Effect of Straw Length and Quantity on Mechanical Properties of Cob

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Abstract:

Three experimental cob mix types are tested to determine the effect of reinforcing straw length and quantity on overall mechanical properties. High straw-content cob mixes are expected to have greater flexural and tensile capacities than a conventional control cob mix while also showing a greater ability to deform under similar loads. To determine these properties, tests for compressive, flexural and tensile strength were administered to multiple specimens of each mix type. While ductile behavior was clearly observed in the straw-reinforced specimens, a significant loss of strength was also observed in the high straw-content specimens, presumably due to loss of soil continuity.

1. Introduction:

This study is based on the theory that natural fibers add tensile strength and ductility to earthen composite materials, analogous to the ability of steel fibers to provide tensile capacity to concrete. In our investigation this theory is applied specifically to the straw reinforcement of cob, a composite also used to create adobe blocks. Cob consists of soil (with clay), sand, straw, and water, and can be created on site without the need for industrialized processes. As it is considerably less expensive than other standardized building materials and therefore very accessible, cob or adobe has been used throughout the world as a primary means of construction. In North America, there is a significant movement toward more sustainable and environmentally responsible building practices. Natural building materials are gaining more and more attention as viable alternatives to conventional building materials which consume greater energy and resources. This study aims to contribute to the growing body of research being conducted on natural materials in an effort to legitimize their widespread use.

Unreinforced concrete is a very brittle and heavy material but it has become standard practice to reinforce concrete with steel to drastically reduce its chance of catastrophic failure, especially in an earthquake. Therefore, concrete buildings around us are considerably ductile, in that they have the ability to deform and provide visual warning signs to the inhabitants within a building if the structure has become compromised. On the other hand, naturally insulating and fire- and insect-resistant conventionally reinforced cob can already exhibit desirable behavior of confinement and ductility in seismic events. This study attempts to observe and characterize the effect of increased amounts of reinforcing straw to further improve the ductility of cob.

Specifically, this study is not prescriptive. It is not intended to be a series of instructions for one to adapt into a particular structure. Rather, this is an investigation to determine the effects of straw length and volume on the mechanical properties of cob, a record of results linked to specific initial conditions. Through the use of one control mix type and two variations of high straw-clay mix types, this report intends to provide the natural building community with a record of cob performance in a particular lab setting. As cob is made of locally sourced earthen materials, it is expected that no two mix types will perform in exactly the same manner and will not have identical mechanical properties. In addition, the builder's experience and the tools and materials at hand will greatly influence the performance of cob.

2. Materials and Their Descriptions:

2.1: Cob Mix Types

The cob mix types presented in this paper explore the effect of straw content in two variations of a conventional cob mix. As seen in *Table 1* below, mix types "Long Straw" and "Chopped Straw" are so named based upon this primary variation. Additionally, the absence of added sand in both experimental mixes is the second variation from the control mix. This is due to conventional wisdom that the addition of fibers supplants the need for additional sand. However, the Conventional, Long Straw and Chopped Straw mix types have identical volumes of soil per mix and soil origin.

The soil itself, of a dark grey-brown composition, was sourced in El Sobrante, California from a private property which may have received some fill material from a local riverbed source. As the critical component of any cob mix, the soil properties were ascertained by lab tests conducted at Applied Materials & Engineering, Inc. of Oakland California. According to the Grain Size Distribution Test, the soil was composed of 6% gravel, 43% sand and 51% fines (silt and clay), while 100% of the soil was finer than a 1" sieve. According to tests for Atterberg Limits, the soil was determined to have a Liquid Limit of 52, Plastic Limit of 32 and a Plasticity Index of 20. The Plasticity Index of 20 classifies the sample within the medium-to-high range of plasticity.

The term "Wetted Soil" of *Table 1* requires some explanation. The dry soil from El Sobrante was mixed with water to create a fluid solution for two reasons. First, the water allows the dry clay and silt particles to activate and form a bond with the sand, straw and larger aggregates, which later harden into a well-mixed composite as the water evaporates. Secondly, the mix must be in a liquid state to be successfully cast into a mold. Refer to section *2.2 Mix Type Creation Procedure* for more about the creation of the wetted soil.

The asterisk in *Table 1* in the conventional mix type calls attention to the addition of 1 volumetric part sand to 1 volumetric part wetted clay to create this mix. Arithmetically these two parts should combine a total volume (3.74 ft^3) far greater than the long straw (2.6 ft^3) and chopped straw (2.87 ft^3) combined. However, in practice this total volume was seen to be much less, as the sand grains occupied the voids within the wetted soil, thus not doubling its total volume.

