Tested R-value for Straw Bale Walls and Performance Modeling for Straw Bale Homes

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ABSTRACT

Since the late 1800's, houses have been built of straw. Contrary to nursery rhymes, these houses have proved sturdy and comfortable and not at all easy to blow down. In the last several years, as people have experimented with new and old building materials and looked for ways to halt rice field stubble burning, there has been a resurgence of homes built with straw. Unfortunately, there has been very little testing to determine the thermal performance of straw bale walls or to discover how these walls affect a home's heating and cooling energy consumption. Reported R-values for straw bale walls range from R-17 to R-54, depending on the test procedure, the type of straw used and the type of straw bale wall system.

This paper reports on a test set-up by the California Energy Commission (Commission) and conducted in a nationally accredited lab, Architectural Testing Inc. (ATI) in Fresno, California. The paper describes the tested straw bale wall assemblies, the testing process, and problems encountered in the construction and testing of the walls. The paper also gives a reasonable R-value to use in calculating thermal performance of straw bale houses and presents findings that show that straw bale construction can decrease the heating and cooling energy usage of a typical house by up to a third over "conventional" practice.

Introduction

California's rice growers are allowed to burn 25% of their acreage in order to get rid of the straw after harvest. The other 75% is either tilled in or baled and removed for other uses. In 1995, the California Legislature passed and Governor Wilson signed into law AB 1314, a bill that authorizes all California jurisdictions to adopt building codes for houses whose walls are constructed of straw bales[1].

The new law provides guidelines for moisture content, bale density, seismic bracing, weather protection, and other structural requirements, but does not provide any guidance on the thermal performance of straw bale houses nor on how to determine the thermal performance (R-value) for purposes of demonstrating compliance with the state's Building Energy Efficiency Standards (Standards). Generally, the Commission provides guidance to the state's building community and building departments on the energy related performance characteristics of residential building envelope features, including wall systems. The purpose of the testing conducted at ATI was to help the Commissioners make an informed decision on what nominal R-value to assign to straw bale walls for purposes of modeling building performance in California.

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1 Health and Safety Code, Chapter 4.5 to Part 2.5 of Division 13 (commencing with Section 18944.30).

Background

Research of the existing data on thermal performance of straw bale wall systems revealed that R-45 was the generally accepted value for two string, 18" wide bales and about R-55 for 23" wide three string bales. These figures were quoted in a 1995 straw bale article in *Architecture* and in DOE's 1995 publication *House of Straw*. In their 1994 book, *Build it with Bales*, Matts Myhrman and S. O. MacDonald ascribe R-40 to R-50 for bale walls. The literature up to early 1996, including the above citations, seemed to rely almost solely on a test performed in 1993 at the University of Arizona Environmental Research Laboratory as part of a masters thesis by Joseph C. McCabe. The testing guideline that he used was ASTM C 1045-90 Standard Practice for Calculating Thermal Transmission Properties From Steady-State Heat Flux Measurements, and the test was an ASTM C-177-85 1991 Standard Test Method for Steady-State Heat Flow Measurement and Thermal Transmission Properties by Means of the Guarded-Hot-Plate Apparatus. This test measures the heat flow through a single bale using a guarded-hot-plate. McCabe reported three R-values in his paper: R-48.8 and R-52.0 for bales on edge (16.5" wide) and R-54.8 for bales laid flat (23"). McCabe concluded that the higher R-values per inch occurred for bales on edge because of the orientation of the straw within the bale. When straw is baled, the straw fibers run the width of the bale and are generally 22" to 23" long (for three-string bales). Bales laid flat orient the fibers parallel to the floor and aligned with the heat flow from the interior (warm) side to the exterior (cold) side. He postulated that the heat flows easier through the fibers oriented with the flow than across the flow as when the bales are laid on edge. McCabe's results form the basis of most opinions on straw bale wall performance. The thermal performance ratings he obtained were quoted in the bible of straw bale builders, *The Straw Bale House*, by Athena and Bill Steen, David Bainbridge and David Eisenberg, as well as in an article on *Straw: The Next Great Building Material*, by Alex Wilson in Environmental Building News, May/June 1995.

