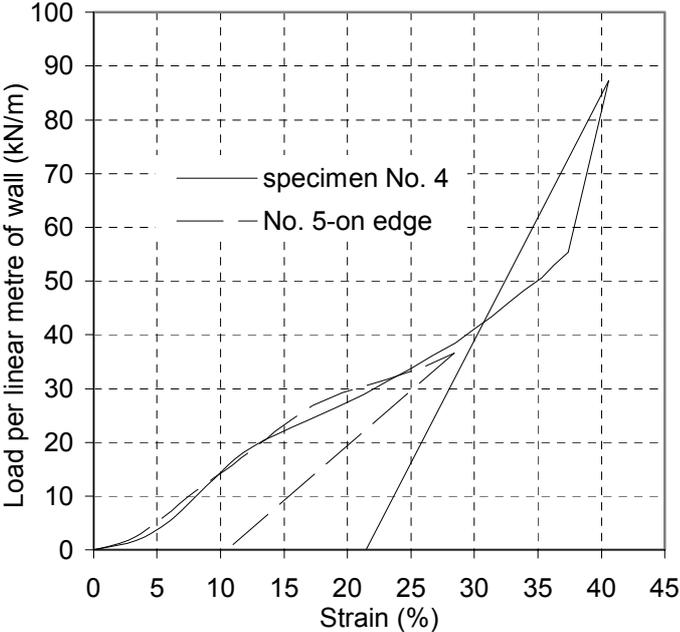


Figure 7 Load per metre wall length

3.3 Low frequency cyclic loading

Specimens No. 1, 2 and 3 were loaded and unloaded by a number of cycles to investigate the load memory effect of straw bales. The typical stress-strain responses were given in Figure 8 together with two other single cycle tests. It is interesting to note that low frequency cyclic loading has no significant impact on the load resistance property of straw bales.

It is also interesting to note that there is always delayed (viscous) effect on the recovery of the deformation as the straw bale is unloaded.

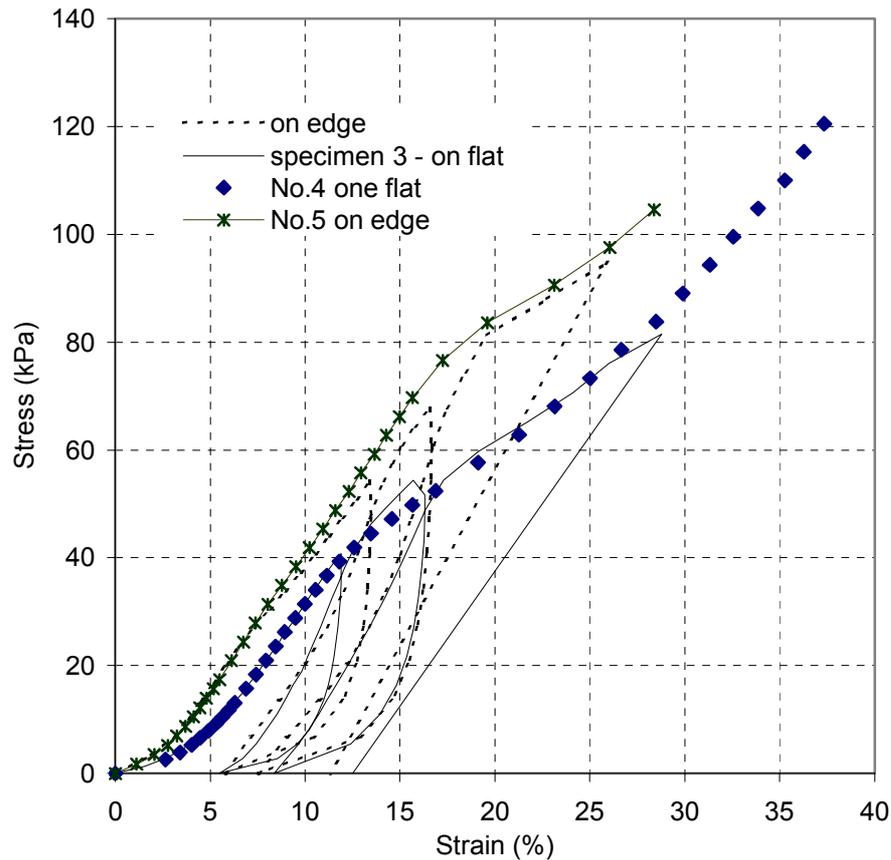


Figure 8 Stress strain curves under three cycles loading

The results for cyclic tests in the form of load vs. deformation and load vs. strain were presented in Appendix in Figures 18 and 19, respectively.

