STRUCTURAL TESTING OF PLASTERS FOR STRAW BALE CONSTRUCTION

December 8, 2003
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ABSTRACT

Over the past hundred years, plastered straw bale construction has shown itself to be strong and durable in both load-bearing and post-and-beam structures. In load-bearing straw bale systems, the relatively strong, stiff plaster plays a significant role as it works together with the ductile straw bale core to function as a stress skin panel, resisting compressive, in-plane and out-of-plane loading. In post-and-beam straw bale systems with properly detailed connections, the plaster can act as a shear wall, resisting in-plane lateral loads. The final strength of these wall systems depends both on plasters and straw bales. The following tests begin to show the basic structural capacity of a variety of plasters.

INTRODUCTION

WHY PLASTERS MATTER

Plasters serve many functions in a wall system. They:

- Protect the underlying surface
- Permit or prevent the migration of vapor or liquid moisture
- Prevent the migration of air currents
- Carry structural loads

In straw bale walls, the relatively strong, stiff plaster plays a significant role as it works together with the ductile straw bale core to function as a stress skin panel. But before we can understand, analyze and model the structural performance of plastered straw bale walls, we must test and understand its elements-straw bales and plasters. The following tests begin to show the basic structural capacity of a variety of plasters.

TYPES OF PLASTER

Plasters are composed of a binder (e.g. clay, cement, lime) and fillers (sand, aggregate, fiber, etc). Plasters can be divided into two main categories

- those with a binder that undergoes a chemical reaction (such as cement, lime, or gypsum)
- those with a binder that does not react chemically (such as clay)

In structural terms, cement, lime, gypsum, and clay-based plasters form a continuum from strong to weak and from brittle to ductile respectively. Cement-based plasters are very strong and resistant to erosion, but often crack near openings (windows, doors, etc.) and corners because they are very brittle when compared to the straw bale wall core. Clay-based plasters are weaker and erode easily, but their relative ductility makes them a better structural match with straw bale walls.

Because cement based plasters have been tested extensively, EBNet focused its testing research on lime and earth based plasters.

EARTH PLASTER – SOIL ANALYSIS AND PLASTER COMPOSITION

SOIL ANALYSIS

Intent

To analyze and describe the soil used in the earth plaster mixes.

Background information

Soils are classified based on their Atterberg Limits (see below) and on particle size as determined by sieving:

gravel	> 4.7mm
sand	> 0.76mm
silt	> 0.002mm
clay	< 0.002mm

Some clay mineral grains are larger than 0.002mm and some soils finer than 0.002mm have no clay minerals.

Atterberg Limits are used to describe the shrinkage limit, plastic limit, and liquid limit of a soil. As water is added to a dry soil, the soil changes from solid to semi-solid to plastic to liquid. The moisture content in the soil at the threshold between semi-solid and plastic is called *the plastic limit*. The moisture content in the soil at the threshold between plastic and liquid is called the *liquid limit*. Subtracting the plastic limit from the liquid limit yields the plasticity index.

A large Liquid Limit indicates high compressibility and high shrink swell tendencies (clay rich soils). A large Plasticity Index indicates low shear strength (clay rich soils). Clayey soils generally have a PL > 20, and a LL > 40. The Plasticity Index can be lowered by adding sand and raised by adding clay.

The following particle size analysis and Atterberg Limits were performed on the base soil, before the additions of sand and chopped straw that make it into a viable plaster. Many different kinds of clayey soils have been used successfully for earth plasters by altering the additions of sand and chopped straw. See Formulations below.

Results of the Soil Testing for Sample Soil

Particle Size Analysis:

- 00.2% Gravel
- 17.1% Sand
- 30.9% Silt
- 51.8% Clay

Atterberg Limits:

Liquid Limit	46
Plastic Limit	18
Plasticity Index	28

FORMULATIONS OF EARTH PLASTER MIXES

Earth plaster mixes vary widely depending on location, available soils, practitioner and application method. Hand applied plasters have a generally higher ratio of straw while machine applied plasters have more sand because straw clogs the application nozzle.

We experimented with several local soils and chose one with a high percentage of clay (see particle analysis above). The soil also contained a relatively high percentage of silt – more than would be desirable in an optimum earth plaster. We chose to work with this soil, in spite of its high silt content, in order to replicate field conditions and test a moderately strong earth plaster rather than a very strong earth plaster.

The clay rich soil was soaked in water to yield a clay slip and then mixed with plaster sand provided by the Shamrock Company of Petaluma and chopped rice straw as reflected in the charts below. The mixes below are representative of the types of plasters currently in use in straw bale construction. For the larger scale structural tests we chose a representative earth plaster near the center of the spectrum that could be applied by hand or by machine.