Further testing at Sandia National Laboratories by R.U. Acton on May 13, 1994, seemed to confirm McCabe's results. Acton measured straw bale conductivity by use of a thermal probe. "The method simulates a 'line heat source' in an infinite medium." Constant, regulated power is supplied to the probe. The resultant temperature rise at the point of heat input is a function of the thermal conductivity of the surrounding medium. Welded to the center of the probe is a thermocouple which registers the temperature rise in the straw. By analyzing the heat input into the probe versus the temperature of the surrounding straw, Acton was able to estimate the R-value of the 16.5" (two-string) bale to be R-44. This testing method cannot take into account the effects of straw orientation. The composition and density of the straw bale were not reported.

As-yet-unpublished results from Oak Ridge National Laboratory (ORNL) tests performed in 1996 indicated a much lower insulation value, R-17, for a wall constructed of 18" (two-string) bales with stucco on the cold side surface and gypsum board on the warm side surface. Jeff Christian of ORNL stated that in order to attach the gypsum board to the straw bales, he drove 2"x4" stakes into the bale wall and then screwed the gypsum board onto the ends of the stakes. The technique was described in *Build it with Bales*, by MacDonald and Myhrman. Christian commented that this technique created an air gap that could have resulted in convection currents between the gypsum board and the bale structure that reduced the R-value of the wall. This may be indicative of a problem with homes that are constructed using drywall or paneling for the inside surface treatment[2]. The exterior surface was stucco over chicken wire and it also had slight air gaps that were discovered upon the disassembly of the test wall. The publication of Christian's report was expected last year but was delayed while he explored the possibility of re-running the experiment with some tighter controls on the construction of the wall.

In 1996 Commission Staff presented information on the various tested R-values for straw bales to the Commissioners. This was done so they could decide what R-value to assign to straw bales for use with the state building standards. The Commissioners decided to advise interested parties that, pending additional test results, parties should use the wall insulation values required by the Standards' Prescriptive Packages appropriate for the climate zone in which the building was to be constructed. In other words, if the standard prescriptive wall insulation requirement for a project's climate zone is R-19, then the builder can assume straw bale walls to perform as R-19 walls. If the Package requirement is an R-13 wall, then the straw bale wall is assumed to be R-13. These very conservative values were given partly to encourage straw bale advocates to perform definitive testing.

The CEC Test

There is very little funding for thermal testing of straw bales and it appeared unlikely that any new testing would be done very quickly. For this reason, the authors of this report contacted individuals and testing labs in California to see if another test could be run using only volunteers. In January of 1997, ATI agreed to test sample straw-bale walls in their new, state-of-the-art, ASTM C-236[3] style guarded-hot-box test chamber. Commission Staff arranged for donation and delivery of the requisite bales from the California Rice Industry Association, experienced straw-bale builders to construct the walls, a plasterer experienced with straw-bale construction, and a panel of experts to advise and review. The authors of this report assisted in building and demolition of the test walls and evaluation of the test results. The test at ATI's Fresno, California lab was begun on May 29, 1997 and concluded on June 6,1997. Two straw bale walls were constructed in their test chamber. For one test wall, the three string bales were laid flat (23"), and for the other they were laid on edge (16"). Test results yielded R-26 for the bales laid flat and R-33 for the bales on edge; significantly lower than the widely accepted performance.

Upon disassembly of the wall, several problems that would lower the apparent R-value were discovered. One problem was residual moisture under the stucco. Water had been sprayed on the stucco during curing in order to reduce cracking. Moisture migrated through the stucco and into the straw bales, and because the constructed walls in ATI's test chambers prevented the lab from being able to perform any other tests for their clients, we ran these tests after less than a week of drying time. Under the stucco, the bales were moist to a depth of approximately one half inch away from edges and

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2 Discussions with contractors building with straw bales in California indicate that the method used for the interior finish in the ORNL test is not typical of California construction. Typically, the interior is plastered and there is no air space between the straw and the plaster.

3 American Society for Testing Materials (ASTM) test procedure C-236: Test Method for Steady State Thermal Performance of Building Assemblies by Means of a Guarded-Hot-Box. Annual book of standards, Philadelphia, PA

up to six inches deep along some edges of the bales. It is reasonable to assume that the moist straw conducted heat much more rapidly than did the bales at the center of the walls.

