STRAW-BALE AS A VIABLE, COST EFFECTIVE, AND SUSTAINABLE BUILDING MATERIAL FOR USE IN SOUTHEAST OHIO

A thesis presented to

the faculty of

the College of Arts and Sciences of Ohio University

In partial fulfillment

of the requirements for the degree

Masters of Science

Leanne R. Marks

June 2005

This thesis entitled

STRAW-BALE AS A VIABLE COST EFFECTIVE AND SUSTAINABLE BUILDING MATERIAL FOR USE IN SOUTHEAST OHIO

by

LEANNE R. MARKS

has been approved for the

Program of Environmental Studies and

the College of Arts and Sciences by

Christopher Boone

Associate Professor of Geography

Leslie A. Flemming

Dean of College of Arts and Sciences

Marks, Leanne R. M.S. June 2005. Environmental Studies.

Straw-Bale as a Viable, Cost Effective, and Sustainable Building Material for use in Southeast Ohio. (118pp.)

Director of Thesis: Christopher Boone

In Southeast Ohio, the humidity is relatively high all year round; the maximum monthly average humidity readings exceeded 80% during the ten months of sampling. Precipitation levels, and its' effect on moisture accumulation within straw-bale walls, had been a concern to individuals skeptical about the use of straw-bales as a viable building material. Athens County, Ohio, is located within the Appalachian region, a poverty stricken region that desperately requires livable, affordable housing. Throughout this document, it becomes evident that straw-bale construction is in fact, a viable, cost effective and sustainable and safe building method for use in southeast Ohio.

Within the study the moisture content of three Athens County straw-bale homes were recorded during a ten-month period (Dec. 2001–Sept. 2002.) The daily weather data was also recorded on-site and collected from Ohio University's Scalia Lab. The results were grouped into monthly averages, to compare different areas of the houses to other areas, other houses, and correlate to the weather data. It was discovered that when straw-bale buildings are constructed using the correct and specific techniques, moisture intrusion did not seem to be detrimental to the health of the building, regardless of

environmental location. The elevated moisture readings resulted from a variety of causes including:

- Lack of toe-up,
- Unstuccoed wall sections,
- Inappropriate footer system,
- Use of moisture barriers between straw-bales and stucco, and
- Insufficient overhangs.

Approved:

Christopher Boone
Associate Professor of Geography

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF GRAPHS

I. History of Building with Straw

Figure 1. *Re-make of an early 19th century straw-bale home.*
Now an exhibit at a historical tourist attraction, which informs its visitors of the lifestyles, homes, and work of the era's homesteaders.

For centuries structures have been built using locally accessible materials such as straw, grass, and reed. In the African prairies, houses have been built from straw since the Paleolithic times (Solomon, 1995:155). Many European houses built with straw or reed over two hundred years ago still stand as healthy structures today. In Germany, straw-bale construction dates back four hundred years (Solomon, 1995:155). Roofs thatched with straw were traditional across northern Europe, Russia, and in the northern portions of eastern Asia, including Japan. The tatami floor mats of Japan are flat straw bundles with woven grass faces and cloth edges. In cold weather, the teepees of North America were insulated with loose straw between the inner liner and the outer cover (DSAA, 2000). Mixtures of straw and mud comprise the second major traditional use of straw.

After the invention of the mechanical hay/straw-baler in the mid-1800s, homesteaders in the Great Plains began turning to straw for use in construction. This was particularly evident in the northwestern Nebraska “sandhills” area during the homesteading period of the early 1900’s. Unlike most of the Great Plains region, the thin sod that laid over the sand dunes in this area was too fragile for building sod cabins. Hay balers were first introduced in the 1850’s, and by the 1890’s hay presses were common. Poverty, restrictive means of transportation, and high lumber prices prevented homesteaders from building with wood. It is no surprise that between 1896 and 1945 some 70 bale buildings, including homes, farm buildings, churches, schools, offices, and grocery stores had been constructed within the region. The use of straw as a building material seemed to be the easiest, cheapest, and most structurally sound option that the homesteaders had (Bainbridge, 2000:9).

Figure 2. *The first straw-bale church, Arthur NE (1920).*

The first known straw-bale house built in the United States was built in the Sandhills of Nebraska. Stacked bales pinned together with wooden stakes, plastered on inside and out and covered with a hip roof, the 900 foot home sufficiently housed the Burke family and their five children until they abandoned the home for a “conventional” farmhouse in 1956. The house remains standing today, although the abandonment has left much of its structural qualities in disrepair. The hay within the walls however, remain in sound condition. Many other homes in Nebraskan towns such as Alliance, Arthur, and Dannebrog that were built with straw-bales are still standing today.

Burritt Museum, a large mansion built in 1938 in Huntsville, Alabama remains in prestige condition after 62 years in a climate with over 50 inches of annual rainfall and average relative humidity in excess of 50%. (TLS, 1994). A 1978 building near Rockport, Washington receives up to 75 inches of rain a year; and an unplastered building near Tonasket, Washington, with no foundation and unplastered walls shows no apparent deterioration of the bales since 1984. Recent bale structures in northern New York (humid winters) and Nova Scotia (cold/humid winters) have been monitored and also demonstrate good performance in difficult climates.

