INDEX AND ENGINEERING PROPERTIES OF OREGON COB

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ABSTRACT

Cob is an earthen building material comprised of sand, clay, straw, and water used for millennia to construct dwellings. Although cob construction largely died out during the nineteenth century, it is experiencing a revival in England and the Pacific Northwest of the United States. Little scientific research has investigated the engineering properties of cob, knowledge of which is important for modern-day design practices and code requirements. Researchers at Oregon State University investigated six different Oregon cob mixtures using a series of standard soils and concrete tests adapted for this material. The objectives were to characterize the constituents, to establish estimates for the magnitude of, and degree of variability in, the mixture properties, and to develop correlations between the engineering properties and mixture composition. Results indicated low to moderate variation in basic mixture properties (i.e., unit weight, moisture content, and sand equivalent), moderate variation in strength properties, and high variation in the elastic modulus. Several reasonable correlations were found between shrinkage, compressive strength, elastic modulus, and sand equivalent and between flexural strength and fiber tensile strength.

KEYWORDS

Cob, Oregon cob, earthen building material, properties

INTRODUCTION

Cob is reportedly one of the first materials used by humans to construct "permanent" dwellings, with evidence of use dating back ten millennia (Smith 2000, Evans, et al. 2002). Cob walls are built using a mixture of sand, clay, straw, and water. Cob construction differs from other earthen-material building techniques in that walls are built up as one monolithic structure without the use of forms (as with rammed earth) or preformed bricks (as with adobe). Williams-Ellis et al. (1947) give a detailed account of the traditional technique of cob construction.

The first cob homes in England were built during the thirteenth century and, in some regions, became the standard method of construction by the fifteenth century, mainly in

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places with an abundance of sandy-clay soils and a deficiency of other building materials such as wood or stone (Evans, et al. 2002). Houses of similar construction have been built in other areas of the world including Northern Europe, the Ukraine, and the Middle East, in parts of East Asia, Africa, and the Southwestern United States, where it is called "coursed adobe" (Smith 2000). In England, the demise of cob construction appears to have resulted from the availability of cheap bricks coupled with cheap transport, and according to Williams-Ellis, et al. (1947, p. 82), "…the ignoble rage for fashions from the town went far to oust provincial Cob from the affections of those whom, with their forbears, it had housed so well for several centuries." However, Smith (2000) notes that it experienced a revival in the County of Devon in the 1990s.

Smith (2000) also notes that, led by a company in southwestern Oregon, a parallel revival of cob construction occurred in the United States, concurrent with that in England. Spurred by recognition of the need for inexpensive and healthy housing well suited to the natural ecology of its surroundings, the founders of the company developed a method of construction that has come to be known as "Oregon cob." Although founded on the traditional British cob mixture and methodology, Oregon cob differs with regard to attention given to the quality of the ingredients, the proportions of the ingredients in the mixture, and construction technique; hence, warranting a distinctive name.

Evans et al. (2002) provide a detailed account of Oregon cob construction practices. In brief, Oregon cob is typically mixed in small batches using what is referred to as the "tarp method." Soil and sand are poured out on a ground cloth and any large chunks of soil are broken up. The tarp is repeatedly pulled over itself to mix the sand and soil with water being added to the builder's preference. Straw is then sprinkled on top and tread in with bare feet (Figure 1). The builder continues to roll and tread the mixture adding water if needed until the desired consistency is achieved. Walls are constructed on top of a waterproof stem wall of concrete or masonry to reduce wicking of ground moisture into the wall. The cob is added by hand without the use of formwork and compressed downward to ensure good bonding with previous layers. Fingers are pressed into the wet mix to "knit" the straw fibers to the previous lifts creating a single monolithic wall. Lifts are added until the sides begin to bulge at which point the wall is allowed to dry before subsequent lifts are added. Later, the rough walls are

FIGURE 1. Mixing cob using the tarp method.

trimmed smooth using a machete or shovel and a protective finish of plaster is usually added to improve durability. Finished walls are typically 12 to 18 inches in thickness.

Smith (2000) identifies many environmental benefits of building with cob relative to the construction of modern-day, conventional homes. Consumption of fossil fuels for hauling materials is minimized through use of on-site and locally-available materials (sand, clay, straw, and water) and minimal or reduced use of processed materials (e.g., lumber, cement, etc.). In addition, use of electrically- or engine-powered machinery is not needed for mixing materials and construction of walls. Natural (e.g. lime-based) plasters can be used for external coating, thus eliminating the need for chemically-based products that could potentially be harmful to the environment. One of the most significant benefits is that buildings constructed of materials native to the immediate environment in which they are built can be easily assimilated back into the environment without introduction of toxic residues.

To date, very little scientific research has been conducted to investigate the engineering properties of cob. Successful construction and acceptable performance has relied on rules-of-thumb and builder experience. While such empirical knowledge is useful, it is not sufficient for modern-day design purposes and code requirements.

This paper describes a study conducted at Oregon State University (OSU) to investigate several index and engineering properties of six different Oregon cob mixtures (Pullen 2009). These included properties of the constituent materials (soil plasticity, gradation and angularity of the sand, and tensile strength of the straw) and of the mixtures (unit weight, water content, sand equivalent, shrinkage, strength, and stiffness). The principal objectives of the study were to characterize the constituent materials in the mixtures, to establish estimates for the magnitude of, and degree of variability in, the engineering properties amongst the mixtures, and to develop correlations between the engineering properties and mixture composition.

This study was intended to be an initial survey of typical Oregon cob mixtures, not an in-depth study of cob mixture design. As many cob buildings have already been constructed in the Pacific Northwest and in southwestern Canada (Figure 2), it was considered important to establish, retroactively, how structurally sound these buildings might be, and to develop baseline values for future cob design.

FIGURE 2. Cob house in British Columbia (Thomasen, 2007).

