Thermal Performance of Straw Bale Wall Systems

Nehemiah Stone

ABSTRACT

In this analysis we provide a summary of the results of research that has been done, examine the implications of each to residential thermal comfort, and suggest a reasonable thermal performance value for plastered straw bale walls as a synthesis of the data.

There are four ways that have been used to estimate the thermal performance of straw bale walls:

1) Testing of bales using a hot-plate or thermal probe methodology,
2) Testing of bale wall structures in a guarded hot-box facility,
3) Monitoring of straw bale wall performance under ambient conditions, and
4) Modeling of straw bale wall performance using known or assumed physical properties of the materials.

Honest researchers will admit that any of the approaches mentioned above provides only an estimate. Each method has its advantages and proponents, just as each has shortcomings and detractors.

In the first two, testing under controlled conditions allows the researcher to estimate the thermal resistance to heat flow through the material. This is expressed as an R-value. R-value is the inverse of U-factor, or conductivity. U-factor is a measure of Btu/(hr. s.f. °F), or British thermal units per hour, per square foot of material, per degree Fahrenheit of temperature difference between the two sides of the material.

The third method has been used to estimate the amount of heat lost through the entire envelope over a year (or other specified period). The results can then be compared to the amount of energy that a "comparable" house of other materials might use as measured or modeled.

The final method relies on principles of physics, and computer software. In its simplest form, the modeling simply uses known resistance values of straw, air, and the materials that act as the interior and exterior finishes for a straw bale wall system, to develop an overall thermal resistance of the system. This can be compared to the R-value estimates obtained by either of the first two methods, or used in a building modeling analysis to attempt to verify the results of the building monitoring (third method described above).

The attempts to determine the R-value of straw bales and straw bale wall systems began in 1993 as a masters thesis project by Joe McCabe. McCabe tested both wheat and rice straw bales at various moisture conditions using a guarded hot plate. He obtained R-values that ranged between 2.38 and 3.15 per inch of thickness. (More detailed descriptions of each test follows later in this report.)

Tests of single bales at Sandia Labs in 1994 resulted in estimates of R2.67 per inch. R.U. Acton conducted the Sandia tests using a thermal probe methodology.

In 1996 Oak Ridge National Labs (ORNL) performed the next test on a straw bale wall system, more as a teaching experience for elementary school teachers than as a serious attempt to determine the R-value of straw bale walls. These tests were run by Jeff Christian using a guarded hot box. There were controversial issues with how the interior and exterior finishes were applied, and the results provided an estimated R-value below R-1 per inch—little more than a third of what the two previous tests had attained. (The use of a "per inch" R-value is itself misleading in that this and subsequent tests measured heat flow across stacked bales with plaster on both sides—a composite assembly with heterogeneous properties.)

The next year, Nehemiah Stone organized a set of hot box tests at a commercial test lab in Fresno California. The specimens were constructed by experienced builders who were familiar with straw bale construction. However, the constraint of building a test specimen into an existing opening, and the inability to allow the specimen to fully cure (dry) due to the commercial need for the lab equipment, resulted in thermal performance data that was also disappointingly low: R-1.13 to R-2.06 per inch.

Because of the concern that tested R-values varied so much, researchers and straw bale practitioners from around the country cooperated on another effort at ORNL to build and test a straw bale wall specimen representative of actual field practice. In 1998, Jeff Christian, David Eisenberg and others (including a member of Stone's 1997 team) built a wall at ORNL and, after sufficient curing time, tested it to have a thermal performance of R-1.45 per inch.

There are a couple of straw bale building monitoring studies of note. One was conducted in 1996 by Gail Brager of UC Berkeley as a model of the Real Goods Center in Hopland, CA. Sensors logged indoor air, outdoor air, and indoor and outdoor surface temperatures over a ten day period. The data showed a remarkable ability for straw bale walls to mitigate significant ambient temperature swings, but the data were not used to estimate a wall system R-value. Instead, the walls were assumed to be R-65 based on "common knowledge" of the straw bale community, and the heat capacity (thermal mass) of the walls were calculated. Based on the fact that the thermal mass appeared to be lower than air, it can be assumed that the assumption of R-65 is high. The data from this monitoring project could potentially be reanalyzed to provide an estimated R-value.