A second problem arose because of an attempt to get as much vertical compression on the walls as possible to simulate the conditions they would experience with an imposed roof load. To do this we placed wood assemblies on the bottom and top of each wall and then wrapped polypropylene strapping around the walls. This strapping was cinched down in order to compress the wall. After compressing the wall there was a three inch gap left between the top of the bale and the test chamber wall. As much loose straw as possible was stuffed into this gap and other voids in the wall. Upon disassembly we found that there were still many areas either without straw or where the straw was very loosely packed. It is our assumption that these areas may have decreased the R-values in the overall wall assembly by allowing convective currents.

The 1998 ORNL Test

On May 15, 1998 ORNL completed a second test in their guarded hot box test chamber. Several nationally known builders of straw bale homes as well as Tav Commins of the CEC were invited to oversee construction of the test wall. ORNL built the wall using 19" two string bales laid flat and stuccoed on both sides. It was allowed to dry for almost two months in their temperature- and humidity- controlled lab where it reached a reached a moisture content of 13% The wall was then placed in the test chamber where the interior and exterior air temperatures were brought to 70°F and 0°F, respectively. It was then given a full two weeks to reach steady state heat flow conditions. At the end of the two weeks the 19" wall was found to have an R-27.5. The authors of this report feel that this is the most accurate test to date.

Analysis

The table below provides data on all of the known tests done to date and compares them to the CEC nominal R-value and assumptions.

TABLE 1. Straw Bale R-values

	Joe McCabe	Sandia Lab	ORNL	CEC	CEC	ORNL
Test Procedure	Hot plate Single bale	Thermal probe Single bale	Hot box Full wall	Approved Values	Hot box Full wall	Hot box Full wall
Test Date	1993	1994	Oct. 1996	Dec. 1996	May 1997	Feb. 1998
Type of Straw	Wheat	Not Listed	Wheat	Any	Rice	Wheat
Bale Type	3-string, 23"	2-string, 18"	2-string, 18"	3-string, 23"(assmd)	3-string, 23"	2-string, 19"
Moisture Content	8.4%	Not Listed	Not Listed	<20%	11%	13%
Density lbs/Ft^3	8.3	5.2	Not Listed	7	6.7	8.0
R-value Per Inch	2.38	2.67	.94	.56 - .91	1.13	1.45

Hot box testing is the most accurate test method for finding the R-value of a type of wall construction. For this reason the results from ORNL and CEC tests should carry a greater weight when determining the value for modeling performance of homes. Given our assessment of the accuracy of the 1996 and 1997 tests, and the greater accuracy of the 1998 ORNL test, we use an R-value of 1.3 per inch (R-30 for 23" walls) for purposes of comparing the energy performance of straw bale construction to "standard" construction. The results of that analysis across five climate zones in California are presented in Table 3 below.

Another physical property of straw bale construction that affects energy usage is its high thermal mass. In order to calculate the thermal mass effects in a home, one must know the specific heat as well as the density of the mass materials. Our research did not reveal any reported value for the specific heat of straw. The authors compared values for comparable materials found in the 1997 ASHRAE Handbook Fundamentals.

TABLE 2. Specific Heat of Materials

Material	Specific heat Btu/ lb °F
Cellulose, Hemp(fiber), Paper, Wool and Silica	.32
Wool	.33
Softwoods with 12% Moisture Content	.39

The specific heat of these materials are very close in value. Using the above information the Energy Commission decided that when modeling straw bale homes a specific heat of .32 Btu/ lb °F should be used until further testing is done.

Commission approved building simulation programs require that the density of a material also be specified in order to receive thermal mass credit. The density of straw bales can vary depending on how tightly the bales are packed as well as how much moisture is in them. The California Energy Commission has been instructing people to model a density of 7 lbs/Ft^3 with a maximum moisture content of 20%, the minimums specified in the California Health and Safety Code, Chapter 4.5, Section 18944.35(d) and (e). If the actual density of the bales is known, then that number should be used.