Earth Plaster Samples – Composition by Dry Volume				
Sample	**Soil**	**Sand**	**Chopped Straw**	**Notes**
A	**1**	**0**	**3**	
B	**1**	**0.75**	**2.25**	**Best Machine Application**
C	**1**	**1**	**2**	**Possible Machine Application, Possible hand application**
D	**1**	**1.5**	**1.5**	**Best hand application**
E	**1**	**2**	**1**	
F	**1**	**2.25**	**0.75**	
G	**1**	**3**	**0**	
1.00 part dry clay soil = 1.33 parts Clay Slip				

Earth Plaster Samples - Composition by percentage				
Sample	**Clay**	**Silt**	**Sand (from soil and additional)**	**Chopped Straw**
A	13%	8%	4%	75%
B	13%	8%	23%	56%
C	13%	8%	29%	50%
D	13%	8%	41%	38%
E	13%	8%	54%	25%
F	13%	8%	60%	19%
G	13%	8%	79%	0%

PORTLAND CEMENT-LIME PLASTER COMPOSITION

The portland cement-lime mix consisted of 1 part portland cement, 1 part lime and 6 parts sand, with just enough water added to produce a workable mix for plastering. This mix produced a "portland cement-lime plaster" conforming to the specifications in Chapter 25 of the 2000 Uniform Building Code and referred to in the California Straw Bale Construction Guidelines (Sections 18944.30 through 18944.41 of the California Health and Safety Code). The cement was portland cement type 1, the lime was "High Calcium Hydrated Lime" manufactured by the Chemical Lime Company of Scottsdale Arizona and the sand was washed plaster sand provided by the Shamrock Company of Petaluma.

The "High Calcium Hydrated Lime" consisted of 92% calcium hydroxide and 8% inert products. Note that this is not "Type S" lime where virtually all the lime and the other various oxides are completely hydrated in a special double hydration process under optimal pressure and temperature conditions. It is possible that the unhydrated oxides in limes other than Type S lime rob some of the water added to the plaster mix that should hydrate the portland cement, thus yielding a weaker plaster than that made with Type S lime. We believe that a portland cement lime plaster produced with Type S lime would yield a plaster with about twice the compressive strength of our plaster. This belief is based both on some our field-testing with Type S portland cement-lime plaster and examination of other published values. It should be further noted that portland cement-lime plaster gains significant strength over the years as the calcium hydroxide hydrates to produce the stronger calcium carbonate.

Due to the low portland cement-lime plaster test values, we used a quikrete premixed stucco mix consisting of 1 part plaster cement to 3 parts plaster sand for our medium-scale and large-scale tests. The mix for this plaster conformed to the UBC definition of "portland cement plaster" and is specified in the reports for those tests.

STRUCTURAL TESTS

SHRINKAGE

Intent

This test was designed to measure the shrinkage of an earth plaster. Clay (the binder in earth plaster) is a hydrophilic material that expands when wet and contracts as it dries. The expansive properties of clay can be tempered in a plaster by additions of aggregate (sand) and/or fiber (chopped straw). Different clays are naturally more or less expansive. This test measures the overall shrinkage of a particular plaster, sample C. This test can be used to predict cracking behavior and/or to examine the relative performance of different earth plaster mixtures – with differing proportions of clay soil-sand-fiber or with differing clay soils.

Test Protocol

This test is akin to ASTM D4943-95, but was designed to be carried out in the field by a layperson with limited specialized equipment (See Building with Earth, by John Norton, 1997).

Description of Test

The earth plaster was packed in a wooden box with interior dimensions of 2" wide x 2" high x 24" long. The box had sides, but no top or bottom and the inside surfaces of the box were smooth to avoid bonding between the wood and the plaster. The plaster was mixed to the same consistency that is used for application in the field, tamped firmly into the box and the top surface was screeded off level with the top of the box.

The sample was completely dried (56 days). The shrinkage was measured by pushing all of the sample (including separated lumps) tightly up to one end of the box and measuring the gap created by the shrinkage.

Results of Shrinkage Testing

The shrinkage for sample C was 0.1875 inch (3/16 inch) in the 24 inch mold. The whole sample held together and a crack opened all on one end of the mold.

EROSION

Intent
This test was designed to show the relative erosion rates of three types of plaster – one with high sand content and no straw (sample G), one with a medium sand content and a medium straw content (sample C), and one with a low sand content and a high straw content (sample B).

Test Protocol
No comparable test protocol was found in a search, so a test was designed for the stated purpose, and is not based on any ASTM specification. The test was designed to be carried out in the field by a layperson with limited specialized equipment (See Building with Earth, by John Norton, 1997).