4. TESTS OF RENDERED STRAW BALES

4.1 Specimen preparation for rendered tests

Two types of renders were used, earth based render and cement based render. Two coats of materials were rendered on to the specimens. This is different from the common straw bale building practice where a minimum of three coats should be applied. The argument is that the last coat in the practice is the finishing coat, which is usually very thin, therefore will not alter the structural response significantly.

The render thickness varies but an average of 40 mm each side was achieved.

4.2 Test set-up

To study the effect of interaction between the render and the straw bale, the following loading regimes were adopted for the rendered tests.

- Only straw bale was directly loaded at both top and bottom;
- Straw bale loaded at the top only while at the bottom both render and straw bale were loaded;
- Straw bale and render both loaded directly.

The different loading methods are described in detail below.

Direct loading of straw bale only

Timber frame inserts were placed in both the bottom and top loading platforms. The insert is slightly less wide than the width of an unrendered bale, therefore the loading was applied directly onto the straw bale only, not on the render. The loading was transferred to the render by only the bonding effect between the render and the bale. This occurred at the early stage of loading, however as the frame sunk into the bale as it was pressed, both bale and renders were loaded directly. This generally occurred at the later stage of loading when significant deformation and cracks had occurred.

Partially direct loading

In this method, a timber insert was placed at the top while the rendered straw bale sat directly on the bottom platform. Again initially there was a buffer effect at the top when the load was applied to the straw bale only. However, due to the reaction effect at the bottom, renders were partially directly loaded.

Direct loading of both straw bale and render

As in the tests for unrendered straw bale, load was applied to both straw bale and render simultaneously via the top spread platform.

The purpose of using different loading regimes is to investigate what is the best way that a straw bale wall should be loaded? Will there be a need to isolate the render from any direct loading transferred from floor or roof? Or will there be any additional gain in terms of strength if both the bale and render are loaded simultaneously? Observation in the preliminary study on the full-scale wall has indicated that it could be advantageous to load the straw bale only. This way, it will prevent premature occurrence of cracks on the render, which otherwise will happen due to the brittle nature of the render, especially with cement based render. As the straw bale wall is compressed the whole render layer will move down relatively freely like a curtain and avoiding cracking and damage.

4.3 Test observation and result discussion

Tests results for six rendered straw bales were presented below. Similarly they were graphed in the form of stress vs. strain for easy comparison in Figure 9. They were also presented as load vs. shortening and load/m wall vs. strain for ease of interpretation in the Appendix. Specimens No. 8 and 11 adopted the loading regime, where both straw and render were loaded directly.

Comparing with the unrendered test, it can be seen that the strength was increased, especially for Stage 2 of the test, where the strength can translate into real benefit for design. Interestingly, there was almost indistinguishable difference between the earth render and the cement render until the specimens had cracked extensively (15% of strain value).

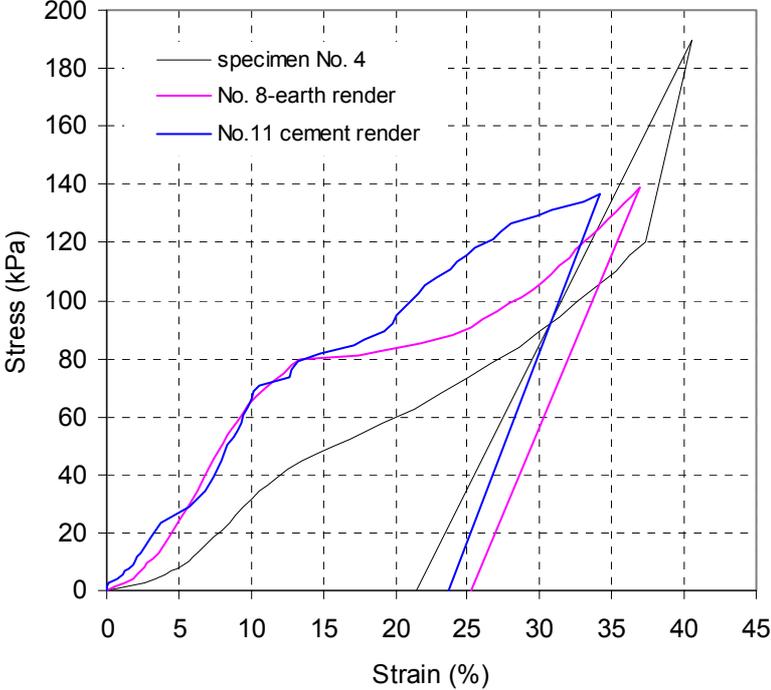


Figure 9 Stress vs. strain for rendered strawbales

The following photographs depict the interesting behaviour for the rendered specimens (Figures 10-16).