Listed in Table 3 below are estimates of energy savings of a straw bale house compared to the energy budget for a conventionally framed house using CALRES2. We modeled a 1761 Ft^2 home assuming only minimum efficiency equipment. In the base case house, all requirements from the prescriptive package for each climate zone were modeled (see Table 4a). The base case, or standard home is a square, house with equal amounts of fenestration on each wall. In the standard 1761 Ft^2 model, each wall is 41.96 feet long. The straw bale house modeled has the exact same wall area and square footage with equal amounts of glass on each wall. Listed below are the values used for modeling the proposed straw bale house in the CALRES2 runs (see Tables 4a. and 4b.).

TABLE 3. Annual Energy Savings From Straw Bale Construction (kBtu/ ft^2, & $US)

California Climate Zones (CZ)	CZ 11	CZ12	CZ13	CZ14	CZ15	Avg.
Heating Energy Savings, kBtu/ ft^2	1.75	1.61	1.36	1.75	.63	1.42
% Heating Savings	11%	11%	12%	11%	21%	13%
Heating Cost Savings, $/Yr.	$15.40	$14.18	$11.97	$15.41	$11.09	$12.50
Cooling Energy Savings, kBtu/ ft^2	2.87	2.82	2.88	2.47	2.93	2.79
% Cooling Savings	31%	46%	21%	21%	11%	26%
Cooling Cost Savings, $/Yr.	$49.36	$48.50	$49.53	$42.48	$50.39	$47.99
Total Annual Energy Savings	$64.76	$62.68	$61.50	$57.89	$61.48	$60.49
Total Annual Energy Cost, Base Case	$360.33	$230.47	$322.23	$341.15	$501.27	$351.09
Total % Savings	18%	22%	17%	15%	12%	16.8%

Notes:

1. **California has 16 climate zones representing geographical divisions based primarily on seasonal temperature differences. Only climate zones very close to where straw is generated were used since the greatest cost of straw bales is transportation. The climate zones used in the report are all Central Valley or Southern California agricultural areas.**
2. **For calculating dollar savings, electricity was assumed to cost $0.10/kWh and natural gas was assumed to cost $0.50/therm. All cooling energy was assumed to be derived from electricity and all heating energy from natural gas.**
3. **The annual cost savings is determined by the following formula:**
   Annual heating cost savings = (q_h X 1761 X 0.50)/100,
   Annual cooling cost savings is determined by:
   Annual cooling cost savings = (q_c X 1761 X 0.10) /10.239

   Where:

   q_h **= Heating energy savings, in kBtu/ ft^2 yr.**
   qc = cooling energy savings, in kBtu/ ft^2 yr.
   1761 = house size, in ft^2
   $0.50 = Cost per therm of natural gas, In dollars
   $0.10 = Cost per kWh for electricity, in dollars

TABLE 4a. Assumptions for CALRES2 Simulations- Building Features

Material	Efficiency
Windows, U-value	0.65
Window Area	16% of floor area
Window Shading Coefficient, CZ 11,12,13,14	South .66, West .40, East .40, North .66
Window Shading Coefficient, CZ 15	South .40, West .40, East .40, North .66
Air Conditioner	SEER 10
Roof Insulation	R-38
Floor	Slab on grade
Walls - Straw Bale	R-30
Walls - CZ 11,12,13	R-19 (2X4)
Walls - CZ 14,15	R-21 (2X6)
Water Heater - Gas	EF .53 with R-12 Wrap

Note: Often builders of straw bale homes install hydronic heating and no air conditioning because of the significant amount, and well-distributed placement of mass in the plastered interior face of the walls. Both features help moderate the temperature in the home and can dramatically reduce heating and cooling loads. This type of heating system, however, was not modeled.

TABLE 4b. Assumptions for CALRES2 Simulations - Straw Bale Properties

Straw Bale Wall	Values
Straw Specific Heat	.32 Btu/ lb °F
Straw Density	7 lbs./Ft^3
Straw Thickness	23"
Stucco Specific Heat	.16 Btu/ lb °F
Stucco Density	116 lbs./Ft^3
R-value Per Inch	R-1.3
R-value for 23" Bale	R-30
Stucco Thickness	1" on inside and 1" on outside of wall