Description of Test
A fully dry earth plaster block (12 inches x 12 inches x 2 inches) was placed at a 30° angle, supported on the high end by a brick . Water was dripped at a rate of 1 gallon per hour from a height of 4.5 feet onto the center of the block. The block was positioned above a catchment trough so that the dripped water could be collected and the block was not sitting in water. The test was conducted outside on a slightly windy day and the water dripped in an irregular circle, approximately 6 inched in diameter. At regular intervals, the depth of the eroded indentation in the block was recorded, along with descriptions. The test ended when the block collapsed or disintegrated. At the end of the test, the total amount of the dripped water was collected and measured. One block of each sample was tested.

Earth plaster block, sample C at the beginning of testing.

Results of Erosion Testing

Sample	Time	Depth of deepest erosion (inches)	Notes	Time to Failure (hours)	Total water to failure (gallons)
A	0:05	0.98			
	0:10	1.06			
	0:15	1.18			
	0:25	1.38			
	0:30	1.46	1/3 of block melting away at lower edge		
	0:35	1.54			
	0:40		**total disintegration**	**0:50**	**0.63**

C	0:05	0.39	straw exposed, large sand loosening, straw cushioning drip		
	0:15	0.66	large sand visible with straw		
	0:30	0.78			
	0:45	0.83			
	1:15	0.87			
	1:45	**0.87**	**large crack through block**	**1:15**	**1.23**

G	0:05	0.08	straw exposed, cushioning drip		
	0:15	0.01			
	0:30	0.35			
	0:45	0.47	straw only visible on top face of block		
	1:00	0.47			
	1:45	0.59			
	2:15	0.79			
	2:45	0.79			
	3:15	0.79			
	4:00	0.98			
	4:30	0.98			
	5:00	0.98			
	5:30	0.98			
	6:00	**0.98**	**Failure: block slumped slightly, but still maintained shape**	**6:00**	**6.2**

Erosion pattern of earth plaster sample G. The soil without straw reinforcement just melted away.

Erosion pattern of earth plaster sample A. The straw-rich block held its shape for six hours.

Preliminary Conclusions

The earth plaster with high straw content performed over six times better than the earth plaster without straw, both in terms of duration and total amount of water dripped, because the straw cushioned the dripping water and also prevented the formation of large erosion channels. The interwoven nature of the straw also holds the shape of the block even when it is totally saturated.

The earth plaster block without straw disintegrated in less that one hour (0:50), because the clay became saturated then washed away quickly, releasing the aggregate (sand). As the sand was exposed, it cushioned the drip of water slightly, but did not slow the erosion by much.

This test conforms to my own field observations of vernacular buildings (China, Korea, Argentina) and with anecdotal evidence from professionals who are using earth plasters. Large quantities of straw in an earth plaster will slow down erosion by distributing the water in many directions rather than allowing it to concentrate in rivulets. An earth plaster without straw is much more vulnerable to erosion.