The cob mixtures investigated in this study were obtained from experienced cob builders from the central and northern Willamette Valley of Oregon and representative of actual cob mixtures used by these builders in the field. The samples were received wet, formed in the laboratory, and subjected to a series of tests to determine index and engineering properties. The findings from this study are, therefore, limited in scope to the materials tested and the limitations of the tests to which they were subjected.

MATERIALS

A total of six cob mixtures were obtained from five experienced cob builders, with one builder supplying two identical mixtures except with respect to straw length. In order to obtain representative samples of cob used in existing structures, the builders provided mixtures with which they would be confident in using to build their own house. Each builder also supplied samples of the constituent materials so that the properties of the individual components could be determined.

Table 1 summarizes several attributes of constituent materials used in each of the cob mixtures, and includes the general location from which the soils were obtained (i.e., source). Mixtures A and B were duplicate mixtures except with respect to fiber length. The product name for the sands refers to the name of the sand as defined by the aggregate supplier from which the builders purchased their sand, and an informal assessment of the angularity of the sand particles is provided. Note that Mixtures A and B contained hay, whereas the other mixtures contained straw.

EXPERIMENT PLAN

The constituent materials of the mixtures were tested to determine various index properties and the mixtures were tested to determine several engineering properties. Table 2 lists the properties evaluated as well as the number of trials for each test. Material quantities limited the number of trials that were conducted.

TABLE 1. General attributes of the constituents used in each mixture.

	Soil	Sand		Fiber
Mixture	Source	Product Name	Visual Angularity	Description
A	Philomath	Coarse Washed River Sand	Semi-rounded	Hand-cut field hay
B	Philomath	Coarse Washed River Sand	Semi-rounded	Hand-cut field hay
C	Estacada	Sharp Concrete Sand	Semi-rounded	Baled oat straw
D	East Portland	Mason Sand	Angular	Bedding straw
E	East Portland	Plaster Sand, Multi-Purpose Sand	Semi-angular	Baled straw
F	Corvallis	River Sand	Semi-rounded	Baled oat straw

TEST PROCEDURES

Standard test methods were utilized to evaluate the index properties of the soils and sands, whereas the mixture properties were evaluated by adapting standard test methods used for concrete. Standard test methods do not exist for evaluating the engineering properties of straw; however, the methods used in this study followed closely common testing methods for other types of material.

To determine the feasibility of performing the concrete mixture tests on the cob mixtures, a trial batch of cob was prepared and run through the various tests. This also provided an opportunity for gaining practice in applying the tests to this unique material to reduce variability due to human error. Data and results from these trials have not been included herein.

Plasticity

The consistency and material properties (e.g., strength) of soils with fine particles vary with the amount of water present. Completely dry fine-grained soils (i.e., clays and silty clays) may be hard and possess good strength, while these soils with very high water contents are soft and weak. At water contents between these extremes, fine-grained soils are semi-solid and may be quite plastic (i.e., able to deform readily under load without cracking or fracture). As examples, clays used by potters are highly plastic, whereas soils deposited on the banks of slow-moving rivers are usually low-plasticity silts.

The Atterberg Limits tests are a set of index tests that are widely used to determine the water contents of fine-grained soils corresponding to transitions between semi-solid and plastic consistency (called the plastic limit) and between plastic and liquid consistency (called the liquid limit). The difference between the liquid and plastic limits, called the plasticity index, describes the range of water contents over which the soil has a plastic consistency. Tests to determine the liquid and plastic limits of the soils used in each cob mixture were conducted in accordance with ASTM D 4318 (ASTM 2009).

TABLE 2. Properties evaluated and number of trials.

Material	Property	Number of Trials
Soil	Plasticity (liquid limit, LL and plastic limit, PL)	2 for LL; 3 for PL
Sand	Gradation	1
	Uncompacted void content	1
Straw	Length	3
	Tensile strength	3
Mixture	Initial water content	3
	Sand equivalent	1
	Shrinkage	4†
	Unit weight	1
	Compressive strength	3†
	Modulus of rupture	3
	Modulus of elasticity	1

†In some cases, one fewer trial was tested as described in the respective section for the test.

Gradation

A sieve analysis is conducted on a sample of mineral aggregate to determine the distribution of particle sizes in the material, referred to as the gradation of the material. The aggregate gradation significantly affects the engineering properties (e.g., stiffness, resistance to deformation, density, etc.) of mixtures such as asphalt concrete and, to a somewhat lesser degree, portland cement concrete. It is not known how it affects the properties of cob; however, it is likely to have some bearing on the shear strength of the material, depending on the relative proportion of sand in the mixture. The sand in each cob mixture was tested in accordance with ASTM C 136 (ASTM 2009).

Uncompacted Void Content

The uncompacted void content is the volume of air voids (space between particles) in a sample of fine aggregate (e.g., sand). It is an index property used to provide an indication of the angularity, sphericity, and surface texture of the aggregate particles within the sample relative to that of other aggregates with the same grading. It can also be used as an indicator of the effect of the fine aggregate on the workability of a mixture in which it is used. For a given gradation of aggregate, samples with high void contents tend to be more angular, possess a rougher surface texture, and have lower workability than those with lower void contents. The test was specifically chosen to assess the angularity of the sand particles used in the cob mixtures. Particle angularity significantly affects compressive strength of graded aggregates; particles with greater angularity interlock better than those with lower angularity resulting in higher strengths. The sand in each cob mixture was tested in accordance with ASTM C 1252 (ASTM 2009).

Fiber Length

Fiber (hay or straw) length in the cob mixture might be somewhat akin to rebar length in reinforced concrete, where the surface area available for bonding with cement increases with increased rebar length resulting in greater bond strength. Hence, fiber length was determined for the purposes of investigating its effect on cob flexural strength.

In this study, individual stalks were measured to determine the average length of long fiber, where long fiber is defined as the portion of the stalk that did not appear to be broken. There is no standard test to evaluate fiber length in this manner.