Using an assumption of R-30 and the above-described thermal mass for the walls, total energy savings from straw bale construction range from 3.56 kBtu/ft^2 in CZ 15 up to 4.62 kBtu/ft^2 in CZ 11 in the climate zones in the Central Valley of California where grains are grown and straw is baled (climate zones 11-15). If all climate zones in the state are included, the range is 2.24 kBtu/ft^2 in CZ 1 to 6.4 kBtu/ft^2 in CZ 10. The average of the total heating and cooling savings, using just CZs 11-15, is approximately 4.21 kBtu/ft^2. This translates, for an average sized house (1761 ft^2), to an annual electricity savings of $47.99, and an annual gas savings of $12.50. This represents a 13% savings of natural gas for heating and a 26% savings in electricity for cooling. There are other energy efficiency factors (see discussion below) regarding straw bale construction which CALRES2 and other simulation tools are not able to model, so the actual savings may be greater.

It was the authors' speculation that with nearly two foot thick walls it would be a good idea to move the south facing windows to the inside of the house in order to have a "built in" 18" overhang. After analyzing the runs, we found that the overhangs decreased the cooling budgets but typically increased the heating budget more. For this reason overhangs were not modeled on any of the runs.

Other Factors

People who live in or visit straw bale homes talk about how comfortable they are. With straw bales having such a high R-value and high thermal mass it is understandable that these homes are able to maintain a relatively constant temperature with very little energy input. Air temperature is only one of the many factors that affect comfort. According to Alan Meir, there are actually six different elements that affect thermal comfort (Meir1994): air temperature, insulation value of the clothing, activity level, temperature of surrounding surfaces, air speed and humidity. In straw bale homes three of the six areas are addressed. These are: air temperature, temperature of the surrounding surfaces, and air leakage. Radiant temperature has perhaps the greatest impact on how comfortable people feel. A home that has warm walls and floors can achieve the same level of comfort at cooler air temperatures than can a home with a lower mean radiant temperature (MRT). Meir states that raising the MRT 1°F allows a 1°F reduction in the air temperature with no reduction in comfort. Because straw bale homes have such high R-value and also have a high thermal mass, the perceived comfort is very great compared to other types of wall systems.

Air leakage also has a dramatic impact on perceived comfort. Tests have shown that any draft over 0.4 feet per second causes the surface air film on individuals to collapse (Meir 1994, 39). In Jeff Christian and Jan Kosny's report (1996), they stated that "many of the leakage paths through an exterior wall of a residential building occur at the wall connections and not through a typical clear wall." Because of the construction techniques used with straw bales (stucco on the outside and plaster on the inside), there is an almost solid air barrier to keep drafts out. Due to the overlapping of bales at corners and the fact that there are no direct interior/exterior connecting paths leading to outlets and switches, air leakage in straw bale homes should be significantly lower. However, this has not been tested to date, and in fact settling of the bales may cause plaster cracks and result in leakage around doors and windows.

Conclusions

Straw bale walls are widely accepted as contributing much more to the energy efficiency of a home than 2"x4" or even 2"x6" walls. However the early declarations of R-2.38 to R-2.68 per inch, which were based on tests of individual bales, appear now to have been overstated for how bales perform in wall systems. Likewise, the somewhat later tests which showed R-values of approximately 1 per inch were understating the actual performance of straw bale walls. It appears that once enough testing is done the performance will settle out to be somewhere between R-1.3 and R-1.5 per inch, though it is unlikely that straw bale walls will ever obtain the same volume of testing that more conventional wall systems have. The most accurate test to date obtained R-1.45 per inch. Even at the conservative R-1.3 per inch with standard[4] (23") bales laid flat, the average homeowners in Central California would save $60.49 annually on their heating and cooling bills. Assuming only half the expected 90,000-100,000 homes to be built in California per year in the near future are going to be close enough to sources of straw to make its use cost effective; and assuming that only the 20% of houses that are not in large subdivisions are candidates for straw bale construction; and assuming that only 15% of the builders of the remainder actually choose the technology;

a) approximately 1500 homes (per year) could be built to the higher level of comfort afforded by straw bale construction,
b) the occupants of these homes would save approximately $60.49 for a 1761 ft^2 home each year in heating and cooling energy representing an average energy savings of 39%,
c) Approximately 1.2 million board feet of lumber would be displaced each year, and
d) Rice and wheat growers would receive approximately $1.5 Million for straw they now burn or plow under.

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4 "Standard" bales outside of California may be 19" instead of 23".

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