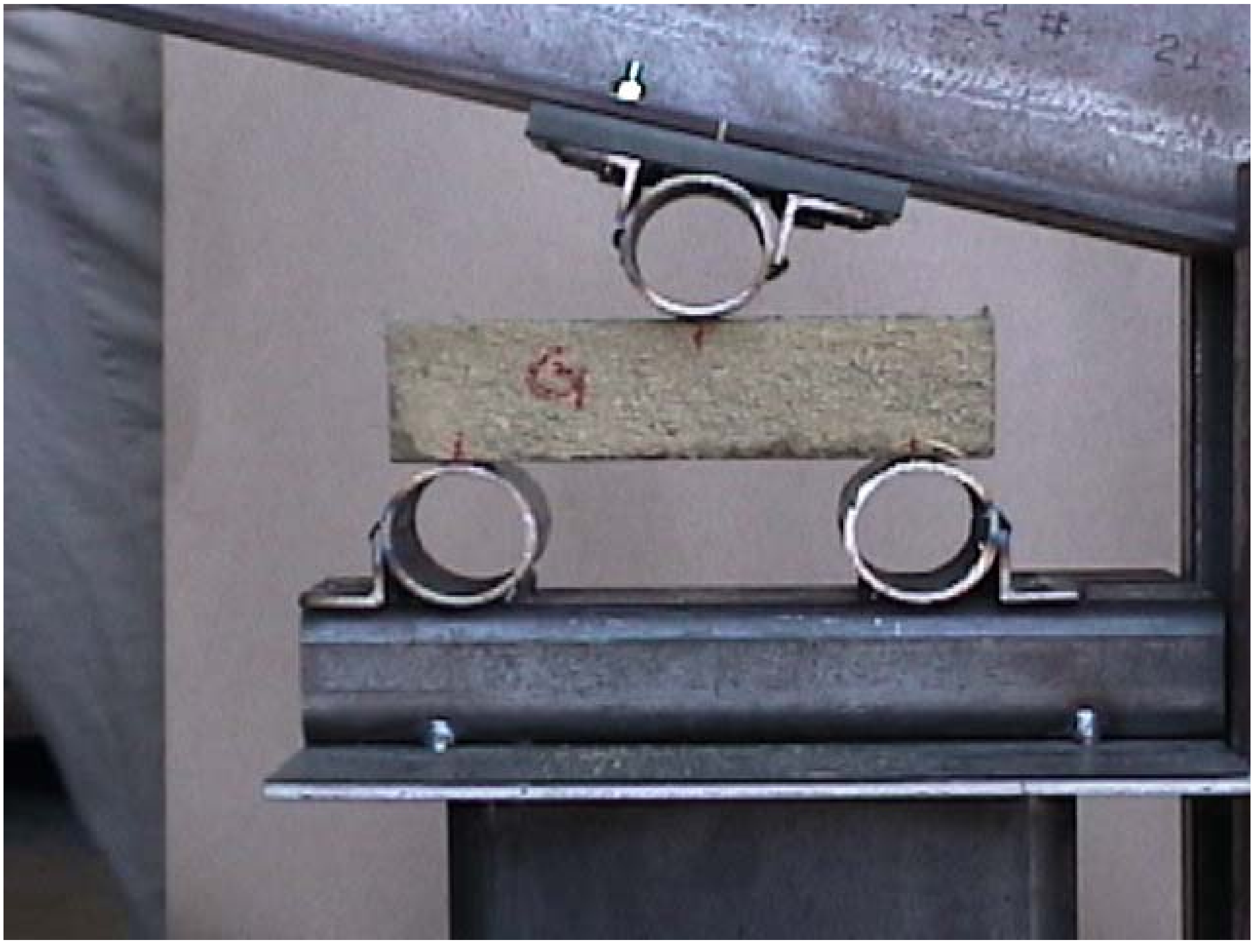
OVERVIEW OF COMPRESSION AND MODULUS OF RUPTURE TESTS

Compression and Modulus of Rupture testing of earth plaster samples was done both by AME (Applied Materials & Engineering of Oakland, CA) and field tested at the Parr Street Warehouse leased by EBNet (the Ecological Building Network of Sausalito, CA) for the testing program. The tests executed by AME were done in controlled conditions according to ASTM standards (ASTM C109 for the compressive tests and ASTM C293 for the modulus of rupture tests). The tests executed at the Parr Street Warehouse were undertaken less rigorously utilizing a field-testing devise affectionately named—and henceforth referred to as—"the nutcracker." This procedure allowed for the preliminary testing of a broad range of earth plaster mixes and determining their relative strengths before proceeding to the lab tests and large scale tests with the optimal mixes.

The nutcracker operated on the simple lever principle, where a load placed at the end of the lever arm 50 inches from the hinge was magnified by five when applied to the sample ten inches from the hinge. For the modulus of rupture tests this mechanical advantage was reduced to 4.74 due to the 13-degree upward angle of the lever arm when the steel half-round was added to apply a point load to the sample. Also in the modulus of rupture tests a value of ten pounds was subtracted from the calculated load at the sample to allow for friction loss at the hinge. This friction-loss value was determined by reading the load delivered to a scale at the sample location (ten inches from the hinge) and comparing it to the calculated expected load. For the compression tests, the friction loss was taken into account in the initial reading. Refer to the discussion below.

Following are photos of the nutcracker as built, with detailed photos of the modulus of rupture and compression configurations. Note how the modulus of rupture configuration causes the 13-degree upward angle of the lever arm, resulting in a reduction of the mechanical advantage from 5 to 4.74.

The nutcracker in the MOR configuration with counterweight installed



Modulus of rupture configuration. Two-by-two-by-eight inch sample spans six inches between two-inch pipes. Load applied to sample by two-inch pipe bolted to bottom of lever arm beam. Sample placed such that top of sample is level with hinge and load from pipe is applied vertically.

Compression configuration. Two-inch cube sample placed on 2x4 tube steel between two-inch pipes. Load applied to sample directly from bottom flange of lever arm beam. Sample placed such that beam is level and load is evenly applied.

COMPRESSION TESTS

Intent

Three or more two-inch cube samples of each of the seven earth plaster mixes specified above (mixes A through G) were tested for compressive strength. These samples were field-tested with the "nutcracker" apparatus described above. The preliminary results of these tests were used to select two earth plaster mixes for further testing by testing lab. Also, two-inch portland cement-lime plaster cubes were tested for compressive strength at three dates at the testing lab.

Test Protocol

Compression testing of plaster cubes at the testing lab was conducted according to ASTM C109 "Standard Test Method for Compressive Strength of Hydraulic Cement Mortars (Using 2-in. Cube Specimens)." Testing was conducted using a calibrated United universal testing machine. Field-testing using the "nutcracker" was based on ASTM C109.