Figure 10 ‘Sinking-in’ of the top-loading frame (Note how render has behaved)



Figure 11 Final compressed state of earth rendered strawbale



Figure 12 Cracking in earth render at the end of the test



Figure 13 Difference in adhesion on two sides of the bale



Figure 14 Loading of both bale and cement render directly (note cracking pattern)



Figure 15 Destruction of cement render



Figure 16 Bonding between straw and cement render

5. COMPARISONS OF RESULTS

All the tests were plotted in Figure 17 as stress vs. strain. It is clear that comparing with unrendered specimens, render does offer some strength gain whether it is earth render or cement render. Different loading paths do not appear to have significant impact on the behaviour, although observation indicates that it does affect the timing of cracks.

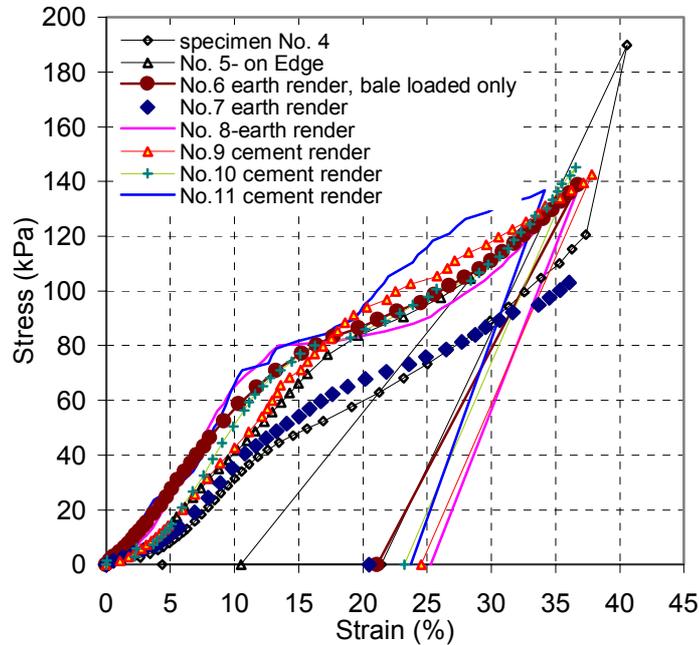


Figure 17 Comparison of all test results

6. CONCLUSIONS AND RECOMMENDATIONS

11 strawbales were tested under compression. 5 were unrendered. These were the reference for comparison. Of these 5, 3 were tested under three low cycles of loading and unloading. 6 others were rendered with either earth render or cement render. Tests for rendered specimens followed various loading regimes.

Test results shown that there were generally 4 distinct stages in the loading response of unrendered bale. A linear trendline can be established accurately for each of the stages, this is useful in that it provides a mathematical model for the structural response of the straw bale by different producers, i.e. the ‘characteristic’ of straw bales from each source can be established individually using the mathematical model developed here.

The model developed here also provides for the theoretical basis regarding the optimum amount of pre-compaction to be adopted in the practical wall erection. A typical value of 3-4% would be sufficient to improve the performance of the wall significantly. This translates into 80-100 mm for a 2700 mm high wall. Anything more than this would be unnecessary and becomes difficult to achieve in practice.

From the test results it can be concluded that straw bales have excellent properties under low frequency cyclic loading, even at relatively high amplitude. Test results shown that straw bales, regardless of whether it is rendered or not, do have a distinct failure point (at the end of Stage 2) indicated by the significant plateau in the stress strain curve. However, different from the

common familiar plastic flow as seen in steel after yielding, strawbales can further develop significant amount of strength after the ‘yielding’ (Stage 3). The exciting behaviour of hardening seen at the higher strain, although having little significance for service load design, does offer a significant safety buffer and energy dissipation if overloading does occur.

Comparing with unrendered bales, rendered strawbales provide a reasonable amount of increase in strength and in stiffness. Cement render has no significant difference in strength gain when compared with earth render, though cement render does appear to defer the occurrence of cracks longer than the earth render. Different loading regimes for the rendered test do not make a significant difference in the load resistance behaviour.

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The results presented here form part of a major research effort at the Construction Laboratory, University of Western Sydney, to investigate the behaviour of straw bale building system under various conditions. The grant provided by the School of Construction, Property and Planning under the headship of A/Professor Graham Miller made this research possible. The technical assistance of Mr Steve Overmyer, the senior technician and Mr Brett Roddy, the Laboratory Manager for the straw bale test is greatly appreciated. The stimulating discussion with the author’s colleagues, especially Mr Mike Faine, made this research particularly enjoyable.