II. <u>What exactly is straw?</u>

Figure 3. *A typical two-string straw-bale.*

Note the varying degrees of shade (moisture) within the same bale.

Straw consists of dried dead stems of cereal grains such as rice, wheat, oats, barley, rye, spelt, flax etc, after they have been harvested. Bales can also be made from other fibrous materials such as bean or corn stalks, pine needles, or any kind of grass

(TLS, 1994:5). Many of the first bale buildings were constructed from what was abundantly available within the local area: baled meadow or prairie grass. Straw itself is the plant structure between the root crown and the grain head.

Straw does not contain the grain head (like hay) and therefore has very little nutritional value and is less attractive to pests or vulnerable to biological activity than hay. Hay is often grown for livestock feed and is baled green with the leaves and seed head included. Straw can be used as bedding for animals, yet it is often viewed as a waste product (because of its low nutritional value) and therefore burned. Chemically, straw is composed mainly of cellulose, hemi-cellulose and lignin – very similar to wood, yet contains higher amounts of silica (Eisenberg, 1997).

Figure 4*. A chicken wire enclosed straw-bale wall.*

A typical bale consists of a series of 1-2mm (4") flakes compressed along the long axis. Bale density varies, depending on the type of grain, moisture levels and the degree of compression provided by the bailer, but should generally be at least seven pounds per cubic foot (1.1kN/m3) dry density. Three-string bales (often found in the western United States) usually measure 23x46x16 inches and weigh 75-85 pounds. Two-string bales, which are more often found in the mid/eastern/northern United States, measure 18x36x14 inches and weigh 50-60 pounds (U.S. DOE, 1994).

Ohio supports the production of a significant amount of grains (Table 1). The straw yield assumes 80% of the biomass calculated from the harvest index. If an average two-string bale weighs approximately sixty pounds and four hundred bales are needed for an average home. Therefore straw production in Ohio alone could supply walls for more than 200,000 homes.

<u>Table 1</u> – Straw Yield in Ohio

Ohio's Grain and Hay Harvest – 2000				
Grain	**Area Harvested** (1,000 acres)	**Yield Bushels** (tons)	**Production** (1,000 Bu.)	**Straw Production** (1,000 tons)
Wheat (OH)	1110	72	79,920	1443
Oats (OH)	120	76	6840	120
[1]**Rye (OH)**	4	36	144	6
[2]**Hay (OH)**	1400	3.23 (1,000 tons)	4521 (1,000 tons)	3640
Total	2634			5209

(Department of Agriculture. 2001)

- Owner-built walls, finishing, roofing;
- Life cycle – 100 years;
- Finance – construction cost minus down payment of 26% at an annual interest rate of 6% over 100-year life cycle;
- Energy – average cost for heating and cooling a conventional home for this study –$100/month;
- Total – Amount of down payment plus energy and finance.

III. Fire Resistance

Straw-bale walls, once plastered, provide better fire resistance than conventional wood stud wall construction (Everett, 1993:57). The National Research Council of Canada tested a plastered straw-bale wall in the early 1990's and found that it was able to withstand temperatures of 1,850 degrees F. for two hours before cracking. The Canadian Mortgage and Housing Corporation concluded that "The straw-bales hold enough air to provide good insulation value, but because they are compacted firmly, they don't hold enough air to permit combustion" (Everett, 1993:57). It has also been suggested that the high silica content in straw (3-14%) impedes fire by charring and insulating the inner straw (EBN, 1995).

In a test performed in 1993 by SHB Agra Engineering and Environmental Services Laboratory in Albuquerque, New Mexico, a two-string unplastered wheat straw wall withstood thirty-four minutes of fire at 1,691 deg. F. A gypsum plastered wall (on heated side) and cement stucco (on unheated side), withstood temperatures of up to 1,942 deg. F for two hours on the heated side, while the unheated side remained steady at 21 deg. F. After two hours the gypsum plaster formed cracks, where the fire penetrated the bales, charring them no deeper than two inches (Lacinski, 2000:13).

Straw-bale homes have also proved to be relatively fire resistant. Examples of straw-bales reaction to “accidental” fires are given below:

a) A candle left burning within a niche that had been carved into a straw-bale wall sparked a fire in the house. The surrounding wood was completely burned, however, the unplastered exposed straw charred, actually impeding the continuation of fire;
b) In Tucson Arizona, a wood-framed house wrapped with straw-bale was under construction when an arsonist fueled a fire with gasoline upon their incomplete structure. The wood framing burnt almost completely, yet the straw refused to burn at all (however, the bales were destroyed because they had been laid on edge – burning the strings that held them together) (Wilson, 1995:7).