Fiber Tensile Strength

Tensile strength of the fibers could have an influence on the flexural strength of the cob mixtures, provided that adequate bond developed between the fibers (hay or straw) and soil/sand particles. Although there is no standard test for measuring the tensile strength of hay or straw, the methodology used in this study followed closely common tensile strength testing methods for other types of material. That is, the diameter of each fiber was determined and then it was loaded axially until failure, noting the load (force) at which failure occurred. The tensile strength was then determined by dividing the load at failure by the cross-sectional area of the fiber under test, which was determined from the diameter of the stalk using the basic formula for the area of a circle. However, since hay and straw are hollow, this significantly overestimated the actual cross-sectional area and, consequently, underestimated the actual tensile strength.

Initial Water Content

Water content has a significant effect on the engineering properties of fine-grained soils. In soil mechanics, water content is the mass of water divided by the mass of solid particles, expressed as a percentage. For cob mixtures, sufficient water content is required for mixing and construction of walls, but once built, lower water content is essential for strength. In this study, the water contents of the as-received mixtures were determined in accordance with ASTM C 566 (ASTM 2009).

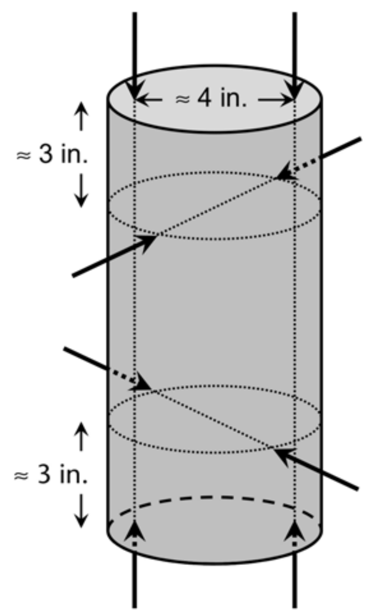
Sand Equivalent

The sand equivalent test is an index test used to determine the relative proportion of claylike or plastic fines (i.e., clay and silt) in granular soils and fine aggregate (sand). The sand equivalent is defined as the height of sand in a standard cylinder divided by the total height of sand and fine-grained particles in the same cylinder, expressed as a percentage. Samples of the cob mixtures were tested in accordance with ASTM D 2419 (ASTM 2009).

Shrinkage

Soils change slightly in volume due to changes in water content (i.e., they swell with increased moisture and they shrink with decreased moisture). Normal volume change would be of little consequence to cob work free of any restraints; but since foundations, doors, and windows provide restraint to cob, significant stresses can develop and may result in cracking, particularly at any corners. Hence, knowledge of the magnitude of shrinkage may be useful in predicting the likelihood of cracking.

FIGURE 3. Shrinkage measurement locations.



The compression test specimens (see below) were used to determine shrinkage. This involved molding the specimens into steel forms that measured 6 inches in diameter by 12 inches in height, drying the specimens in an oven, and then measuring the height and diameter of the specimens. As shown in Figure 3, diametral measurements were made at four locations (each approximately 90 degrees from one another) and height measurements were made at two locations.

The supplier of Mixture E only provided enough material to form three cylinders. As a result, the value provided herein is the average of three trials, rather than four for the other mixtures.

Unit Weight

By definition, unit weight is weight per unit volume. Knowledge of the unit weight of a material is useful for converting weights to volumes, and vice versa. For example, the unit weight of wet cob (i.e., moist unit weight) can be used to estimate the weight of material required for building a wall of known or planned volume.

In this study, the moist (or wet) unit weight of the cob mixtures was determined according to the procedure described in ASTM C 138 (ASTM 2009), with a slight modification. Strictly speaking, ASTM C 138 is used for fresh concrete, but the basic principles of the test can be applied to other materials. It involves filling a measure (metal bucket) of known empty mass and known volume level full with the material under test and weighing the filled container. The mass of material filling the measure is determined by subtracting the known mass of the empty measure from the mass of the measure filled with the material, and then dividing this result by the known volume of the measure to obtain the unit weight.

In the standard procedure, the measure is filled in three lifts of approximately equal volume (with the third lift overfilling the measure) and each lift is consolidated by tamping the material 25 times using a metal rod prior to introduction of the next lift. After tamping the final lift, the excess material is struck off such that the measure is level full. The modification used in this study involved filling the measure with four to six lifts and consolidating each lift by hand, rather than using the metal rod, to better simulate actual cob construction practices.

Immediately following the unit weight test, a portion of the material was used to determine the water content of the mixture. Knowing this (in decimal form) and the moist unit weight of the material, the dry unit weight of the mixture was calculated according to the following equation:

$$\text{Dry Unit Weight} = \frac{\text{Moist Unit Weight}}{1 + \text{Water Content}}$$

Compressive Strength

In soil mechanics, strength is the maximum force a soil can support per unit area or, stated another way, the stress at which failure occurs. In normal service, cob mixtures primarily bear compressive loads; consequently, compressive strength is an important engineering property as it establishes the bearing capacity of a wall.

In this study, unconfined compressive strength of the cob mixtures was determined following the procedure described in ASTM C 39 (ASTM 2009), with some modifications. In the standard procedure, which is for concrete mixtures but the basic principles of the test can be applied to other materials, a cylindrical mold is filled in the same way as described above for the unit weight test (i.e., in three lifts with each lift being consolidated by tamping with a metal rod). A modification used in this study involved filling a steel mold (6 inches in diameter by 12 inches in height) using six to eight lifts and consolidating the cob mixture by hand to better simulate actual cob construction techniques. Following the final lift, which overfilled the cylinder, the excess cob material was struck off using a rigid metal bar such that the mold was level full.