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APPENDIX

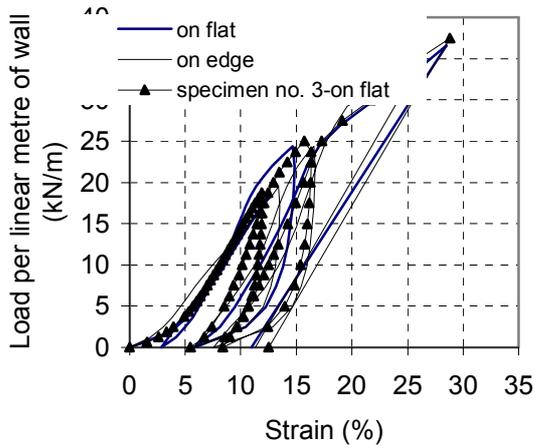


Figure 18 Load per metre wall

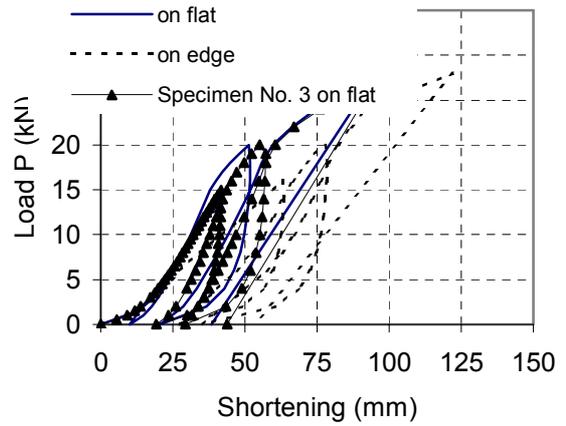