Description of Tests

The lab tests are adequately described above in the protocol description. Four portland cement-lime samples were tested at 18 days, four were tested at 29 days and four were tested at 57 days. Six samples earth plaster mix C and six earth plaster mix E were tested at 57 days.

For the nutcracker tests, refer to the detail photo of the compression configuration. The two-inch cube samples were placed on the 2x4 tube steel inserted between the two-inch pipes. The samples were located so that both the upper surface of the sample and the bottom flange of the lever arm beam were level at the point of application of the load. In this way, load was applied uniformly to the sample from the bottom flange of the beam. The bottom of the beam was also nearly level with the hinge, ensuring that the load was applied vertically to the sample. Before applying load, the samples were cleaned of loose material so the contact surface was as even as possible.

As described in the overview, loads were applied by adding free-weights to a steel rod attached to the end of the lever arm beam 50 inches from the hinge. Since the sample was 10 inches from the hinge, the lever advantage was 5, meaning a one pound load at the end delivered five pounds to the sample. To account for the self-weight of the system, an initial measured scale reading of 30 pounds at the beam end was considered as equivalent to an initial applied load of 30 pounds on a weightless beam. It should be noted that since this was a scale reading, the friction loss in the system (assuming friction was an absolute and not a proportional value) was already accounted for in the initial 30 pound reading. In other words, 30 pounds read on a scale 50 inches from the hinge represented 150 pounds of actual load delivered to the sample 10 inches from the hinge. Further free-weight added to the beam end added a straight 5:1 mechanical advantage to the sample, with friction already taken into account in the initial 30 pound reading.

Weight was added in 2.5 pound increments to the lever end with at least 5 seconds between loads. Load delivered to the sample equaled 5 times the applied load (including the 30 pound initial load). Compressive stress in the sample equaled the sample load divided by the loaded surface area (width times length). Failure was defined as a 1/8 inch height reduction (6.25%). If the sample received load beyond the failure point, the final load is shown in the results. All samples were tested at thirty days.

Results of Compression Testing

EBNET - COMPRESSIVE STRENGTH TESTS

ALL UNITS IN POUNDS AND INCHES - COMPRESSIVE STRESS IN PSI

Lever Arm Ratio = 5.00

Age of all samples - 30 days

Failure Definition = Sample height reduced by approximately 1/8"

Note: the lever load includes an initial scale measured self weight value of 30 lbs

Sample	Height	Width	Length	Weight	Failure Lever Load	Failure Load	Failure Stress (psi)	Avg. Fail Stress (psi)	Final Lever Load	Final sample Ht.	Final Load	Final Stress (psi)	Avg. Final Stress (psi)
A1	1.94	1.94	1.94		55.0	275	73		460.0	1.00	2300	611	
A2	1.94	1.94	1.94	121.4	55.0	275	73		600.0	0.88	3000	797	
A3	2.03	2.03	1.88	140.2	130.0	650	170	105	440.0	0.94	2200	576	662
B1	1.97	2.00	2.09	185.9	115.0	575	138		360.0	1.06	1800	431	
B2	1.97	1.97	2.03	182.7	142.0	710	178		245.0	0.81	1225	306	
B3	2.00	2.00	2.00	191.7	105.0	525	131	149	245.0	0.53	1225	306	348
C1	2.03	2.03	2.09	211.3	155.0	775	183		270.0	1.44	1350	318	
C2	2.03	2.00	2.16	200.5	117.0	585	135		130.0		650	150	
C3	1.97	1.97	2.06	187.0	105.0	525	129	149	115.0		575	142	
C4	2.00	2.00	2.09	195.8					160.0	1.5	800	191	
C5	2.00	2.00	2.13	200.0					165.0	1.59	825	194	
C6	2.00	2.00	2.09	197.9					165.0	1.59	825	197	
C7	2.00	2.00	2.06	202.2					160.0	1.47	800	194	
C8	2.00	2.00	2.06	197.6					167.5	1.44	838	203	
C9	2.00	2.00	2.09	201.6					160.0	1.62	800	191	198
D1	2.00	2.03	2.13	238.8	145.0	725	168						
D2	2.03	2.00	2.03	227.6	105.0	525	129						
D3	2.00	2.00	2.00	222.5	110.0	550	138	145					
E1	2.03	2.03	2.13	246.1	147.5	738	171						
E2	2.03	2.03	2.19	255.3	135.0	675	152						
E3	2.03	2.06	2.13	238.9	120.0	600	137	153					

F1	2.03	2.03	2.06	254.3	135.0	675	161						
F2	2.06	2.03	2.09	241.3	120.0	600	141						
F3	2.03	2.06	2.19	253.6	132.5	663	147	150					
G1	2.03	2.06	1.94	260.0	135.0	675	169						
G2	2.09	2.06	2.13	259.3	100.0	500	114						
G3	2.03	2.03	2.25	250.6	97.5	488	107	130					