The other building monitoring project was conducted by Canada Mortgage and Housing Corporation (CMHC) on eleven straw bale homes built between 1996 and 2001. The data are not complete enough to be able to develop an R-value directly. CMHC compared the energy use of these homes to a predicted energy use for "standard" construction and found that the straw bales homes used an average of 20% less heating energy. This data too could be mined to estimate an R-value range based on the surface area of the walls and all other conducting surfaces. There are limitations to the usefulness of building monitoring results in trying to determine the wall system R-value. These limitations can be summarized by the statement that "building performance is affected by a lot more than the R-value of a wall," such as varying climate conditions, internal heat gains (the heat of the people and appliances), and humidity. In fact, there are other characteristics of the wall itself that affect thermal performance, and which we need to consider: e.g., thermal mass and surface emissivity.

The actual R-value for straw bale wall systems will vary with a number of factors, including type of straw, moisture content of the straw, density and orientation of the straw, presence and size of other wall elements, type and thickness of finish applied, and other factors. This report will provide a range of values, identify the primary controlling variables, and, based on the existing body of research, offer a recommended value for use in building energy flow models.

A good starting point is a discussion of what R-value is, and what it is not. It is not an absolute measure of how energy efficient your building is. It is not even a perfect way of predicting the wall's contribution to thermal comfort. It is one piece of information about the wall that, with other information, can enable you to estimate the heat loss and heat gain through the walls.

R-value is the inverse of U-factor (R = 1 / U). U-factor is a measure of thermal conductance, or how easily a material (or system) allows heat to pass through it. This is how U-factor is defined (in the U.S.): the number of British thermal units that pass through one square foot of a material (or system) per hour with a one degree Fahrenheit temperature difference between the two sides of the material. Mathematically:

$$\textbf{U-factor} = \textbf{Btu} / (\textbf{h}*\textbf{ft}^2*°\textbf{F})$$ [1]

When a laboratory tests a material (or system) to determine its thermal conductance or resistance, they calculate the heat flow from one side to the other on the basis of measured surface temperatures and heat energy required on the warm side of the wall to maintain a steady heat flow. This provides the U-factor, which is then converted to R-value for some purposes.

Before they can say they have a steady heat flow, there must be a number of temperature readings all with the same (or nearly the same) value. This is an important point that has significance for understanding how relevant the R-value of a system (e.g., a straw bale wall) is to the comfort or energy efficiency of a home. For most "standard" construction systems (e.g., 2x6 studs with R-19 insulation), it takes anywhere from 20 minutes to a couple of hours to reach the steady state heat flow conditions. For plastered straw bale walls, it can literally take weeks.

Therefore, what is being measured in the lab has a direct corollary to a straw bale home in a far northern climate where the temperature stays at or below zero Celsius for weeks on end, but may have less direct relevance to homes built in most of the climates where straw bales homes are being built—climates where daytime temperatures climb to well above freezing. In their analysis of the Real Goods Living Center in Hopland, California, three UC Berkeley grad students (Carter, Jain and Hou; 1996) determined the thermal lag (the time it takes for a "pulse" of heat to travel through the wall) was about 12 hours. Other research has provided similar results. In most climates, at most times, the outside temperature goes through a diurnal swing (one full cycle per day), so that just about the time the heat from the inside of the building is reaching the exterior, the air temperature outside rises, and the heat loss at the surface decreases. This effect will make a building wall with a good R-value act like one with a superb R-value.[2]

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[1] In most other countries U-factor is defined in terms of Watts per square meter per degree Kelvin [W/(m^2*K)]. To convert metric (SI) U-factors to inch-pound (IP) U-factors divide by 5.678; to convert the other way, simply multiply by 5.678. To convert IP R-values to metric R-values, multiply by 0.1761.

[2] This is one of the issues mentioned earlier that makes it difficult to use direct building performance data in trying to calculate a wall system's R-value.

Another aspect of R-values, important to an understanding of the testing and other comparative analyses that have been done on straw bales, is that the term "R-value" is not always applied the same way to all systems. Insulation manufacturers advertise the R-value of their product. It is tested and verified and you can count on it being correct – for the material. When insulation (e.g., fiberglass batts or sprayed cellulous) is placed in a wall system, a number of other factors affect how that system performs:

- Size, material, and spacing of the studs (or other structural frame)
- sealing (or lack of it) around wall outlets and switch plates
- sealing (or lack of it) at the junction of the wall and the floor
- fill of the insulation to the top of the wall cavities (ie, is there a gap?)

Standard construction practice in almost all these categories results in R-values for the wall systems that are significantly less than the advertised R-value for the insulation. An "R-19 wall" often has a system R-value around R-14. Straw bale walls, by the nature of the construction, do not suffer these same losses: an R-35 straw bale wall *is* R-35.[3]

One final note before the comparison of the various tests and analyses that have been done. There is a point of diminishing returns in the pursuit of higher R-value wall systems. When comparing two R-values that differ by 10, there is a very significant impact on energy performance if both values are relatively low (e.g., R-9 and R-19). When comparing two R-values that are relatively high (e.g., R-33 and R-43), a difference of 10 has very little significance. To understand why this is true, convert the R-values back to U-factors.