The sand was "Top Sand" type coarse sand obtained from Sugar City Building Materials Co. in Pinole, CA. The straw was wheat straw obtained from Golden Gate Fields Racetrack in Albany, CA.

Mix Type	Conventional	Long Straw	Chopped Straw
Mix Composition by Weight (lbs.)			
Wetted Soil (lbs.)	128.59	128.59	128.59
Added Sand (lbs.)	125.07	0	0
Added Straw (lbs.)	1.86	2.83	132.15
Total Weight (lbs.)	255.52	131.42	132.15
Mix Composition by Weight Percentage			
Wetted Soil (%)	50.3	97.8	97.3
Added Sand (%)	48.9	0	0
Added Straw (%)	0.007	2.1	2.6
Mix Composition by Volume (ft^3)			
Wetted Soil (ft^3)	1.52	1.52	1.52
Added Sand (ft^3)	1.52*	0	0
Added Straw (ft^3)	0.7	1.08	1.35
Total Volume (ft^3)	3.74	2.6	2.87
Mix Composition by Volume Percentage			
Wetted Soil (%)	40.6	58.4	52.9
Added Sand (%)	40.6	0	0
Straw (%)	18.7	41.5	47.9

Table 1 - Composition of Each Mix Type

(*) Sand was only added to the Conventional Mix Type. In the field it is typical to add sand into cob mixes for greater compressive strength and to reduce shrinkage while drying. However, as we are isolating the use of straw's effects on compressive, flexural and tensile strengths, additional sand was not added to Chopped and Long Straw Mix Types. Sand was added to the Conventional mix at a 1:1 volumetric ratio to wetted soil, a typical practice in the field in the creation of cob mixes.

2.2: Creation of Three Mixes

2.2.1: Raw Soil to Wetted Soil

To create the wetted soil of *fig 2* from the raw dry soil, the total volume of dry soil was filled into 5 gallon buckets. These buckets were then filled with the same volume of water as dry soil and were left 24 hours to create a more malleable state. The solution of soil and water at this point was not well-mixed, as organic material, clay masses and rocks were easily observed discretely (*fig 1*). Although the soil could be considered wetted at this point, it was not yet the homogeneous mixture referred to in *Table 1* and *fig 2* as "Wetted Soil".

To achieve a final homogeneity, each bucket was roughly filtered by hand to remove any large organic material which could present a compromise to the structural capacities during testing such as sticks, twigs, roots and leaves, especially those identified to exceed half the smallest dimension of our specimens. After this each bucket became more uniform, but water and soil could still be observed as distinct elements within one unit. Therefore the contents were mechanically forced into the desired mixture through the use of a paddle mixer for approximately 4 minutes within each bucket.

The final step in the creation of this wetted soil was to remove any aggregate which could not previously be removed by hand. Each 5 gallon bucket mixture was then sifted through a ½ expanded lath screen (*fig 3*). This process ensured that the mixture would not contain particles which could ultimately compromise the test data, since our specimens would be relatively small. We were seeking a balance between specimens large enough to accurately model field behavior, and those small enough to produce in quantity in a relatively short time. Through this procedure, approximately 40 pounds of large aggregate was removed from the combined 5 gallon buckets. At this point, the wetted soil was ready to be used to create each distinct mix type. The entirety of all the 5 gallon buckets divided into three parts yielded a 1.5 cubic foot volume of wetted soil for each mix type.

Fig 1. Dry soil soaking in water at a 1:1 volumetric ratio

Fig 2. Creating a homogeneous wetted soil mixture with a paddle extension on a power drill.

Fig 3. Wetted soil was sifted through this ½" expanded lath screen.

2.2.2: Mix-Specific Alterations

The Conventional cob mix is based on typical practice for material proportions and mixing of contemporary North American adobe and cob, according to the natural builders we consulted. This conventional cob mix typically contains local soil, sand, water and straw. At the time of mixing however, a higher than typical straw content was found necessary and was added in by feel and the experience of our collaborating builder. The straw was approximately 2” to 4“ long and varied in diameter. As our control, this was a standard composition of a cob mix which was adjusted to the specific characteristics of the soil material and to the non-standardized manual methods of production.

The Long Straw mix type was created with a very high straw content of varying, but significantly longer straw lengths relative to the lengths used in the control mix. The individual lengths of straw varied from approximately 6” to 12”. Pre-measured quantities of long straw were added to the wetted soil until deemed sufficient, and were recorded at 2.83 lbs. of long straw total at the end of this procedure. This process was qualitatively based upon experience and feel and concluded when a layer of straw was noticed protruding from the surface and when the container was grabbed and shaken, the mixture moved as a unit. Also following conventional understanding of the use of straw in earthen mixes, no sand was added to the Long Straw and Chopped Straw mixes. Sand content was therefore restricted to 6% of the composition of the raw soil itself (Grain Size Distribution Test).