Through scientific investigation and accidental experience, it seems that the risk of fire should not impede one from building a straw-bale home.

IV. Insulative Properties

Straw-bales are comprised of cellulose that acts as an effective form of insulation as well as a building material. The high thermal efficiency of straw-bales lowers the energy requirements for heating and cooling, thus reducing the demand on limited natural resources, pollution, and monetary expenditures. It has been suggested that straw-bale buildings in the United States require less than a third of the usual amount of energy to heat or cool (Wilkins, 1995:7). The Department of Energy (DOE) estimates that in the U.S. the total energy used for home heating and cooling is approximately 11% of the nations' total energy consumption (McCabe, 1993:3). Using more insulation when building could reduce a large portion of this energy use. Preliminary data from straw-bale buildings in the extreme environment of Mongolia suggest that residential energy use can be reduced by approximately eighty percent (Straube, 1998:4). In a place where they use mostly coal for heating, this means a significant reduction in coal consumption and air pollution by using a waste product to build and heat a home.

A wall system's insulation properties are often rated using "R-values". "R-value" is the resistance to heat flow (Wilson, 1998:1). A higher R-value indicates that the wall has a higher resistance to heat loss or heat gain. The R-value of straw-bale buildings has been debated for the past several years. Tests on straw-bales have varied from R-17 to R-55 (Wilson, 1998:1; McCabe, 1993). One test conducted by the Oak Ridge National Laboratory in 1996 found straw-bales to have an R-value of 17. The major problem with the test was that they used gypsum drywall as an interior wall covering rather than stucco, producing an air gap for heat to escape through, between the gypsum and the straw-bales. The test reiterates the importance of stuccoing straw-bale wall surfaces – for its insulative properties and strengthening qualities (see strength and durability section). The thermal mass of the straw-bales and plaster combination contributes to greater insulative efficiency by storing heat during outside temperature fluctuations. A test carried out by Oak Ridge National Laboratory found that it took a straw-bale wall two weeks to begin losing heat at a steady rate when one side of the wall had been heated to 70 degrees F. and the other side chilled to 0F.

Figure 5. 2,000sqft straw-bale home in Ohio.

This 2,000sqft owner-built straw-bale home in south central Ohio is a magnificent example of the insulative properties shared by straw-baled walls. In the midst of winter, a small reused wood fired stove occasionally heats the entire house. In the midst of summer, the interior of the house remains cool without the use of neither fans nor air-conditioning.

Another test conducted by the California Energy Commission in 1997 tested the R-value of bales in an ASTM C-236-style apparatus (guarded-hot-box). They found that bales laid flat had an R-value of R-26 (Wilson, 1998). When deconstructing the test they found the bales to be saturated six inches into the bale. Moisture content, density, and spaces between bales affect the R-values of straw walls. R-26 is actually a good figure, considering that the walls were wet. Dry bales have >2R per inch thickness whereas moist bales are <2R per inch.

A study conducted by Oak Ridge National Laboratory in 1998 found a straw-bale wall to have an R-value of 28 (using cement stucco) (Wilson, 1998). This is significantly lower than the first tests conducted by McCabe suggesting that walls had an R-50 – R60 value, however, an R-28 value is still much higher than that of other building materials (McCabe, 1995). The R-value of wood is 0.2 per inch and brick is 0.05 per inch whereas an R-value of 28 translates to approximately R-1.5 per inch more than ten times the insulation factor of a double brick cavity wall. In another test, two-string bales (18 x 14 x 36 inch) recorded a variable R- value of R-30-40 during the winter (Watts, 1994:13). These results fall within the range of thermal values found in other studies, and supports the statement that straw-bale construction can easily exceed R-values of efficient buildings built with other materials (Bainbridge, 1986).

V. **Current Building Situation and Environmental Concerns**

We currently live in a world where natural resources are being consumed at an accelerating rate and present construction practices largely contribute to this problem (Roodman, 1994:21). Homes in the U.S. (90% of which are wood-framed) have grown from an average 102 square meters in 1949 to 187 square meters in the 1990's; floor space per person has more than doubled (Roodman, 1994:23).

Housing demands continue to increase, as does the pressure on natural resources. Housing demand is the single largest economic force impacting national forests, accounting for more than three-fourths of the world's voracious appetite for wood (Roodman, 1994:22). Americans use more wood than any other single material resource: more than steel, plastic and concrete combined. In the U.S., residential construction alone is the largest contributor to deforestation (Doxsey, 2000).

Ninety percent of single family residences built in 1992 in the United States were wood framed and consumed an average of 11,000 board feet of wood each or approximately one acre of forest (Doxsey, 2000).

Figure 6. Deforested land in the Midwest.

The land is now overused for agricultural purposes half the year, then lay uncovered for months of erosion during the second half.