AME - COMPRESSIVE STRENGTH TESTS

ALL UNITS IN POUNDS AND INCHES - COMPRESSIVE STRESS IN PSI
PCL=Portland cement-lime plaster; C and E are earth plasters
2 inch plaster cubes tested per ASTM C109

Sample	Age(days)	Area	Ultimate Load	Ultimate Stress	Avg Ult. Stress
PCL1	18	4.0	990	248	
PCL2	18	4.0	975	244	
PCL3	18	4.0	1200	300	
PCL4	18	4.0	1380	345	284
PCL5	29	4.0	1200	300	
PCL6	29	4.0	1020	255	
PCL7	29	4.0	1200	300	
PCL8	29	4.0	1170	293	287
PCL9	57	4.1	930	227	
PCL10	57	4.1	1200	293	
PCL11	57	4.1	1060	259	
PCL12	57	4.3	1280	298	269
C1	57	3.9	660	169	
C2	57	3.9	895	229	
C3	57	4.6	560	122	
C4	57	3.9	400	103	
C5	57	4.5	420	93	
C6	57	3.9	400	103	136
E1	57	4.0	410	103	
E2	57	4.1	390	95	

E3	57	4.0	390	98	
E4	57	4.1	390	95	
E5	57	4.1	295	72	
E6	57	4.1	360	88	92

Preliminary Conclusions

The results from the EBNet testing indicate similar strength among the earth plaster mixes that might be considered workable; that is, all mixes except for the extremes of no sand (mix A) and no straw (mix G). At the extremes, the mixes with more straw and less sand tended to "fail" due to their flexibility, and would reach the 1/8 inch height reduction more easily. Indeed, many of the A,B and C samples would never reach a point of ultimate failure, but would just flatten out as more load was applied. The mixes with more sand and less straw exhibited brittle failure, with the no-straw mix G showing less strength.

The results from the AME testing generally agreed with the EBNet earth plaster results. Since AME defined failure as the point of non-linearity, the values are somewhat lower. The relationship between the AME failure stress on C and E (136psi and 92psi) is similar to the relationship between the EBNet ultimate stress on C and E (198psi and 153psi). Again, the general tendency is that higher straw yields greater strength (until the extreme is reached).

The results from the AME portland cement-lime plaster were lower than expected, probably due to the use of non-type S lime, as previously discussed. The tested values were about 280psi compared to expected values of about 500-600psi for plaster with type S lime. Also, the final group was tested at 57 days, and we would expect significant strengthening of the cement-lime plaster over months and years due to the gradual carbonation of calcium hydroxide into calcium carbonate.

In general, it should be noted that the number of tests was too small to establish a reasonable statistical spread or compute a meaningful standard deviation as the basis for exploring values for capacity reduction factors for ultimate design or factors of safety for allowable stress design. In the absence of a more exhaustive testing program, if a small sample of tests such as these is used as the basis of design, a very large factor of safety (in the order of 8 to 10) should be used to account for the uncertainty of statistical spread. This comment would apply to modulus of rupture values as well.

MODULUS OF RUPTURE

Intent

Three or more 2x2x8 inch samples of each of the seven earth plaster mixes specified above (mixes A through G) were tested for modulus of rupture strength. These samples were field-tested with the “nutcracker” apparatus described above. The preliminary results of these tests were used to select two earth plaster mixes for further testing by testing lab. Also, 2x2x8 inch portland cement-lime plaster samples were tested for modulus of rupture strength at the testing lab.

Test Protocol

Modulus of rupture testing of 2x2x8 inch samples at the testing lab was conducted according to ASTM C293 “Standard Test Method for Flexural Strength of Concrete (Using Simple Beam With Center-Point Loading).” Testing was conducted using a calibrated United universal testing machine. Field-testing using the “nutcracker” was based on ASTM C293.

Description of Tests

The lab tests are adequately described above in the protocol description. Six portland cement-lime samples, six earth plaster mix C samples and six earth plaster mix E samples were tested at 57 days.

For the nutcracker tests, refer to the detail photo of the modulus of rupture configuration. The 2x2x8 inch samples were placed to span six inches between the two-inch pipes. Load was applied to the mid-span of the samples with a two inch pipe attached to the bottom of the lever arm beam The samples were located so that the upper surface of the samples were level with the hinge, ensuring that the point load was applied vertically to the sample from the pipe. Before applying load, the samples were cleaned of loose material so the contact surface was as even as possible.