The production of **the Chopped Straw** mix type replicated the process in which the Long Straw mix was produced, but with one exception. The short chopped straw (1” to 2” in length) was able to compact its volume within the 1.52 ft^3 mixture much more efficiently than the other two mixes. This led to a more dense volume of chopped straw at 3.56 lbs./1.52 ft^3 compared to long straw at 2.83 lbs/1.52 ft^3. When the straw was added and mixed into the wetted soil, the final mixture was observed to be very similar to the Long Straw Mix, although the Chopped Straw Mix was not as cohesive and there were fewer protrusions of straw on the surface of the mixture.

Finally**,** the mix type containers were covered with a tarp after a thorough mix and allowed to rest for 24 hours. Waiting an extra day before casting the mix types into the adobe molds was theorized to allow for a better bond to develop between the clay and the straw while still in their semi-liquid state.

2.3: Forming Mix Types into Test Specimens

Approximately 24 hours after covering up the wetted soil mixtures, each mix type was pressed into molds to create large rectangular blocks for compression tests, small beams for bending tests, and circular cylinders for splitting tension tests. For all mix types, the molds used consisted of wooden adobe block molds approximately 10” x 8” x 5”, with no panels on the top and bottom (10” x 8” planes) for ease of push-through, small wooden beam molds approximately 2” x 2” x 8” also with no top or bottom (2” x 8” planes), and 4” diameter x 8” tall standard plastic concrete cylinder molds.

Before any specimens were cast, all wooden surfaces were oiled with Murphy's Oil Soap and then wetted just prior to casting to minimize the possibility of the soil mix adhering to the interior of the molds. All molds were briefly washed off between each specimen creation, and a dusting of coarse sand was laid on the work surface. For the larger blocks, the conventional cob mix was easily placed in 2" layers, pressed into the corners manually and to ensure bond into the previous layer, and tapped and shaken to release air bubbles. These blocks were immediately slipped out of their molds and left on the prep table to dry. For the chopped straw mix, the procedure was nearly identical. The long-straw mix had changed significantly overnight, with the straw fibers becoming much more pliable and easy to manipulate. Since much of the straw was longer than the 10" dimension of the mold, it was necessary to bend and fold the long-straw mixture into the mold, but this was done with relative ease due to the overnight soaking. This did mean, however, that the straw tended to lay with a strong horizontal (in the 10" x 8" plane) orientation rather than isotropic.

For the small beams, the issue of the long straw was more pronounced, as the specimen dimensions were quite small compared to the average length of long straw. The straw was bent and laid into the small forms and pressed into shape. The conventional cob mix and chopped straw mixes did not present any unusual challenges.

The plastic cylinder molds were sliced down their sides and then securely taped back together in order to ease the removal of the specimens afterwards. Their interior surfaces were not treated.

As summarized in Tables 2, 3 and 4, these specimens had some variation in dimensions, primarily due to drying conditions. All block and beam specimens were dried out-of-doors, lightly covered with a tarp, for 4-5 weeks before being moved indoors to a controlled climate. Some exhibited some fine shrinkage cracking at the surface, but nothing unusual was observed. All blocks dried into slightly trapezoidal prisms, with upper surfaces up to ¾" shorter dimension than the bottom surfaces, due to settling (by gravity) in the initial stages of drying. The beams also exhibited this quality.

Cylinders were kept in their molds out-of-doors for 4-5 weeks and removed from their molds 7 weeks after their casting, after which they remained indoors. The plastic molds were un-taped and pried open, but despite the extra step of cutting the sides before casting, these molds proved difficult to remove with a significant amount of the soil adhering to the interior. Several of the long-straw specimens exhibited large voids and one was deemed too damaged for testing.

Fig 4. A prism removed from its mold and set to dry.

Fig 5. A beam drying next to its mold.

Fig 6. The final specimen tally just after being formed.