Considering that there are over 76 million residential buildings in the U.S. this would account for approximately 836 billion board feet of wood or 76 million acres of forest (note that this excludes the five million commercial buildings existing in the U.S.) (Doxsey, 2000). By 2010, another 38 million buildings are expected to be built, requiring another 4.18 billion board feet of wood and 38 million acres of forest. If a mere 10% of these homes could be built with the use of straw, over 1 million tons of a waste material could be used while conserving over 3 million acres of forest.

The construction industry directly consumes more material and energy resources than any other sector of the American (and global) economy (Roodman, 1994:21). It has been estimated that the building sector is responsible for fifty percent of material resources taken from nature, forty percent of energy consumption, and seventy-five percent of waste generated by society (Anink, 1996). The current costs of buildings do not account for energy input and neither output costs nor do they value the life cycle costs. When considering the life-cycle of a building one must consider the use of water, energy, and polluting potential in each and every stage: quarrying and refining, production of raw materials, manufacturing of building products, on-site construction, building use, and the building's afterlife (demolition, re-use and disposal). Buildings account for roughly forty percent of the materials entering the global economy each year, of which some three billion tons of raw materials are turned into foundations and walls, pipes and panels (Roodman, 1994:22). The waste created during the construction of a typical wood-framed home averages from three to seven tons (Doxsey, 2000). The construction and demolition activity involved in the building process feeds approximately ninety million tons of rubble into U.S. landfills each year (Doxsey, 2000).

The energy intensity involved in manufacturing modern building materials is outrageous. Over the past hundred years, the level of carbon dioxide in the atmosphere has risen by 27%, one-quarter of which was emitted from fossil fuels being burnt providing energy for buildings (WWP No. 124). Approximately 49% of sulfur dioxide emissions, 25% of nitrate oxide emissions, 10% of particulate matter emissions and 35% of carbon dioxide emissions are the result of construction (Doxsey, 2000).

When straw-bale structures are built using high energy-input manufactured (conventional) products, a straw-bale building can be considered as detrimental to the environment as many conventional building are. In many straw-bale homes, large amounts of energy-intensive cement are used for foundations and wall coverings. Concrete is one of the most energy intensive materials to produce. Six thousand mega joules are required to produce one tonne of concrete, whereas only 115 mega joules are required to produce one tonne of straw (which would be a much larger quantity) (Roodman, 1994:23). Materials such as earthen and lime plasters and rubble trenches/earth bags/rammed earth tires can be suitable alternatives to cement. Concrete is the most widely used substance on earth (water being the exception) and contributes to four to five percent of the world's greenhouse gases (Bolman, 1994).

Indoor air pollution has become an increasingly important concern, particularly in industrialized countries, where most people spend more than ninety percent of their lives inside buildings (Straube, 1998). Indoor sources of pollution are a significant problem in many "modern" buildings. The United States Environmental Protection Agency ranked Indoor Air Quality as the most prominent environmental problem. Approximately 30% of new or renovated buildings have serious indoor air quality problems (Roodman, 1995). Modern homes typically contain volatile organic compounds such as formaldehyde, xylene, isobutylaldehyde, vinyl chloride monomer, and other organochlorides, aldehydes and phenols from all kinds of manufactured wood protectants, paints, carpets, and synthetic textiles (Straube, 1998). Reducing society's reliance on manufactured products could significantly reduce associated health problems and offer people healthier lives (not to mention large savings from reduced medical expenses).

Figure 7. Degraded straw-bales.

Like wood, straw-bales are at the mercy of weather conditions when unprotected.

To be “environmentally friendly” a building should attempt to re-use products, use recycled, non-toxic, low-energy locally available materials to build a structure which compliments both the surrounding environment and the inhabitants’ lifestyle (which also may need to be altered). Straw is an under-used, low-energy, non-toxic, renewable material that could be used as an alternative to over-used and energy intensive products such as plastic, wood and cement. Straw is plentiful in many areas of the world where hay can be grown in less than six months in a completely sustainable production system, whereas timber (for conventional housing) requires approximately twenty-five years. Straw is generally considered a waste by-product of rice and grain and is often handled as trash. In the United States approximately 200 million tons of straw are under utilized, wasted or burned. Conservative figures from the United States Department of Agriculture indicate that U.S. farmers annually harvest enough straw to build approximately four million 2,000 square foot homes per year – that's almost four times what is currently being constructed (DOE, 2000). Conservative figures show that Ohio harvests enough straw to construct more than two hundred 2,000 square foot homes every year. A mere ten percent of this figure could be a reasonable goal to achieve. It would provide twenty families with comfortable affordable homes and save approximately 84,000 pounds of straw from being wastefully disposed of.

The wasteful handling of straw not only deprives potential homeowners access to affordable resources but also contributes to rising emission levels. In California in the early 1990's, more than one million tons of rice straw was burned each year, generating an estimated 56,000 tons of carbon monoxide – twice that produced from all of the state's power plants (EBN, 1995). Carbon dioxide, a large contributor of greenhouse gases and respiratory illnesses, is also emitted in heavy quantities. In New South Wales, Australia, over 600,000 tonnes of rice straw are burned each year, releasing 30,000 tonnes of carbon dioxide and 2,000 tonnes of PM directly into the atmosphere.