As described in the overview, loads were applied by adding free-weights to a steel rod attached to the top end of the lever arm beam 50 inches from the hinge. Additionally, loads were placed to the top of the steel beam directly over the sample. Note that the modulus of rupture configuration causes the 13-degree upward angle of the lever arm, resulting in a horizontal distance to the beam end of (50)(cos13)-(6)(sin13)=47.4. Since the sample was 10 inches from the hinge, the lever advantage was 4.74, meaning a one pound load at the end delivered 4.74 pounds to the sample. Since it was necessary to apply small loads to the MOR samples, the lever arm was counterbalanced with weight on the opposite side of the hinge so that no initial load was applied to the sample before adding load. In all cases a value of ten pounds was subtracted from the calculated load at the sample to allow for friction loss at the hinge. This friction-loss value was determined by reading the load delivered to a scale at the sample location (ten inches from the hinge) and comparing it to the calculated expected load.

Weight was added in 2.5 pound increments directly over the sample with at least 5 seconds between loads. After ten pounds had accumulated above the sample, this load was removed and a 2.5 pound load was placed at the end of the lever arm. Loading continued in this manner until failure occurred. Load delivered to the sample (P) equaled the load applied over the sample plus

4.74 times the load applied to the lever end minus 10 pounds for friction loss. Given the 6 inch span and sample breadth b and depth d, modulus of rupture stress in the sample equaled the $9P/bd^2$. In all cases, failure clearly occurred when the sample was unable to hold vertical load. All samples were tested at thirty days.

Results of Modulus of Rupture Testing

EBNET - MODULUS OF RUPTURE TESTS

ALL UNITS POUNDS AND INCHES - MOR IN PSI   Age of all samples - 30 days
Span (L) = 6.0 inches   Lever Arm Ratio = 4.74   Friction Loss at Sample = 10.0 lbs
$MOR=3PL/2bd^2$ psi

Sample	Breadth	Depth	Load on Lever	Load over Sample	Failure Load	MOR (psi)	Average MOR (psi)
	b (in)	d (in)			P (lbs)		
A1	2.03	1.97	20.0	30.0	115	131	
A2	2.09	1.94	25.0	2.5	111	127	
A3	2.00	2.03	20.0	0.0	85	93	117
B1	2.13	2.00	20.0	15.0	100	105	
B2	2.00	1.97	15.0	20.0	81	94	
B3	2.13	2.00	15.0	17.5	79	83	94
C1	2.19	2.00	15.0	30.0	91	94	
C2	2.13	2.00	20.0	7.5	92	98	
C3	2.09	1.97	15.0	20.0	81	90	94
D1	2.25	1.94	15.0	15.0	76	81	
D2	2.19	2.03	15.0	7.5	69	68	
D3	2.19	2.03	15.0	0.0	61	61	
D4	2.19	2.00	15.0	5.0	66	68	70
E1	2.00	2.09	10.0	20.0	57	59	
E2	2.06	2.22	10.0	17.5	55	49	
E3	2.06	2.13	10.0	27.5	65	62	57
F1	1.97	2.25	7.5	20.0	46	41	
F2	2.00	2.25	7.5	27.5	53	47	44

G1	2.22	2.00					
G2	2.22	2.06	12.5	5.0	54	52	
G3	2.09	1.97	7.5	17.5	43	48	50

AME - MODULUS OF RUPTURE TESTS

ALL UNITS POUNDS AND INCHES - MOR IN PSI   Age of all samples - 57 days
PCL=Portland cement-lime plaster; C and E are earth plasters
2x2x8 inch plaster samples spanning 6 inches with center point load tested per ASTM C293
$MOR=3PL/2bd^2$ psi   Span (L) = 6 in.

Sample	Breadth	Depth	Ultimate Load	MOR (psi)	Average MOR (psi)
	b (in)	d (in)	P (lbs)		
PCL1	2.32	2.04	192	179	
PCL2	2.25	2.07	252	235	
PCL3	2.29	2.06	248	230	
PCL4	2.23	2.07	228	215	
PCL5	2.26	2.03	168	162	
PCL6	2.30	2.06	220	203	204
C1	2.16	1.92	76	86	
C2	2.15	1.95	84	92	
C3	2.09	1.95	64	72	
C4	2.14	1.90	72	84	
C5	2.14	1.93	82	93	
C6	2.14	1.95	72	80	84
E1	2.13	2.00	68	72	
E2	2.25	1.97	50	52	
E3	2.13	2.00	54	57	
E4	2.05	1.92	55	66	
E5	2.10	1.98	62	68	
E6	2.14	1.99	64	68	64

Preliminary Conclusions

The results of both the EBNet and AME testing of earth plasters indicate a strong correlation between increased straw content and increased MOR strength. This would suggest that the optimally strong earth plaster mix would be one with as much straw as possible while maintaining plaster workability. The results from the AME testing generally agreed with the EBNet earth plaster results. The somewhat higher EBNet values may be due to the fact that the two-inch pipe supports and load point spread the point loads out a bit on the sample, resulting in a bending moment somewhat less than would be predicted by calculation (perhaps about 5%).