2.4: Physical Properties of Specimens by Mix Type

Conventional Cob Mix Type					
Test ID#	Height (In.)	Width (In.)	Depth (In.)	Weight (kg)	Weight (lbs.)
P5	9.75	5.0	8.0	9.557	20.07
P6	9.75	5.0	8.0	9.644	21.26
P7	9.75	4.75	8.0	9.555	20.07
P8	10.0	5.0	7.75	9.679	21.34
B7	1.9	2.2	8.0	0.863	1.90
B8	1.9	2.3	8.0	0.857	1.89
B9	1.9	2.2	8.0	0.845	1.86
B12	1.9	2.2	8.0	0.855	1.88
C1	8.0	4.0	n/a	not recorded	not recorded

Table 2: Conventional Cob Mix Type

Long Straw Cob					
Test ID#	Height (In.)	Width (In.)	Depth (In.)	Weight (kg)	Weight (lbs.)
P9	9.0	5.0	7.5	5.435	11.98
P10	10.0	5.0	7.5	5.625	12.40
P11	9.25	5.0	7.5	5.724	12.62
P12	9.5	5.0	7.5	5.871	12.94
B13	1.9	1.9	8.0	0.479	1.06
B14	2.0	2.0	8.0	0.483	1.06
B15	1.9	2.1	8.0	0.497	1.10
B16	2.0	1.9	8.0	0.519	1.14
B17	2.0	2.0	8.0	0.510	1.12
B18	1.9	2.0	8.0	0.494	1.09
C7	8.0	4.0	n/a	not recorded	not recorded
C8	8.0	4.0	n/a	not recorded	not recorded

Table 3: Long Straw Cob Mix Type

Chopped Straw Cob					
Test ID#	Height (In.)	Width (In.)	Depth (In.)	Weight (kg)	Weight (lbs.)
P1	9.75	4.50	6.88	5.290	11.66
P2	9.75	4.50	7.00	5.411	11.93
P3	10.00	4.75	7.00	5.320	11.73
P4	10.00	4.50	6.88	5.304	11.69
B1	1.9	2.1	8.0	0.535	1.18
B2	2.0	2.1	8.0	0.527	1.16
B3	1.8	2.2	8.0	0.535	1.18
B4	1.9	2.2	8.0	0.524	1.15
B5	1.8	2.1	8.0	0.523	1.15
B6	1.6	2.4	8.0	0.525	1.16
C13	8.0	4.0	n/a	not recorded	not recorded

Table 4: Chopped Straw Cob Mix Type

3.1: Testing for Compressive Strength of Prisms

The prisms were to be tested in straight compression along their longest dimension (height) in a calibrated Universal Testing Machine. However, their heights on either side varied due to having dried into trapezoidal prisms as opposed to ideal rectangular prism geometries. The height discrepancy in these prisms of up to ½” across their 5” widths did not allow for the specimen to be easily tested perpendicular to the loading mechanism. To compensate for this discrepancy the specimen had to be fitted so that their loading surface would be perpendicular to the vertical axis of compression.

The ideal method to fit these specimens was to cut the prisms on either end to create a perpendicular testing surface. Prism No.11 was therefore cut using a concrete chop saw, however far too much dust was created for the capacity of the testing facility and this process could not be repeated for the remaining prisms.

Due to time restrictions and the desire to complete all tests in one day, a solution was devised to use an anchoring gypsum cement called Pour-Stone which creates a rapidly hardening cement paste when mixed with water. A table was covered in a plastic tarp, and one by one the cement paste was spread generously to cover the surface area of each prism. Once the specimens were placed onto the cement, they were positioned to an estimated 90 degrees to the table surface (*fig 7)*. Excess cement was troweled from the footings as they set into level testing surfaces deemed acceptable to create a perpendicular compression axis. During the testing procedure of each prism, any remaining eccentricity was compensated for by the use of wood shims about ⅛” thick (*fig 8)*. This solution was assumed not to affect the results since the cob material would have a significantly lower strength than the capping material.

Once the testing had begun, it was observed that the blocks of each mix type endured for similar lengths of time prior to apparent ruptures. All blocks failed in a similar manner consistent with a shear fracture. These typically started from a point of compression (due to residual unevenness) and continued through the block to the bottom corners. Testing stopped once load capacities declined rapidly. This was accompanied by a rapidly increasing deformation of each block as its failure load was met (*fig 9)*. Load & displacement data was individually recorded for each test.

Fig 7. Caps compensate for uneven geometry

Fig 8. Wood shims create a more even testing surface under loading cell.

Fig 9. Prism tested to failure.

3.2: Testing for Modulus of Rupture

We determined the Modulus of Rupture *(MOR)* to compare the flexural capacity of the Long and Chopped Straw mix types to that of our Conventional Cob mix. The *MOR* will aide in identifying which of these mix types may best yield adobe blocks when ductility is desired. To obtain these values, beams of generally 2”x2”x8” in dimension were tested in single-point compression. Each beam was supported by two points inset 1” from either end of the beam’s bottom surface. The point load was applied at the mid distance between these two supporting points. The points allowed for the beam to displace vertically as the point load was applied. These beams were tested on a different date than our compression tests, therefore we do not have test-time observations of these beams as they were tested.