Environmentally, the use of straw for constructional purposes seems to be one appropriate response to the current building crisis: to using a waste material to provide affordable housing. It is important to note however that both monetary and environmental costs would be dramatically reduced, not only by constructing with straw, but by making it a priority to use low energy input, renewable, sustainable, non-toxic, re-used, recycled local products. Ann Edminster (1995), found that straw-bale homes can be either low impact or high-impact. Two straw-bale houses were compared to each other and to a conventional stick-framed house. She categorized the energy consumption of various building materials through their use of water, energy and waste production. Dramatic differences were found between the two (Table 2), proving that a building's environmental impact is dependant upon not just one but also all of the materials used during construction. As seen from Table 2, the high impact house required twenty times as much energy, sixteen times as much water, and produced one hundred and twenty-two times as much waste as the low impact house.

<u>Table 2</u>. Constructional Materials and Their Environmental Impact

	High-Impact	**Mid-Impact**	**Low-Impact**
Foundation	Concrete	Rubble Trench	Rammed Earth
Roof Covering	Shingles	Clay Tile	Thatch
Roof Insulation	Fiberglass	Straw	Recycled Cotton
Interior Walls	Concrete Block	Straw-bales	Adobe
Bale Assembly	Steel Rebar		Bamboo Stakes
Bale Wall Finish	Cement Stucco	Lime Plaster	Earthen Plaster
Floors	Tile	Concrete	Adobe

(Edminster, 1995:89-122)

Edminster found that the energy input was greater for a high impact straw-bale house than it was for a conventional house. The low-impact straw-bale house, however, required only one-twelfth of the energy to construct than that of a conventional house (Edminster, 1995:73-74). It is therefore safe to conclude that straw could be *part* of the answer, but not *the* only answer.

VI. **Affordability**

Housing is in great demand throughout the world and is the largest economic force impacting forests (Eisenberg, 1998). Residences in the U.S. are more than three times larger per inhabitant than they were during the 1940's (Wilkins, 1995:7). They have more bathrooms, more garages, and use more energy. The energy inputs into a building are significant over a building's lifetime. They require a great deal of energy to construct and require a great deal of energy to maintain. The continual growth of homes, both in number and in size displaces productive land and demands more and more energy. The U.S. consumes more energy per capita than any other country in the world – using more than five times the world average (Wackernagel, 1996:85). The cost of fuel/energy in the U.S. does not represent the true cost of mining, manufacturing and delivering these fuels, nor do prices account for the consequences to human health. (plus military costs, in money and human lives, to maintain oil supplies from the Middle East).

Residential and commercial buildings combined consume one-third of all the energy used in the U.S. and two-thirds of all electricity (Doxsey, 2000). The Department of Energy estimated that home heating and cooling uses 11% of the total energy consumed in the United States. A typical stick-house consumes a significant amount of energy during construction (approximately 700,000b Btu's) and continues to consume a significant amount of energy. One-third of global primary energy use is devoted just to keeping existing structures up and running (Straube, 2000). Costs of housing could be greatly reduced if energy dependency deflated. The American Housing Association estimate that approximately 22% of the monthly median income is being allocated to home energy requirements. Again, straw-bales are not the *single* answer, but considering their low-cost and high insulative values, they are an appealing option. It has been estimated that straw-bale homes require less than a third of the energy requirements for heating and cooling than conventional homes, in terms of costs these energy savings can be significant (Wilkins, 1995:7). The Working group Reports found that over a buildings' life cycle, a straw-bale house could save their homeowners approximately $60,000 (Table 3).

Table 3. ***Projected long-term life-cycle costs of straw-bale buildings compared to conventional buildings***

	Construction	Finance	Energy	Total	Savings
Conventional	$82,000	$396,000	$120,000	$532,000	------
Straw-Bale	$78,375	$376,000	$60,000	$451,675	$83,875
Straw-Bale*	$40,000	$192,000	$60,000	$260,000	$272,500

(Working Group Reports, 1993).

Figure 8. Addie Gould and her home.

Addie stands outside the "home" she raised her seven children in. It represents the "typical affordable home" for so many poverty- stricken Appalachian residents.

Buying a house is the largest single investment most middle-class Americans will make in their lifetime (Miner, 1995:4), one that many people living in Appalachian Ohio cannot conceive. The median income family in the U.S. attempting to buy their first home would have to spend nearly 50% of their annual pre-tax income on mortgage payments (Urban Institute, 1994). In Athens County in 1990 the median monthly mortgage payment for owner-occupied households was $541. When 30% of Athens County households have an annual income of less than $10,000 more than 70% of their income is given to mortgage payments, making it practically impossible for many Athens county families [i]to afford purchasing their own home (NLIHC, 2000).