Figure 19 Load vs. deformation

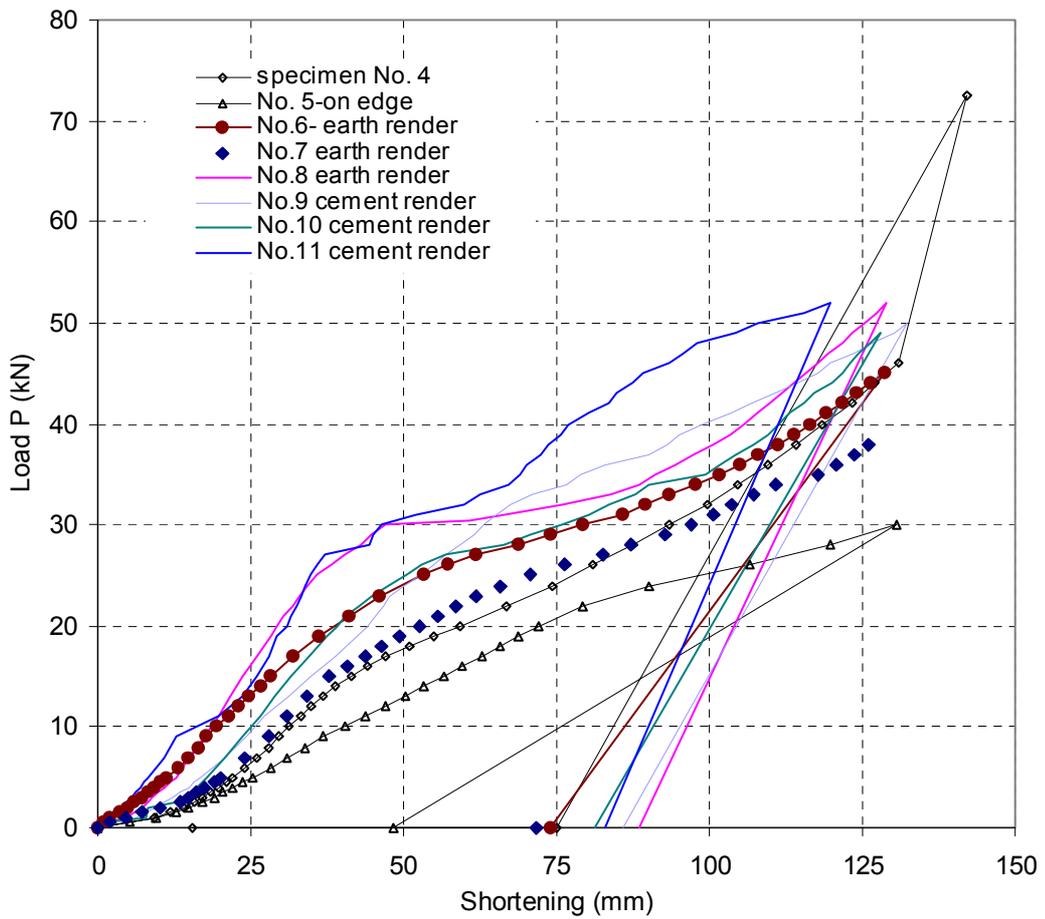


Figure 20 Comparison of all test results

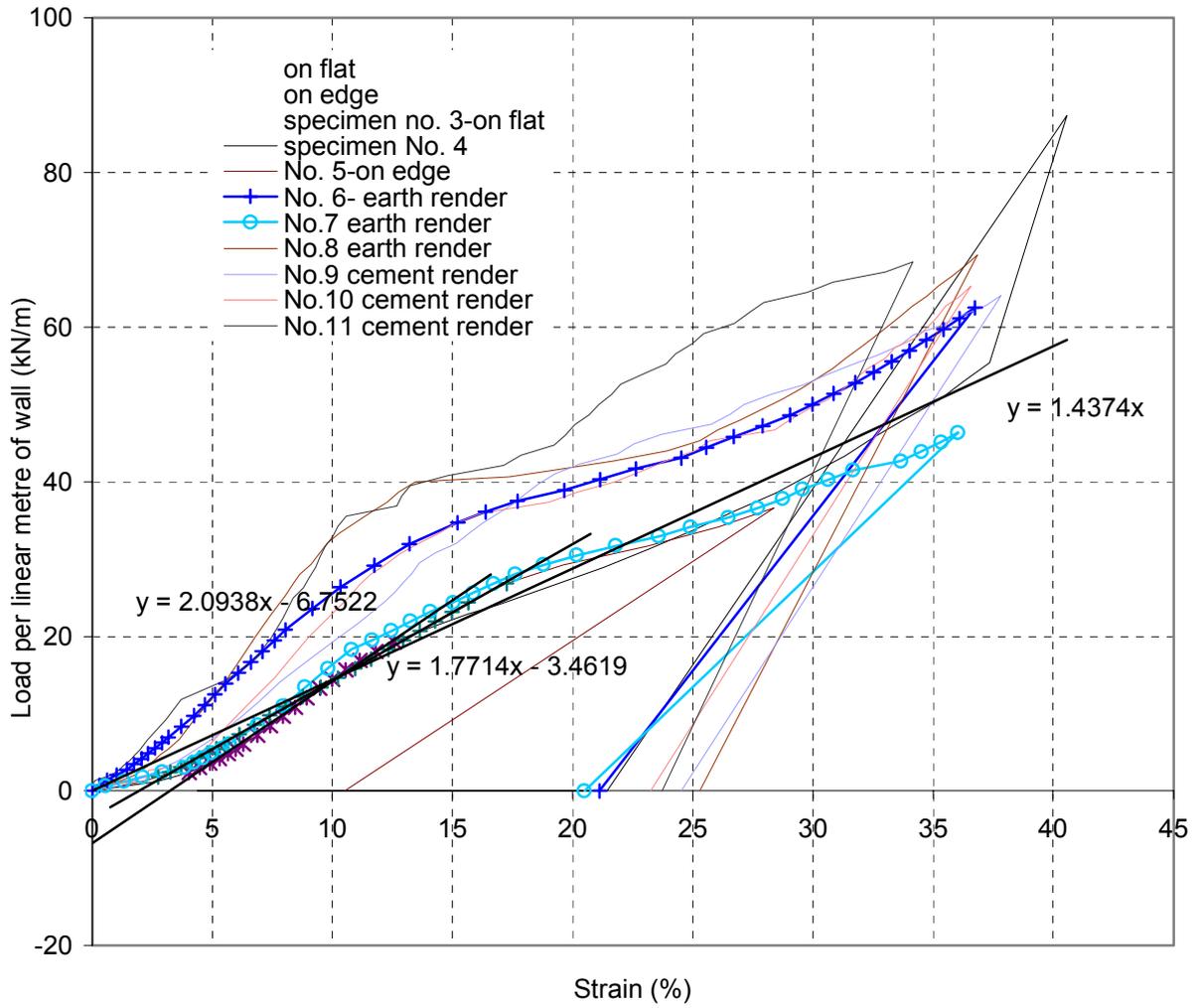


Figure 21 Comparison of all test results