Another modification to the procedure involved drying the cob mixtures in an oven whereas, in the standard procedure, the concrete mixture is cured in water. The procedure used for drying the cob mixtures entailed drying the mixtures in an oven set to 167°F (75°C)—hot enough to dry the samples quickly and thoroughly but not hot enough to burn the straw—for a total of six days; two days in the molds, followed by four days after removal from the molds. Originally, only four days of drying was planned. However, on testing the first specimen (one from Mixture A), it was found to appear slightly damp in the center. Hence, another two days of drying was added to the overall duration for all remaining specimens. Following the sixth day, the specimens were removed from the oven and measured for the purposes of determining shrinkage (see above) and for determining stress during the compression testing.

Tests were then performed at a rate of loading of approximately 20 psi/s using a conventional concrete compression testing machine, which recorded the maximum load (force) at failure, defined for this study as severe cracking and at least one inch of deformation. The stresses at failure (i.e., compressive strengths) were calculated by dividing the force at failure by the shrunken area prior to loading. The results presented herein are the average of four trials, except for Mixtures A and E, which are the average of three trials (the first test result for Mixture A was discarded since it had been dried for only four days, and the supplier for Mixture E only provided enough material to form three specimens).

Modulus of Rupture

For concrete, the modulus of rupture is the maximum tensile force the material can withstand per unit area when loaded in flexure or, in other words, the tensile stress at which failure occurs. It is important in concrete design since concrete is much weaker in tension than in compression, and is used to calculate the resistance of a wall to lateral loading such as with wind and seismic events. For these reasons, the test was used in this study to investigate the flexural strength of the cob mixtures.

Tests were conducted on beams of the cob mixtures with dimensions of 6 by 6 by 21 inches according to the procedures described in ASTM C 78 (ASTM 2009), with a few modifications. Strictly speaking, this test is for concrete but the basic principles of the test can be applied to other materials. In the standard procedure, the concrete mixture is formed in the mold using three lifts of approximately equal volume, and each lift is consolidated as described above for the unit weight test. Once formed, the concrete is allowed to cure until it is hard enough to remove from the mold, and then cured in water prior to testing. One modification made to the standard procedure involved filling the molds using four to five lifts and consolidating the mixtures by hand, rather than using a metal rod, to better simulate actual cob construction practices. The other modification involved drying the mixtures in an oven in the same way as described above for the compressive test specimens. Following the drying process, the length, width, and depth (height) of the specimens were measured for the purposes of determining stresses during testing.

FIGURE 4. Modulus of rupture test setup.

Tests were performed using a conventional concrete compression machine fitted with a beam loading apparatus (Figure 4). Loading was applied at a rate that maintained the stress at the bottom of the beams at approximately 125 psi/min until failure occurred, defined for this study as severe cracking and at least one inch of vertical deflection. The shrunken dimensions of the beams (prior to loading) were used to calculate the moduli of rupture.

Modulus of Elasticity

The modulus of elasticity is a fundamental engineering property of a material used in many relationships describing the behavior, under loading, of an element (beam, column, wall, etc.) made from the material. It is defined as the change in stress (force per unit area) per unit change in strain (which, for many applications, is the change in length divided by original length) determined within the elastic limit of the material (i.e., returns to its original form upon removal of the load).

Tests were conducted on cylindrical specimens 6 inches in diameter by 12 inches in height that were molded and dried as described above for the compression tests. Following application of a seating load of approximately 100 pounds, the specimens were loaded in approximately 100-pound increments using a conventional concrete testing machine, and the actual load and the deformation of the specimen were recorded for each increment. Loading and recordings continued until the cylinder showed signs of failure (Figure 5).

FIGURE 5. Modulus of elasticity test setup.

RESULTS AND DISCUSSION

Soil Properties

Based on the Unified Soil Classification System (USACE-WES 1960), all of the soils were classified as low plasticity silts as indicated in Table 3 and Figure 6. This is not surprising since the top layer of soil in the Willamette Valley of Oregon tends to be silt with occasional lenses of clay (Balster and Parsons 1968).

However, as indicated in Figure 6, the plasticity indexes and liquid limits of four of the six soils plotted just below the A-line indicating that they were near the dividing line that separates the more claylike materials from those that are predominately silt. The results also indicate that the soils had low plasticity indexes indicating that they are likely to behave in a plastic manner over a narrow range of water contents, possibly creating a challenge in getting just the right water content during construction processes. On the other hand, the low plasticity values also likely indicate that the cob will dry out faster and thereby gain strength quicker as compared to soils with higher plasticity indexes.

TABLE 3. Plasticity test results of the soils used in each mixture.

Mixture	Liquid Limit	Plasticity Index	USCS Classification	Soil Type
A	36	9	ML	Low plasticity silt
B	37	6	ML	Low plasticity silt
C	41	13	ML	Low plasticity silt
D	28	3	ML	Low plasticity silt
E	23	1	ML	Low plasticity silt
F	38	6	ML	Low plasticity silt
Average	34	6	—	—
Std. Dev.	7	4	—	—
COV, %	21	67	—	—

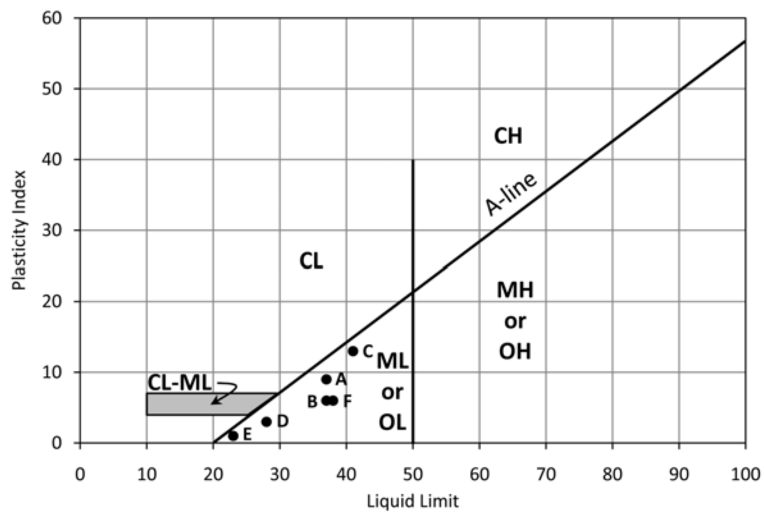


FIGURE 6. Plasticity test results plotted on a classification chart.