Addie Gould represents many Athens County citizens – living in poverty and dependant upon corporate policies, which do not cater to the needs of low-income peoples. AEP (American Electric Power) forced her out of her home (due to coal mining rights), threatening court action if she opposed their demands. Forced to sell and move, Addie now lives within a run-down $5,000 trailer home now with three of her five children. A home where the leaky roof has caved in, windows have fallen, and they remain dependant on corporate supply of gas and electric energy. She pays approximately $130 of her $530/month income to the gas company, and budgets $50/month to the electric company – AEP – the very company that forced her out of her once comfortable homestead. This is not the first or last time such an incident has or will happen within (or without of) Athens County (Gould, 2001).

The story of Addie Gould shows that there is a large demand for affordable housing in Athens County. In Athens County the poverty rate is 28.7% the highest in Ohio. What more, Athens County's poverty rate is over 218% more than the average U.S. poverty rate (U.S. Census Bureau, 1997). Per capita income in Appalachia Ohio stands at $12,500, that's 20% below the state average. In 1989, Athens County per capita income was at $9170, less than 50% of the U.S. average. More than 57% of Athens County households had an income of less than $20,000 and over 51% of these households were bringing in less than $10,000, yet median household income stood at $19,000 (including investments) (NLIHC, 2000). With fair market rent priced at $678/month for a three bedroom unit, an average Athens County resident would have to spend 72% of their wages on rent alone (NLIHC, 2000). Athens County is one of the wealthier regions in Appalachian Ohio due to influx of money from university students. Nearly one-fifth of Ohio's population is poor in Ohio's southern and southeastern Appalachian counties. Appalachian Ohio occupies one third of Ohio land but only 12% of population and of this population 17.4% are living below poverty levels (132.7% of the U.S. average) (NLIHC, 2000) (Dept. of Commerce, 1990). The poverty rate in Appalachia Ohio is 15% higher than the state average and increasing. Morgan county residents receive 25% less income than Athens County residents, and Meigs County residents receive almost half as much income as Athens County's renters (NLIHC, 2000).

Figure 9. Deteriorating home of Addie.

With the roof caving in, gas leaks, unrepaired and broken windows, and constant plumbing problems, Addie Gould had raised and continues to raise children within this residence.

Figure 10. Side view of Addies' home.

Straw could be a viable building material to use in southeast Ohio. Over 5,000 tons of straw are produced in Ohio each year – enough to build over 200 beautiful, comfortable and affordable 2,000 square foot homes (Table 3), yet dependency on conventionality keeps them living in inefficient, gas heated, manufactured houses or trailers. Straw is not the single answer but can be part of the answer towards building comfortable and affordable homes for southeastern Ohio's low-income residents. Given below are two separate cost analysis reports on the affordability of straw-bale homes.

Figure 11. House No. 2 southern wall.

Straw-bale pioneers put together a cost estimate of straw-bale homes using different building methods, materials, designs, and labor input levels:

Very Low:

- 120-1000/square foot @ $5-$20/square foot;
- Scavenging, salvaging materials;
- Material costs only, owner-builder labor throughout;
- Initial start-up costs, ongoing improvements, pay as-you-go;
- Nebraska-style, timber frame, and post and beam.

Low:

- 1000-1500/square foot @ $30-$50/square foot;
- Contractor-built, owner-build wall, finishes;

- Subcontract foundations, plumbing, mechanical, roof;
- Experienced job-site supervisor;
- Materials at market cost;
- Typically post-and-beam or Nebraska-style;

Figure 12. House No. 3.

Owner participation to reduce labor costs. Use of both new and re-used building materials. Total cost approx. $20,000.

Moderate:

- 1500-2500 square foot @ $50-$80/ square foot;
- Standard, contractor-built;
- Production housing;
- Speculative development;
- Typically post-and-beam.

High:

2500-4000/ square foot @ $80-$120/ square foot

- Luxury homes;
- Custom design;
- Site specific;
- Marginally less than conventional construction;
- Typically post-and-beam with custom features.

(Hofmeister, 1994).

A cost comparison study between 14 straw-bale, 9-cordwood masonry, 4-cob buildings located in the United States, British Columbia and South Africa found that:

1. 18/27 built for less than $40,000;
2. Total house costs ranged from $500 to $187,000.
3. Average cost was $27.50 per square foot, whereas standard cost data suggests that a stud-frame home costs $65-$75 per square foot.

In the case study given above, the two major costs investments were:

a. The amount of owner labor – all but one of the 27 owners built at least the walls of their house;

   AND

b. The amount of "deconsumer" materials – "deconsumer" refers to materials that were not bought at retail cost (2nd hand materials).

A wall system typically represents only 15-20% of the total cost of a home and that labor is the largest expense invested into building a "conventional" home and can be for a straw-bale home too. It represents approximately 50% the total cost, so obviously owner participation is the best way to reduce building costs. Building a home with straw-bales is relatively simple when compared to the construction of a conventional home, requiring more labor than specialized skills or tools. The ease of building with and modifying bales opens the design and building process to creativity and individualization of even the most basic buildings. It can also inspire a sense of community through group wall raising and stuccoing while also offering a sense of personal empowerment by building one's own home with an environmentally sound material. Re-using materials, using recycled materials, using little wood and other manufactured materials, can also cut building costs. Due to a straw-bales building's high insulative values further cost savings come from energy savings (Table 3).