3.3: Testing for Splitting Tension

The third test in addition to compression and flexural strength tests was the test for tensile strength and therefore our final geometry, the cylinder was used. Of the six cylinders which were created, two for each mix type, only four were able to be tested due to damages in one of each of the Conventional and Chopped Straw mix types. The more typical method of testing for this value in direct tension would require either end of the cylinder (or other form) to be pulled apart from each other in single-axis tension. However, this method was implausible as the gripping mechanism on either end would likely crush the relatively weak ends. Instead, the splitting tensile stress method was used, which has the added advantage of being more easily replicable for field testing.

This testing method is illustrated in *fig 10*. Each cylinder received a line load along the length of the cylinder (lying on its side) as the vertical plane of compression essentially splits the specimen down the middle. The ideal testing method to determine tensile stress, the direct testing method, could be somewhat replicated with a different specimen type. Refer to figure 11 below, in which wetted cob mixtures such as that described in sections 2.2.1 and 2.2.2 are molded by hand into “snake-like” compositions and wrapped around a wattle and daub framing. In this situation, it would be interesting to conduct an in-field direct testing method for these “snake-like” compositions. This type of in-field testing is similar to slump tests conducted in the concrete industry to provide a qualitative measure of the concrete mix’s integrity and consistency across pours. Perhaps the tensile strength could be verified in a manner similar to that of the slump test, prior to the casting of the cob into the adobe molds.

Fig 10. Cylinder tested in splitting tension to determine tensile capacity

Fig 11. "snake-like" cobbing method around wattle frame

Fig 12. Ductile nature of long-straw cylinders

4.1: Results of Compression Test

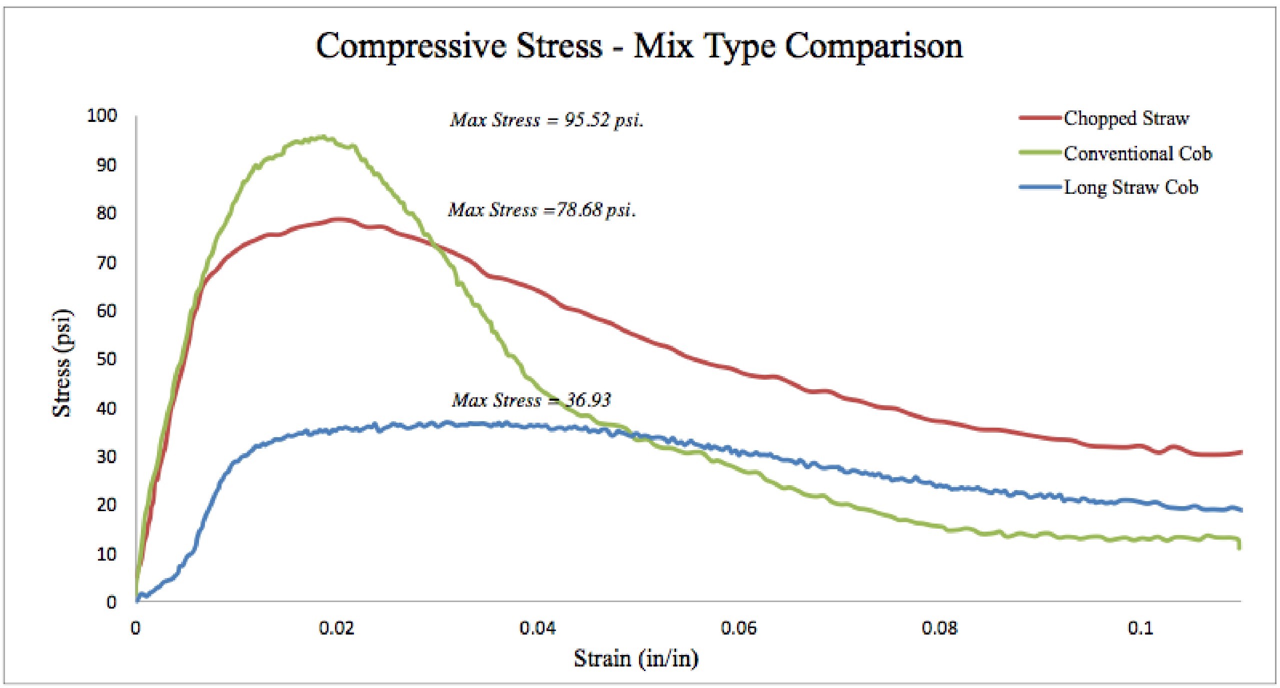

Fig 13 - Compressive Stress by Mix Type

Young's Modulus:

Conventional (P7): **10371 psi/(in/in)**

Chopped Straw (P1): **9414 psi/(in/in)**

Long Straw (P11): **5405 psi/(in/in)**

Young's Modulus (E) calculated using the following equation:

$E = (F/A)/(\Delta L/L_o)$

where F = *maximum load at failure (lbs)*

A = *cross sectional area* (in^2)

L_o = *original specimen height (in)*

ΔL = *change in specimen height at failure (in)*

Specimen I.D	Max Load (lbs)	Discplacement at Max Load (in.)	Max Stress (psi)
Chopped Straw Specimens			
P1	2436	0.26	78.68
P2	2286	0.314	72.57
P3	2461	0.382	74.02
P4	2406	0.28	77.71
Conventional Adobe Specimens			
P5	3080	0.15	77
P6	3216	0.158	80.4
P7	3637	0.187	95.71
P8	3864	0.16	99.72
Long Straw Specimens			
P9	1524	0.47	40.65
P10	1619	0.4	43.17
P11	1385	0.288	36.93
P12	1601	0.338	42.69

Table 5 - Results of Compression Tests.

The results seen above in Table 5 and *fig 13* indicate that our conventional cob mix had the greatest compressive strength, with those samples having an average of 88.21 psi ultimate strength. The greatest stiffness (Young's Modulus) was exhibited by the Conventional cob specimen and great ductility was observed in both long straw and chopped straw specimens, although the significantly lower compressive strength of the long straw specimens would seem to negate the benefit of having a ductile material.

Although significant effort was made to ensure that the compression specimens accepted their load on a vertical axis parallel to their long dimension, many specimens were still seen to be quite eccentric due to settling into trapezoids while drying. This seems to have caused the blocks to fail in shear (*fig 6*) rather than in pure compression, as witnessed by the strong diagonal cracks which developed over the height of the specimens during loading.

The chopped straw specimens show great promise as they were capable of loads almost as high as the conventional cob, while improving the ductility by nearly 100%. The average density of the chopped straw blocks was also very low (65.0 lbs/ft^3 average), approximately ⅔ that of the conventional mix (92.5 lbs/ft^3 average), making them economical and less susceptible to tensile forces. The primary drawback that can be observed from the creation of the chopped straw blocks is that their very short lengths makes it easy to incorporate very high, perhaps too high, quantities of the straw, thereby limiting the ability for the soil to retain continuity throughout. Several "balls" or "nests" of the short straw were observed within the broken specimens.

One likely reason for the very low strength of the long-straw specimens is the anisotropic nature of the blocks. When creating these specimens, the straw was so long in comparison to the wooden molds that it was often bunched and laid into the molds in layers, with a strong horizontal layering effect in the 10” x 8” plane. Since these specimens were tested along their longest (10”) dimension, the long straw was essentially on-end, with their soil binder not able to retain continuity in that direction, a condition which would not occur in practice. The second reason for the low strength could be the possibility that whole (unsplit) straws could trap air within the mix. This mix, not surprisingly, has the lowest density at 60.5 lbs/ft^3 on average.

4.2: Results of Modulus of Rupture

Beam Testing for Modulus of Rupture		
Cob Mix Type	***Max. Load (lbs.)***	***Modulus of Rupture***
Chopped Straw		
B1	*121*	143.64
B2	*140*	150
B3	*134*	169.19
B4	*93*	105.38
B5	*97*	128.3
B6	*105*	153.9
Conventional		
B7	*78*	88.41
B8	*76*	82.41
B9	*71*	80.47
B12	*52*	58.94
Long Straw		
B13	*107*	140.39
B14	*103*	115.897
B15	*104*	117
B16	*94*	111.31
B17	*106*	119.25
B18	*71*	88.5

Table 6 - Modulus of Rupture results for Beams

To ascertain the *MOR* using their tested maximum loads at rupture and their geometry, we used the following equation:

$$MOR = (3Pl)/(2bd^2)$$

where P = *maximum load at rupture (lbs.)*
l = *length of supported span (in.)*
b = *width of specimen (in.)*
d = *depth of specimen (in.)*

The result of the Modulus of Rupture calculations most clearly identifies that the addition of extra straw to a typical cob mix will yield a greater flexural strength. This can be referred to in Table 6 (above) in which the Conventional mix specimens yielded much smaller *MOR* values with a range of 58.94 -88.41 psi as opposed to Chopped and Long Straw mix types at 105.38 - 169.16 psi and 88.5 -140.39 psi respectively. This result was expected as we hypothesized that the tensile strength of straw would result in a specimen with greater flexural capacity.