Table 3 also indicates a substantial variation in the plasticity index results as indicated by the large coefficient of variation (COV), defined as the ratio of the standard deviation to the average, and multiplied by 100 to express it in percent. That is, a coefficient of variation of say, 15 percent or less, would indicate relatively low variation in the results, whereas the value listed in the table for the plasticity index indicates a relatively wide variation, as can also be seen by considering the range of values. For the liquid limit, a moderate variation existed amongst the soils.

Sand Properties

The sands from all mixtures had similar gradations, with the exception of the sand from Mixture D, as indicated in Table 4 and Figure 7. Based on the coefficients of uniformity (C_u) and curvature (C_c), all of the sands were classified as being poorly-graded, except the sand from Mixture E, which was classified as well-graded.

The results also indicate that the sand from Mixture D was significantly finer than the sands from the other mixtures. It also had the highest uncompacted voids, as shown in Table 5, indicating it had the greatest angularity (confirming the observation listed in Table 1).

TABLE 4. Sieve analysis results of the sands used in each mixture.

Sieve Size		Percent Passing					
U.S.	Metric (mm)	A	B	C	D	E	F
No. 4	4.75	100	100	100	100	90	95
No. 8	2.36	83	87	85	98	84	78
No. 16	1.18	68	74	66	93	67	64
No. 30	0.60	53	61	44	79	48	51
No. 50	0.30	21	26	15	41	27	17
No. 100	0.15	4	5	2	2	14	3
Coefficient of Uniformity, C_u		4.2	3.3	4.2	2.5	9.8†	4.3
Coefficient of Curvature, C_c		0.87	1.1	0.86	0.83	1.2†	0.78

†Estimated by extrapolating the curve to obtain the particle size corresponding to 10 percent passing (i.e., D_{10}).

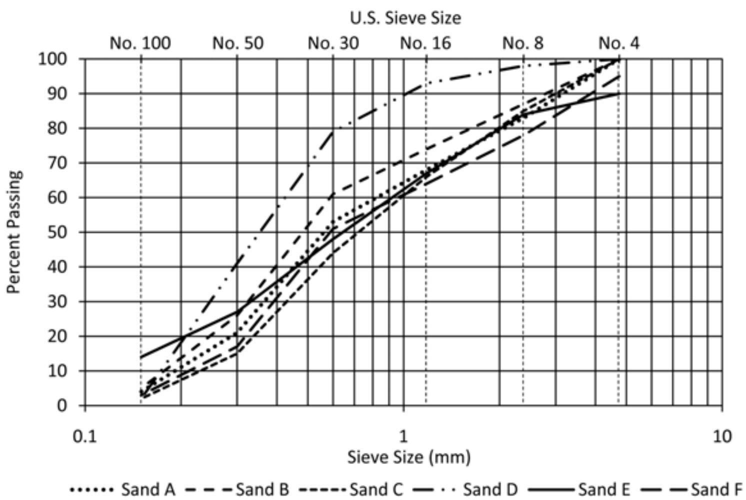


FIGURE 7. Gradations of the sands used in each mixture.

These observations suggest that the engineering properties of Mixture D, particularly compressive strength and modulus of elasticity, should be expected to be markedly different from the other mixtures, as these properties are significantly influenced by the gradation (structure) and angularity of granular aggregates (among other properties) in soil-aggregate mixtures. Note that the coefficient of variation listed in Table 5 indicated a low variation in the uncompacted voids amongst the sands used in the cob mixtures.

TABLE 5. Uncompacted voids of the sands used in each mixture.

Mixture	Uncompacted Voids, %
A	40
B	41
C	43
D	50
E	43
F	44
Average	44
Std. Dev.	4
COV, %	9

Fiber Properties

Table 6 lists the approximate tensile strengths of the fibers used in the cob mixtures, whereas the actual strengths would be expected to be greater than those listed for the reason given earlier in the description of the test procedure, the values shown may still be used for relative comparison of fiber strength. Note that there was a high level of

TABLE 6. Tensile strength of the fibers used in each mixture.

Mixture	Average Long Fiber Length, in.	Average Fiber Diameter, in.	Approx. Tensile Strength, psi
A	6	0.05	2,400
B	12	0.06	2,600
C	8	0.16	700
D	3.5	0.09	1,900
E	7	0.11	1,100
F	9	0.16	500
Average	7.6	0.11	1,500
Std. Dev.	2.9	0.05	890
COV, %	38	45	59

variation in the results. However, there was consistency in the results with respect to the hay from Mixtures A and B, which was from the same source but differed in length. It is worthy to note that it had much greater strengths than the straw from the other mixtures, except for the straw from Mixture D. It is not known, however, if this is generally true for hay versus straw.

Also of note is that the oat straw used in Mixtures C and F had, by far, the lowest strength. However, not knowing the type of cereal plant from which the straw used in Mixtures D and E was derived, comparisons of strengths between types of straw (e.g., wheat versus barely versus oats, etc.) cannot be made from these results.

Basic Mixture Properties

The average dry and average moist unit weights were approximately 96 and 119 lb/ft^3, respectively, as shown in Table 7 and very little variation existed within the results as indicated by the low coefficients of variation. Based on the average dry unit weight, the average dead load at the base of a 6-foot high wall (i.e., on a 2-foot high foundation) would be about 576 lb/ft^2, exclusive of any other loads on the wall and if the cob became completely dry. Since it is unlikely that the cob dries out completely in service, the dead load would be higher than this value, with the actual value depending on the equilibrium water content in the mixture. In

TABLE 7. Basic properties of the cob mixtures.