There is no doubt that an alternative; affordable form of housing is needed in the Appalachian Ohio region. In southeast Ohio, straw-bales cost between $3.00-$3.50 per bale (delivered). The cost of straw-bale houses built in Athens County, according to local straw-bale owner-builders, averages between $10 and $30 per square foot (Worrel and Gilcher, 2000) compared to the standard stud-frame home costing approximately $65-$75 per square foot (Whitton, 1998-99).

Realistically, straw-bale buildings can cost anywhere from $1.50 per square foot in Mexico to more than $200 per square foot for custom upscale homes in Santa Fe, NM (Bainbridge, 2000:9).

Figure 13. A southwest Californian million dollar straw-bale home.

To lower costs does not simply mean building with straw, but modifying and simplifying the way we live, so that simpler and more practical structures can cater for such lifestyles without dramatically impacting the earth or our health. By doing this we could also reduce both energy and monetary expenditures, build community and house the needy, while minimizing the negative impacts we have on the earth.

VII. Wall Coverings

Figure 14. Moisture barrier use.

House No. 2 -an example of what NOT to do or use – chicken-wire, tarpaper, loose straw, exposed walls.

A major part of the function of any wall system is to separate the interior from the exterior. As part of this job, walls must control heat, air, and moisture flow. Specialized layers and materials, sometimes several of them, are typically needed to control air flow and moisture flow in all of its forms: vapor, rain, ground water, etc.

Standard building practice dictates the use of Moisture Barriers (which are intended to stop liquid moisture, generally in the form of rain), Vapor Diffusion Retarders (more simply known as vapor barriers, intended to stop moisture vapor, which in heating climates is generally humidity in the interior air that's trying to get out), and Air Barrier Systems (which are intended to stop air leakage) (Quirouette, 1998:1).

There are a number of different types of wall coverings that have found to be appropriate for straw-bale buildings. The most common are cement stuccoes (the most popular modern day covering), gypsum plaster (interior walls), lime plaster and earthen plaster. Stucco and other plasters act as strong bonding material when layered upon straw – particularly when it is forced in-between the layers of straw fibers – binding them together and to the exterior covering – it acts as a strengthener and a sealant. Stuccoes also provide an essential air barrier for straw-baled walls - increasing its insulative values and reducing its vulnerability to fire and pest infestation. Plastered straw-bale walls are generally uniformly permeable. They therefore tend to disperse and "breathe off" moisture rather than collect moisture, unlike plywood sheathing which traps moisture in walls and maintains high humidity levels (Bolman, 1994).

It has been found that moisture barriers inhibit a straw-baled walls' ability to "breathe" or to "perspire" and therefore are not recommended. In fact the Building Codes established for straw-bale buildings prohibit their use (City of Tucson and Pima County Arizona Building Code). This means that if a moisture barrier were used and water were to penetrate a straw-baled wall moisture would then be trapped within the wall system (like we'll see later in House No. 2), rather than seeping through porous lime and earth (and cement to a lesser extent) wall coverings. The decision to use a sheet membrane over bales not only affects the permeability of the baled wall, but the strength and integrity of the plaster coating it. The stucco infiltrates the crevices in the bale, gripping it like fingers gripping a wire fence. This prevents the creation of potential air channels behind the plastic/paper barriers. The use of moisture barriers have been recommended to cover areas which are vulnerable to moisture intrusion, such as around window and door bucks, around the lower course of bales (if vulnerable to splash-back), and any other openings in the wall system (this is not necessary though). It is important that the moisture barriers are not penetrated, for then they will simply act as a tunnel for infiltrating water. Vapor intrusion through baled wall systems is of little significance according to Platts (1997). It seems that the critical source of water vapor migration into wall systems is from gross air leakage. George Tsongas (a mechanical engineering professor at Portland State university) suggested that air leakage carries 100x more moisture into a wall than what a very permeable plaster would allow (Tsongas, 1995:10).

Figure 15. A straw-bale "truth window"

Often placed within a straw-bale home to prove to disbelieving visitors that the house is made of straw. In my opinion, it is just another unnecessary detail vulnerable to moisture intrusion.

Types of Stucco

i. Cement Stucco

Basically, cement stucco is a mix of Portland cement, sand and water. In the U.S. cement is relatively cheap and readily accessible, making this a preferred choice for many builders. Cement is also found to be a very strong material, particularly when it is reinforced with steel. Tests carried out by Fibrehouse Limited found that a cement-stuccoed wire reinforced straw-bale wall actually performs as a stressed-skin panel – meaning that it is actually the stucco that holds loads (Lacinski, 2000:231). A later study carried out by Jeff Ruppert in Colorado found that stucco mixed with fiber mesh proved to be far superior in strength than to a bale wall reinforced with wire (Ruppert, 2000). Basically, these tests have proven that the stuccoes adhesion to the straw-bale wall adds significant strength and stability to the wall's structure, and it would be beneficial if tests of a similar nature could be carried out using alternative wall coverings because the use of cement stucco, however convenient, offers many negative implications.