R-value	U-factor
9	0.111
19	0.053
33	0.030
43	0.023

Figure 1: R-value vs. U-factor

It is obvious from this that an R-9 wall allows more than twice as much heat to flow through each hour as does an R-19 wall. An R-33 wall, by contrast, allows less than a third more heat to flow through compared to an R-43 wall. Add to this the previous points that an "R-19" wall is really only at R-14, and a straw bale wall, due to the thermal lag, actually significantly outperforms its rated R-value, and the long running debate about whether the true R-value is around R-35 or R-45 or R-55 becomes pointless (if not empirically meaningless).

Testing History

The first testing of the thermal properties of straw bales was done in 1993 by Joe McCabe as part of his Masters Thesis at the University of Arizona (McCabe; 1994). He tested rice straw and wheat straw bales using a guarded hot plate technique. He placed a hot plate between bales, located thermocouples on probes at various distances from the hot plate, and measured the temperature differences once heat flows reached a steady state. His results indicated an R-value of 2.38 to 3.15 per inch (R-54 to R-71 for three string bales, R-39 to R-52 for two string).

3 Note that the effect discussed in the previous paragraph argues that the straw bale wall system will actually perform much better than the laboratory tested R-value in most climates.

The next test was performed in 1994 at Sandia National Lab by R.U. Acton. These tests used a thermal probe that has a heat source and thermocouple near the point of the probe. When buried in an insulating material such as a straw bale, the temperature rise at the probe can be used to calculate the insulating value of the material. Using this technique, Acton was able to estimate the R-value of two string (16.5") bales to be R-44. Acton did not report the moisture content of the straw and the density was 5.2 lb/cu.ft. (less than 2/3 that of McCabe's bales, and significantly below the code allowed density for construction).

Both of the first tests were tests of straw bales, not plastered straw bale walls. In 1995, Watts, Wilkie, Thompson and Corson (Watts et al; 1995) performed in situ testing of a straw bale wall in a house in Nova Scotia using a hot plate and numerous thermocouples on the interior and exterior faces of the wall. They performed three tests and from the results, calculated an average R-value of 28.4 for an 18.4" thick wall (or R-1.48/inch). Obviously density could not be measured for a wall in an existing house, and unfortunately, the moisture data was lost due to a computer failure. The equivalent R-value for a 23" wall would be R-33. The testing was performed on behalf of the Canadian Society of Agricultural Engineering.

In 1996, Jeff Christian at Oak Ridge National Laboratory performed the next test on a wall system that included stucco on the exterior and sheet rock on the interior. They used a guarded hot box technique, considered by many to be a more accurate means of testing large, non-homogeneous materials and systems. The purpose of the testing was to educate educators on some of the abilities of the lab – not to determine accurate R-values for the straw bale wall system. The "workers" attaching the sheet rock and applying the stucco where K-12 teachers, most of whom had little or no experience with either. This test provided an R-value of about R-17. Christian stated that there was an air gap between the bales and sheetrock, and between the bales and the stucco.

The next test was conducted in 1997 at Architectural Testing Labs (ATI) in Fresno, California, by Nehemiah Stone, ATI, and experienced straw bale builders from California. ATI used side-by-side guarded hot boxes to test a wall with bales on edge and one with bales laid flat. The walls were constructed of 23" bales and plastered on the interior and exterior faces. The set-up at ATI is designed for testing windows and other similar wall components, and has fixed apertures for the test specimens. Consequently, the wall sections had to be built in place, to the size of the openings. Compressing the walls to the normal degree left spaces above the walls that were then back-filled with stuffed straw, resulting in an area of lower density. Additionally, the laboratory needed to complete the tests and reclaim their space for commercial uses sooner than would have been optimal. Much of the moisture from the plaster (including two days of spraying it to prevent cracking) was still in the wall system. The results from these tests yielded R-26 for bales laid flat and R-33 for bales on edge.

ORNL ran another set of tests on straw bale wall systems in 1998. This time the focus was on replicating as closely as possible actual conditions of walls in home construction. The wall sections were built on rolling platforms that could be left out of the way to dry for two months and then rolled into place at the guarded hot box. Christian enlisted David Eisenberg (a widely regarded authority on straw bale construction) to advise on the construction of the walls. They used two string (19") wheat straw bales and plastered both sides. Other than the fact that the bales were at 13% moisture (higher than any of the other tests, but well within acceptable limits for construction), there is little, if anything, that one could say to discount the results.