Mixture	Unit Weight, lb/ft^3		Water Content, %	Sand Equivalent, %	Shrinkage, %		
	Moist	Dry			Diametral	Vertical	Volumetric
A	117.0	92.7	26.2	31	2.2	1.2	5.5
B	118.2	93.8	26.0	31	2.1	1.3	5.4
C	122.0	99.2	23.0	31	1.8	1.4	4.8
D	118.6	95.0	24.9	46	0.7	0.1	1.5
E	123.0	103.7	18.7	42	1.1	0.5	2.7
F	116.2	93.9	23.8	44	1.6	0.6	3.8
Average	119.2	96.4	23.8	38	1.6	0.9	4.0
Std. Dev.	2.7	4.2	2.8	7	0.6	0.5	1.6
COV, %	2.3	4.4	12	18	37	62	41

a study that aimed to develop, through geological and geotechnical investigations, a set of guidelines and best practices for building with cob, Harries et al. (1995) found that the equilibrium water content of cob to be about 4 percent. Assuming this for the equilibrium water content of the cob in this study, the dead load at the base of a 6-foot wall, again excluding any other loads on the wall, would then be, on average, about 600 lb/ft^2.

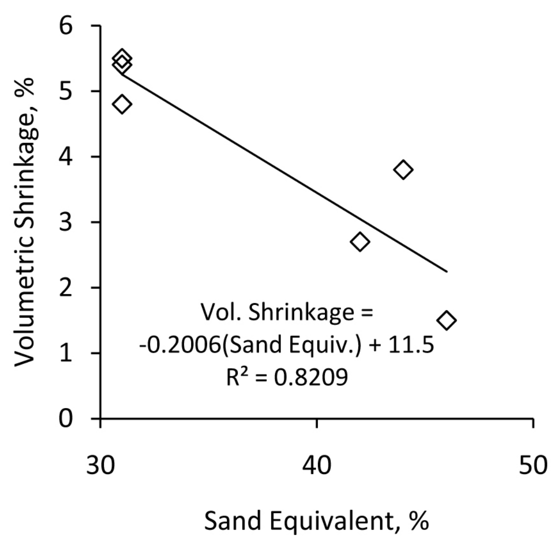
The results in Table 7 also indicate that little variation existed amongst the initial water contents of the mixtures, with the exception of that for Mixture E. It is interesting to note that the water contents of the as-received mixtures were lower than the plastic limits (i.e., liquid limit minus plasticity index in Table 3) of the mixtures in four of the six cases (i.e., for Mixtures B, C, E, and F). Had they been slightly higher, these mixtures would likely have been easier to mold and consolidate in the laboratory. Nevertheless, all water contents of the as-received mixtures were near to the range of water contents whereby the soils were in a plastic state indicating that the amount of water added by the builders, which was done subjectively by consistency or feel of the material, was close to where it should be.

The sand equivalent values varied from 31 percent to 46 percent. Although the values do not represent absolute proportions of sand and claylike particles in the cob mixtures, they do provide a valid measure for comparisons between the cob mixtures.

The shrinkage values listed in Table 7 show that, for all six mixtures, the vertical shrinkage was less than the diametral (or lateral) shrinkage. This is likely due to the forming process whereby the mixtures were compacted vertically in the molds. However, since cob construction also involves vertical compaction of the material, it is reasonable to expect similar behavior of cob mixtures as they dry out during construction. Using the average value for vertical shrinkage, a 6-foot high wall would shrink by approximately five-eighths of an inch, on average. The coefficients of variation, however, show that a moderate to high degree of variation existed amongst the results owing, in part, to the particularly low values for Mixture D, which is not surprising given that it had the greatest proportion of sand relative to soil.

Figure 8 displays the volumetric shrinkage results plotted against sand equivalent showing a decrease in shrinkage with increasing sand equivalent (p-value = 0.013). The figure also includes a least squares linear regression model (line) fitted to the data wherein the coefficient of determination (R^2) signifies that at least 82 percent of the variability in the results is explained by the model; thus, indicating a reasonable relationship between volumetric shrinkage and sand equivalent.

FIGURE 8. Volumetric shrinkage versus sand equivalent of the cob mixtures.



Engineering Properties

Table 8 summarizes the engineering properties of the cob mixtures. The unconfined compressive strengths of the cob mixtures ranged from 65 to 129 psi, and had merely a moderate degree of variation as indicated by the reasonably low coefficient of variation. The findings

TABLE 8. Engineering properties of the cob mixtures.

Mixture	Compressive Strength, psi	Flexural Strength, psi	Modulus of Elasticity, psi
A	102	34.6	1,600
B	107	31.5	2,000
C	90.4	23.5	2,100
D	65.1	10.8	43,000[†]
E	119	23.6	10,000
F	129	26.2	4,700
Average	102	25.0	11,000
Std. Dev.	22.5	8.3	16,000
COV, %	22	33	145

[†]The modulus value listed is comparable to that of a dense-graded crushed aggregate of sound quality typically used for base courses in airfield and highway pavement structures. It is suspected that a problem occurred with the deformation measurements during the test on this mixture.

from this study are lower than those reported by Saxton (1995), who investigated the effect of variable moisture and straw contents on the compressive strength of cob. He found that, for cob mixtures with water contents between 1 and 4 percent, the compressive strengths varied from about 87 to 188 psi, depending on straw content, which ranged from 0.2 to 3 percent by weight. One completely dry mixture specimen exhibited a compressive strength of about 250 psi. However, it is important to note that the cob mixtures investigated by Saxton contained approximately 30 percent gravel, 35 percent sand, and 35 percent silt and clay. As a result, the higher strengths were likely due to the inclusion of the gravel as well as the higher proportion of granular aggregate. In addition, had the cob mixtures investigated in the OSU study contained plastic clay, rather than silt, it is likely the compressive strengths would have been higher.