It is worth comparing the relationship between compressive strength, MOR strength and expected shear strength for both the earth and cement-lime plasters. If we take concrete as a model, the expected MOR=(7.5)sq.rt.(f'c) and the expected shear strength=(.5)MOR. For earth plaster C, 84=(7.2)sq.rt.(136) and expected shear strength=42psi. For earth plaster E, 64=(6.7)sq.rt.(92) and expected shear strength=32psi. These values adhere well to the concrete formula. For cement-lime plaster 204=(12.2)sq.rt.(280) and expected shear strength=102psi., so cement-lime plaster appears to have significantly more MOR strength, and by extension shear strength, than would be predicted by the concrete formula.

And finally, the previous comments about statistical spread would pertain to MOR as well as compressive values.

MODULUS OF ELASTICITY

Intent

Two six inch diameter by twelve inch portland cement-lime plaster cylinders were tested at 57 days at the testing lab for modulus of elasticity. Also three two-inch cubes of earth plasters C and D were tested at the testing lab for load-displacement relationships, with the modulus of elasticity of each sample determined from these results.

Test Protocol

Modulus of elasticity testing of portland cement-lime plaster cylinders was conducted according to ASTM C469 "Static Modulus of Elasticity and Poisson's Ratio of Concrete in Compression." Testing was conducted using a calibrated ELE testing machine. Testing of the earth plaster cubes was conducted according to ASTM C109 described above in the Compression Tests section. Load-displacement reading was taken during this testing and the results were analyzed for modulus of elasticity following the procedure of ASTM C469.

Description of Tests

The cylinder tests are adequately described above in the protocol description. The modulus of elasticity as defined in ASTM C469 is the linear portion of the stress-strain curve occurring between a 0.00005 strain and a stress of 40 percent of ultimate stress. The first data point is taken at 0.00005 strain to remove any anomalies associated with the initial loading conditions.

The load-displacement results of the plaster cubes were analyzed following a similar method, with data point one being the first reading with strain greater than 0.00005(0.0001 inches displacement) and data point two being the first reading with the load P greater than forty percent of the ultimate load. From these points, the formula for modulus of elasticity is MOE=(P2-P1)L/(Δ2-Δ1)A, with P being the load, Δ being the displacement, L being two inches, and A being the measured loaded area (approximately four inches).

Results of Modulus of Elasticity Testing

AME - MODULUS OF ELASTICITY TESTS

ALL UNITS POUNDS AND INCHES - MOE IN PSI

PCL=Portland cement-lime plaster Age of all PCL samples - 57 days

PCL samples - 6 in. diameter x 12 in. cylinders tested per ASTM C469

f1 and 1 are measured at 1(strain)= 0.00005

f2 and 2 are measured at f2(stress) = 40% Ultimate Strength

MOE=(f2-f1)/(2- 1) MOE(AME) best fit for graph points between point1 and point2

Sample	Ultimate Strength(psi)	Stress-1	Strain-1	Stress-2	Strain-2	MOE	MOE(AME)
		f1(psi)	1(in/in)	f2(psi)	2(in/in)		
PCL1	540	100	0.00005	210	0.00017	916667	979000
PCL2	570	100	0.00005	210	0.00013	1375000	1290000

ALL UNITS POUNDS AND INCHES - MOE IN PSI

C and D are earth plasters Age unknown L=2

Earth plaster samples - 2 inch plaster cubes tested for load and displacements

Earth plaster results analyzed following ASTM C469

P1 and Δ1 are measured at first reading with strain > 0.00005 (Δ>0.0001 in)

P2 and Δ2 are measured at first reading with P > 40% Ultimate Load

MOE=(P2-P1)L/(Δ2-Δ1)A

Sample	Area A(sq.in.)	Ultimate Load(lbs)	Ultimate Strength(psi)	P1 (lbs)	Δ1 (in)	P2 (lbs)	Δ2 (in)	MOE
C1	3.94	348	88	40	0.015	160	0.040	2437
C2	4.10	394	96	40	0.033	160	0.090	1027
C3	4.06	244	60	40	0.029	120	0.049	1970

D1	4.10	310	76	40	0.019	160	0.041	2661
D2	3.88	308	79	40	0.012	160	0.029	3639
D3	4.20	328	78	40	0.007	160	0.026	3008

Preliminary Conclusions

The average tested portland cement-lime plaster MOE was 1140000psi, which is very close to the value predicted by the concrete formula MOE=57000sq.rt.(f'c)=1343000psi, with the average f'c being 555psi.

The average tested earth plaster MOE values of 1811psi for plaster C and 3103psi for plaster D were about 200 times smaller than the values predicted by the same formula, indicating far more flexible behavior of earth plasters for a given strength than that of cement based plasters.

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