ORNL determined the R-value to be R-27.5 (or R-1.45/inch). That equates to R-33 for three string (23") bale wall systems, almost exactly matching the data from the Canadian test in 1995.

Calculated R-values

Another way to estimate the R-value of straw bales and straw bale wall systems is by modeling or calculating them using known physical properties. This method always involves making assumptions about the relationship between the system we are representing and the system about which we know the physical data. For example, we can find data on conductivity of various materials used in construction in the ASHRAE Handbook of Fundamentals.[4] Unfortunately, there is no data on straw, straw bales, or straw bale wall systems. At first blush, it would appear that the closest representative data would be for "Cellulosic insulation." However, the only density given for this material is from 2.3 to 3.2 lb/ft^3. According to the data from the tests that have been done, straw bales range from 5.4 to 8.3 lb/ft^3. One thing that all researchers in the field agree upon is that thermal resistance of straw bale systems vary by moisture content and density.[5]

Another of the issues associated with modeling the thermal resistance (R-value) of straw bales or straw bale wall systems is that straw bales are not homogenous. When straw is baled there are pockets of very tight straw and pockets where it's loose. Compared to the locations where the strings bind the bales, the edges can be two to four inches longer. Straw in one portion of the bale will appear to have fairly uniform orientation of the straws along a particular axis, whereas in other portions of the bale the straws could be oriented along some other axis or not of a uniform orientation at all. It is difficult to represent this in a model, and it is more difficult to accurately predict what impact such discontinuities will have on heat flows.

To be convincing, a model would have to have reasonably accurate values for:

- moisture
- density
- conductivity of the straw itself
- amount of convective exchange between and around the straw
- emissivity of the straw surfaces

Unfortunately, at least some of those values can only come from testing, and the testing that has been done provides a range of answers. The other values are likely to vary widely in the straw that is used and the location in which it is used.

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4 The American Society of Heating, Refrigerating and Air Conditioning Engineers, Inc. publishes a handbook that provides basic data on building materials, gas and liquid properties, HVAC equipment design parameters and other information useful for understanding how buildings and the equipment used to condition them work. The Handbook of Fundamentals is one of four parts and the one that lists the data for materials.

5 McCabe's and Stone's tests also indicate that resistance varies by orientation of the bales, with resistance across the width of the bales being lower than resistance through the height of the bales. ("width" and "height" here refer to the medium and least dimension, respectively, of the bale. In a typical bale, the straw is very generally oriented parallel to width, or perpendicular to height.

Conclusion

Tests have shown a range of values from R-17 (for an 18" bale wall) to R-65 (for a 23" bale). Analysis at Oak Ridge National Lab, among other places, has shown that R-values for insulation materials used in "standard" walls are generally much higher than the R-value for the wall as an assembly of disparate materials. Joe McCabe recently postulated that the same phenomenon could account for the difference between the high values from his testing of bales and the lower values obtained in the 1998 Oak Ridge test of a straw bale wall system. While it is possible that the relatively low densities where bales abut each other might contribute to greater heat loss than would be measured through an individual bale, it is unlikely that this would account for the entire difference. This difference between bales and bale walls is nothing like the difference between standard insulation and what is found in stud framed walls (insulation voids, thermal bridges, uninsulated headers, and other faults).

It is noteworthy that all tests of straw bale wall systems prior to the Oak Ridge test in 1998 had potentially significant shortcomings and should not be considered particularly reliable. The last Oak Ridge test had no identified deficiencies and is considered by most to be an accurate determination of the thermal resistance of straw bale walls. ORNL determined the R-value to be R-27.5 (or R-1.45/inch), or R-33 for three string (23") bale wall systems. Shaving a bit off the top just for conservatism's sake, the California Energy Commision officially regards a plastered straw bale wall to have an R-value of 30.

A final note is a reiteration of a point made earlier: it matters little whether the final truth about the R-value of straw bales walls is R-33 or R-43 or even R-53. Above R-30, the differences are minor and will usually be overshadowed by windows, floors, doors and ceiling/roof details. Whatever the value, it is at least three times better than the average "R-19" wood studwall system.

Nehemiah Stone is an energy consultant with the HESCHONG MAHONE GROUP, Inc. in Fair Oaks, California. He is a charter member of the California Straw Builders Association (CASBA), and until late 2002, served on the Board of CASBA. He comes from a construction background rather than an academic or laboratory, having been a licensed building contractor and the Chief Building Inspector of Humboldt County, CA in the 1980s. He and his wife, Elizabeth live in a straw bale home that they built with the help of many, many friends in Penryn, CA. He can be reached at StoneAndStraw@earthlink.net or PO Box 324, Loomis, CA.