Comparing the compressive strengths of the mixtures, Table 8 indicates that the strength of Mixture D was much lower than the strengths of the other mixtures. A possible explanation for this might be that the straw fibers in Mixture D were not long enough to mobilize the reinforcing effect of the fibers, thus resulting in pull-out of the fibers (i.e., slip between the fibers and the sand/soil particles) before a significant portion of the load could be taken up by the fibers. Figure 9 supports this premise in that Mixture D failed suddenly along well-defined shear failure planes as shown in Figure 9a indicating brittle failure, whereas the other mixtures failed by slowly bulging outward indicative of ductile failure (Figure 9b). These observations suggest that the compressive strength of Mixture D was dominated by the sand and soil particles, while the strength of the other mixtures was at least partially influenced by the straw fibers. The observations also suggest that the length of fibers needs to be at least 6 inches, on average, to develop adequate bond in order to mobilize a discernable reinforcing effect.

In this study, the cob mixtures had varying proportions of sand and silt (Table 7). Figure 10 displays the effect of the sand equivalent value on the compressive strength of cob mixtures. The figure also includes a least squares regression model fitted to the data, but excluding the results from Mixture D so as to compare only those mixtures containing fibers with an average length of 6 inches or greater. The chart shows that the mixtures that had higher sand equivalent values had greater compressive strengths (p-value = 0.034), and that approximately

FIGURE 9. Failure modes during unconfined compression tests.

a) Brittle (Mixture D)   b) Ductile (other mixtures)

82 percent of the variability in the results is explained by the regression model, indicating a reasonable correlation.

Table 8 also indicates that the moduli of rupture (flexural strengths) ranged from about 11 psi to nearly 35 psi and, consequently, had a fairly high level of variability. However, note that the flexural strength of Mixture D was substantially lower than that of the other mixtures, likely due to inadequate length of fibers to develop sufficient bond for mobilizing their reinforcing effect. All specimens exhibited failure as shown in Figure 4, with a crack forming in the middle third of the beam. In addition, observations of the broken faces of the beams revealed that the fibers broke along the crack in most cases. However, in a few cases, it simply pulled out of the surrounding cob, but the strands were invariably of short length under these circumstances.

Figure 11 shows cob flexural strength versus fiber tensile strength, with the numbers adjacent to the data points indicating the length of fibers in the mixtures. The results suggest that fiber length was largely irrelevant and that cob flexural strength was influenced by the tensile strength of the fibers for fiber lengths 6 inches or greater; that is, cob flexural strength increased with increasing fiber tensile strength (p-value = 0.053).

The least squares linear regression model, which excludes the results from Mixture D, explains at least 76 percent of the variability in the remaining results, thus indicating a reasonable correlation. It should also be noted that the relative proportions of sand and soil

FIGURE 10. Compressive strength versus sand equivalent of cob mixtures with long fibers.

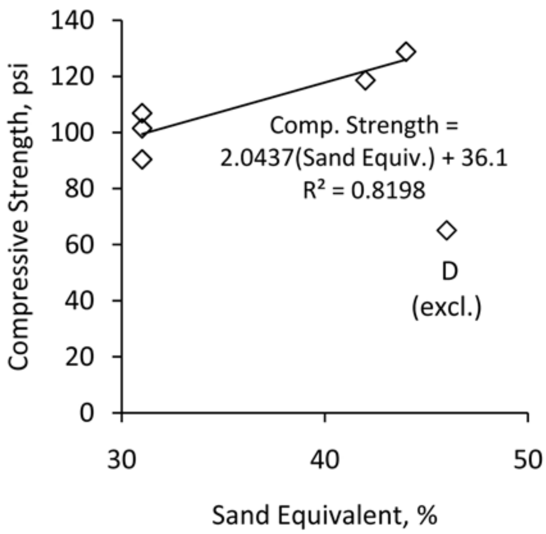
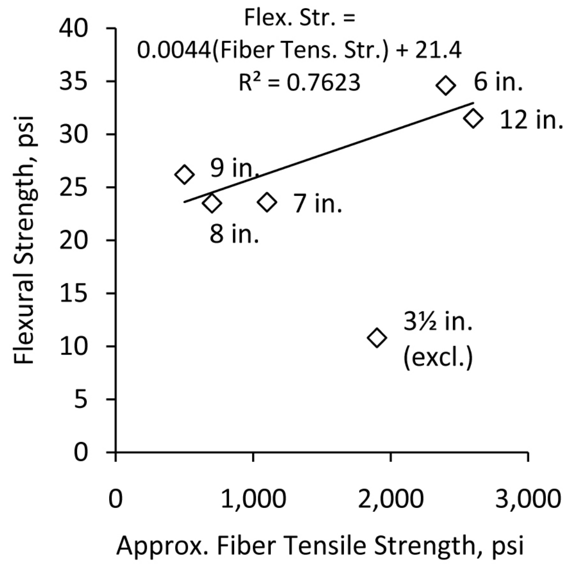


FIGURE 11. Effect of fiber tensile strength on flexural strength of cob mixtures with long fibers.



appears to have had little, if any, influence on the cob flexural strength given that the mixtures with fiber lengths of 6, 8, and 12 inches all had essentially the same proportions of these constituents.

On initial loading during the modulus of elasticity tests, the specimens experienced plastic (i.e., inelastic) strain that ranged from approximately 0.3 percent for Mixture E to about 1.5 percent for Mixture B, as shown in Figure 12. However, this was likely due to particle reorientation near the ends of the specimens due to the high shear stresses at the loading platen-specimen interfaces.

After this initial permanent deformation, all specimens exhibited elastic behavior over the next several load increments. The moduli reported in Table 8 were derived from the slope of the least squares regression lines shown as solid lines in Figure 12, and indicate the range over which the specimens remained elastic. The regression line for Mixture E explained at least 99.7 percent of the variability in the results, whereas those for the other mixtures explained at least 99.9 percent of the variability, indicating a very high degree of linearity in all cases.