Based upon the hypothesis that a longer straw length would yield a greater flexural strength, we expected this to be replicated in the *MOR* values of Long and Chopped Straw mix types. However, the Chopped Straw had not only the highest calculated *MOR* value, but this type also produced *MOR* values higher than those of the Long Straw type. These calculations directly correlate with their maximum loads at rupture, implying that Long Straw specimens ruptured at a lower typical load than Chopped Straw specimens. However, according to our observations during the compression tests, the Long Straw specimens visibly deformed to a much greater degree. They also endured a greater calculated mean displacement of .37” as opposed to that of .31” for the Chopped Straw specimens (derived from Table 6). This could possibly be explained by variations in the method of testing, specifically regarding the apparatus set up and the determination of “failure”.

The apparatus used a consistent set-up with a maximum allowance of vertical deflection, approximately two inches under the bottom surface of the beam. This allowance could have been the cause of the unexpected results of the greater recorded flexural strength values of Chopped Straw specimen to Long. That is, if the Conventional mix is our most brittle, then a complete fracture would mark the end of the test. However, Long Straw specimens could have deformed greater than 2”, thus contact with the UTM base would mark the completion of the test. Since load-displacement data was not recorded for these specimens, we cannot determine with certainty the conditions at the end of each test. Therefore the maximum load endured could in fact be not the maximum load at rupture, but the maximum load at which the beam displaced 2”. Since our Chopped Straw values were greatest, this could imply that the testing of these beams ceased at complete rupture like those of the Conventional mix and not by making contact with the apparatus base. If there was a greater vertical allowance of deflection, Long Straw beam testing could have been ceased at complete rupture as the other two mix types were, possibly yielding values greater than the Chopped Straw specimens.

Despite this test-condition inconsistency, Chopped Straw beams did yield the highest *MOR* values and therefore warrants further investigation. This could be due to a more efficient cohesion between smaller straw lengths and the rest of the cob components. Perhaps longer and more longitudinally placed straw created less opportunity for friction within the soil than shorter and more erratically placed straw. In this regard, longer straw pieces could have created a straw to soil ratio greater than ideal. Further investigation into the volume, cut and placement of straw within the soil, and its effects on flexural properties is warranted.

This test type for the *MOR* is clearly successful in at least one regard. It shows a correlation between additional straw to a conventional cob mix and greater flexural performance. It was successful as it pointed us to future investigations into straw and flexural strength that would allow the determination of the most ideal proportions of straw.

4.3: Results for Splitting Tension

Similar to the expected results of the flexural and compression tests, we expected to see a greater ductility in general through the use of both Long and Chopped Straw mix types in comparison to the Conventional. However, the Conventional mix type performed much better than either of the other mix types. This was surprising as it was originally hypothesized that the Conventional cob mix would exhibit less tensile capacity than the other mix types.

<u>Results for Splitting Tension:</u>

<u>Conventional.</u>
C1 - 26.14 psi
<u>Long Straw:</u>
C7 - 16.71psi
C8 - 16.32psi
<u>Chopped Straw:</u>
C13 - 15.91 psi

With the recorded maximum load at rupture, and the given geometries, the tensile stress of the cylinder was calculated using the following equation:

Tensile Stress: $(F_{st}) = (2P)/(\pi \cdot L \cdot D)$

where (F_{st}) = *splitting tensile stress (psi)*
P = *load at rupture (lbs)*
L = *height of specimen (in.)*
D = *diameter of specimen (in.)*

The low tensile capacities of the Long and Chopped Straw specimens can be explained thusly: the Long Straw mix type has straw lengths in too great a volume, and oriented in a manner parallel to the plane of loading. A cylinder of this description can be seen in *fig 12* above. It can be noted from this image that the long straw were over-crowded which prevented the distribution of the fibers within the soil mix, thus not creating a proper bond. This phenomenon was observed in the two Chopped Straw specimens as well. When the high straw mix cylinders were removed from the testing platform it was quite plain to see that the soil spilled out in a powder like manner, leaving the straw as a distinct geometric framework.

However, this type of test was successful with regard to the manner in which the cylinders of each mix type failed. Referring to fig 10 above, it can be noticed that the plane of fracture bisects the specimen in the same direction of the loading mechanism, essentially creating two fairly even halves. This type of fracture is characteristic of how a brittle material would fracture in a similar loading apparatus. However, both Long and Chopped Straw mix types fractured in a similar fashion to *fig 12*. Therefore, it could be said that even when failing at a lower load the specimens deformed quite a bit and quite thoroughly. This observation implies that even though the fibers did not increase the tensile strengths of these specimens, it did cause more cracking throughout the specimen compared to the brittle fracture of the Conventional mix type, corresponding to greater energy dissipation.

5: Conclusion

This investigation has provided us with several solid conclusions regarding the high straw-clay cob mixes that were tested in comparison to a conventional cob mix. First, our compression tests show that the additional straw components of our Long and Chopped mix types yielded greater ductility in relation to the Conventional mix at the cost of maximum compressive strength. The Chopped straw specimens were most similar to our control. Long Straw specimens acted uniquely under compression. The plot can clearly identify this mix type's ability to dissipate energy through deformation earlier and for a longer amount of time than the other two mix types but with a severe compromise in compressive strength.

However, it is most important to note that the performance of the Long Straw mix type in compression best resonates with our prime motivation for this investigation: to identify a cob mix type that could communicate its structural soundness during a seismic event through high energy dissipation in the form of observable deformation. Additionally this mix type is the least dense at 60.5 lbs/ft^3 which is nearly one third of the conventional mix. Therefore if an earthquake would strike a structure of this mix type, it would only endure an inertial force of about ⅔ the magnitude that a conventional mix type would, if approximated simply by Newton's Second Law of Motion. The Chopped Straw mix type is similar with a low density of 65.0 lbs/ft^3, retains compressive strength and exhibits greater ductility. Added straw reduces density, and these types may be a safer compromise to heavier and more brittle types. A future investigation may be to test this at the scale of an entire wall to see the effect of overall lower density.

In regards to the Modulus of Rupture values for the beams of each mix type, a similar conclusion can be drawn regarding the correlation of increased flexural strength and ductility to added straw. This test also identifies the need for future investigations into not only the length of straw but also its volume and concentration within the soil due to the better performance of the Chopped Straw mix than the Long. Additionally, this test provided an example of earthen building materials taken from the field setting and tested with standardized testing methods originally intended for concrete, and suggests considerations for how cob-specific standards might be developed.

The tests of this investigation surely warrant future improvements. Perhaps there is a need for different specimen types or tests that would reflect a more efficient manner of testing earthen materials as opposed to deriving our methods from the testing of more standardized building materials. For example, in creating prism testing surfaces most perpendicular to the loading mechanism, P11's edges were cut by a saw intended for cutting concrete. This method was not reproducible primarily due to the enormous dust cloud, but it also did represent fairly accurately the preparation of an adobe block on any kind of real construction site.

Many considerations in regards to preparation of mix types can also be derived through this investigation. Perhaps setting limits to the proportions of straw to soil is necessary to create a cob mix in which both components facilitate a more homogeneous mix in order to prevent straw clustering. This could be done by using a workability rule-of-thumb. Upon observation of our long straw specimen after destruction, we noticed an axial relationship between the straw lengths. If our long straw lengths operated with a majority axis due to their settling within the wetted soil, the mechanism of loading against or with this axis most likely had an effect on our results. This likely explains the outlier data in our results. The shorter straw of our Chopped Straw mix we believe did not form a majority axis within a specimen, and this could be the reason behind the relatively high *MOR* values.

Another conclusion that can be made concerns the scalability of the specimens that we tested and how a larger scale may be more ideal. For example, a mud plaster edge condition of a cob wall in an adobe structure may vary from 2-4" in thickness. Our beams tested were only 2" thick and our Prisms were 5" thick. It could be said that we were testing only the edge conditions of a wall rather than a representation of the typical interior of a wall. Although this claim is not quantitatively supported, this could have played a major factor in our derived properties. If this is the case, then we would need larger-capacity testing machines as their dimensions limited our geometries. Short of building a wall in order to extract a handful of core specimens, our specimens were the most realistic geometries to test.

However, cob as an earthen material is naturally inconsistent as the best products are based upon varied human experience, the tools and materials at hand. Therefore while it is important to consider this method of testing as an effective way to yield mechanical properties of a material, one is typically not given this opportunity. We can also immediately realize the effects of our experiments in the lab setting by gathering data on specimens after they are tested as opposed to analyzing structures after they have collapsed. It is important that we realize the inherent mistranslations between an earthen material such as cob into this more formal environment, but in a lab setting we can control some conditions more effectively for the sake of determining specific effects of variables. The steps taken in this experiment allow us to not only better our understanding of earthen materials in general, but perhaps more importantly promote their application toward more accessible and sustainable building design.

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7:Sources

forthcoming