Note, however, that Mixture D exhibited elastic behavior over a narrow range of loads (only two additional load increments after application of the seating load). Although the results for this mixture have been included, it is suspected that they may be erroneous. With the result for Mixture D included, Table 8 indicates that a very high degree of variability existed amongst the elastic moduli of the mixtures. Excluding the result for Mixture D would reduce the variability considerably (i.e., to a coefficient of variation of about 87 percent) but, nonetheless, still quite high.

Despite the high variability in the test results, Figure 13 shows that a reasonably strong correlation was found between the modulus of elasticity and sand equivalent when the results from Mixture D were excluded (p-value = 0.116). Moreover, the regression model explained at least 61 percent of the variability in the results.

FIGURE 12. Stress/strain relationships of the cob mixtures.

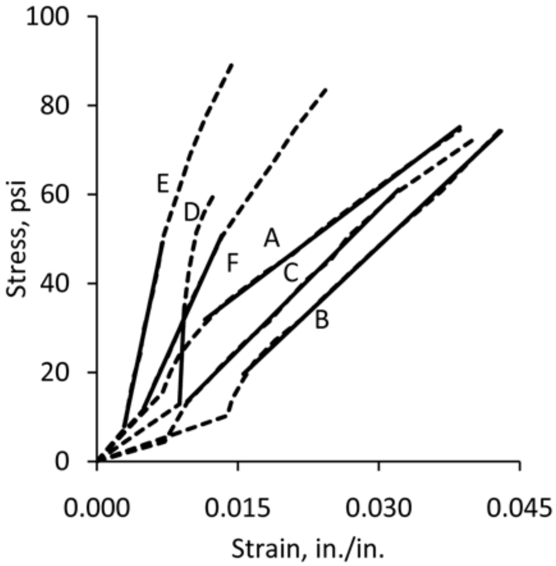
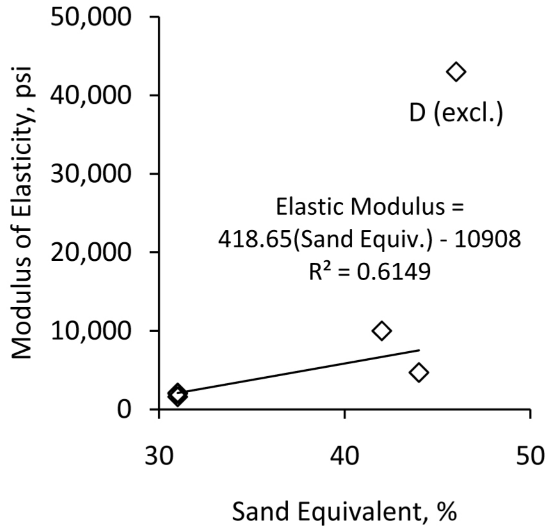


FIGURE 13. Elastic modulus versus sand equivalent of cob mixtures with long fibers.



CONCLUSIONS

The paper summarizes the characteristics of the constituents of six typical Oregon cob mixtures provided by experienced cob builders. Index property tests (i.e., soil plasticity and gradation and angularity of the sands) indicated similarity amongst the soils and sands used in the mixtures, with the exception of the mason sand used in one of the mixtures (it was much finer and had greater angularity relative to the sands used in the other mixtures). One builder utilized hay in the mixtures, whereas the others used straw, and tensile strength tests indicated that the hay possessed greater strength. However, there was also a high level of variation amongst the tensile strengths.

The paper also summarizes various properties of the mixtures. Basic properties included moist and dry unit weight, water content, sand equivalent, and shrinkage. Little variation existed amongst the mixtures with regard to unit weight and moisture content, but a much higher level of variation existed amongst the mixtures with regard to shrinkage. Sand equivalent values indicated a moderate range in the relative proportions of sand and claylike particles in the mixtures. Nevertheless, a reasonable correlation between volumetric shrinkage and sand equivalent was established indicating a decrease in shrinkage with increasing sand equivalent value (p-value = 0.013 and $R^2 \approx 0.82$).

Unconfined compressive strengths of the mixtures ranged from 65 psi to nearly 130 psi, with a moderately low degree of variation amongst the mixtures (coefficient of variation of 22 percent). Sand content appeared to have influenced compressive strength of the mixtures with long fibers (6 inches or greater) in that a reasonable correlation was established indicating an increase in compressive strength with increasing sand equivalent value (p-value = 0.034 and $R^2 \approx 0.82$).

Flexural strengths ranged from about 11 psi to nearly 35 psi, with a moderate level of variability (coefficient of variation of 33 percent). Fiber length did not appear to influence cob flexural strength, but a reasonable relationship was found indicating increased cob flexural strength with increasing fiber tensile strength for fiber lengths of 6 inches or greater (p-value = 0.053 and $R^2 \approx 0.76$).

Modulus tests indicated a very wide range in the elastic moduli of the mixtures, from 1,600 to 43,000 psi (however, error is suspected in the highest result). Conservatively, a range from 1,600 to 10,000 psi seems more reasonable from the mixtures tested in this study, but still with a high level of variability. Through exclusion of the suspect results, a reasonable relationship was established indicating increased elastic modulus with increasing sand equivalent (p-value = 0.116 and $R^2 \approx 0.61$).

It is important to note that, strictly speaking, the correlations contained herein only apply to the materials investigated in this study and are dependent on the results from the tests used to investigate the mixtures and their constituents. Hence, the correlations may not apply to other materials or results derived from other tests. However, the correlations do provide strong evidence to suggest that certain properties or proportions of the constituents significantly influence the engineering properties of cob.

The study also demonstrated that conventional test methods used for soils and concrete were readily adapted for use in evaluating cob mixture properties. Further, it demonstrated that use of these tests could effectively assess the impact of differences in the constituent material characteristics on the performance (i.e., strength and modulus) of cob mixtures. That is, the tests could be used to optimize compressive and flexural strength properties through varying proportions of constituent materials (e.g., sand-soil proportions) and other characteristics of the materials (e.g., fiber tensile strength, sand angularity, etc.).

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