Figure 16. House No.2 – northeast wall.

Some of these include:

- Energy intensive product (see Current Building Situation and Environmental Concerns section for more details);
- Produces larger shrinkage cracks than any other plaster;
- Most brittle of all plasters;
- Least vapor permeable;
- Poor drying potential;
- Readily wicks liquid moisture.

(Lacinski, 2000:232-234).

Cement stuccoes are the most common wall covering used in the United States (and most developed countries) to seal and support straw-baled walls. It is important to note however, that cement stucco is not necessarily the superior product, quite the contrary in fact. All plasters crack, and cement is no exception. The major concern for using cement stucco, in regard to moisture, is that it readily absorbs liquid moisture, while also acting as a low permeability wall, thereby significantly delaying the drying regime. Unfortunately, all three houses in this study have been coated with cement stucco – interior and exterior.

ii. Lime Plaster

Lime plaster is formed by heating calcium carbonate (limestone) at extremely high temperatures to form calcium oxide, then adding water to produce calcium hydroxide or what is known as lime putty. Lime putty is mixed with sand and fiber then applied to the wall where it proceeds to react with carbon dioxide and return to its original form – calcium carbonate (limestone). This procedure has been used for thousands of years, in ancient Greece and Egypt, and then later refined by the Romans, the Mayans, and the Aztecs (Holmes, 1997).

Figure17. An early 19th century straw-bale home uses lime in its plaster.

As a wall covering for straw-bale buildings, the use of lime plaster holds many advantages over cement plaster, including:

- Higher vapor permeability;
- Less prone to cracking;
- Possesses ability to “heal” itself;
- Easier to work with;
- Easier to repair;
- Less energy intensive;
- Recyclable;

(Lacinski, 2000:244-250).

Daubois Inc. has carried out permeability tests under norm ASTM-E-96 and by John Straube. Both concluded that lime has a significantly higher permeability rating than cement. Daubois and Straube found that a 1:1 cement/lime mix is ten times more permeable than that of a Portland cement only mix (Lacinski, 2000:247) (Straube, 2000). Permeability in straw-bale walls is of great concern. Straw is a biodegradable material; therefore if moisture became trapped within (due to imperfect construction detailing) it would be vital that the wall coverings would be permeable enough to allow the moisture to escape. Lime plasters have a higher drying potential than that of cement stuccoes and are therefore more suitable for enclosing straw-baled walls (except in dry regions) (Lacinski, 2000:246).

Lime plaster however does offer its imperfections (as classified by fast-paced North Americans). Lime takes time to cure. It often requires a drying period of five to seven days between applications (Lacinski, 2000:252).

iii. Earth Plaster

Figure 18. Earth brick samples. Soil, straw, water compressed into a mould then dried.

Earth plasters are composed of clay, sand, chopped straw (or other similar materials), and water. Clay and straw have been incorporated into buildings in Germany, Britain, northern Europe, Denmark, Africa and South America for centuries, many of which still exist today. Clay and straw work extremely well together – clay binds and preserves straw while straw adds necessary tensile strength (and can also direct water molecules away from the building, thereby reducing erosion) (Lacinski, 2000:263).

Qualities of earth plasters include:

- Highest vapor permeability of all three;
- Assists in regulating interior moisture levels;
- Compatible with lime;
- Non-toxic;
- Easily workable;
- Usually locally available (depending on clay content of soils, one could use the dirt from their own backyard);
- Low embodied energy;
- Re-useable – no waste;
- Relatively cheap.

An interesting phenomenon observed by Volhard found that clay retains relatively low moisture readings compared to the straw it encompasses, regardless of relative humidity levels (Volhard: 1995). This suggests that a earthen plaster may in fact protect a straw-baled walls' vulnerability to high relative humidity levels. It has also been suggested that clay has the ability to draw moisture out of straw-bales (Lacinski, 2000:264). German tests have also found that clay releases water vapor much more quickly than any other building materials (Volhard, 1995:54). For prevention of moisture accumulation in straw-bale walls, these two qualities make earthen plasters almost ideal for wall coverings on straw-baled buildings. However, like any section of bare earth, when exposed to extreme weather conditions erosion will occur.

There are methods to reduce erosion, some are:

- Incorporate sufficient overhangs and/or porches;
- Use straw reinforcement;
- Treat walls with limewash or linseed oil;
- Annual maintenance.

VIII. Stuccoes and Moisture

The two largest sources of moisture for enclosed walls are air leakage and rain penetration. Straw-bales are very vapor and water permeable and therefore rely on the wall coverings to control the entering of moisture. Vapor permeability is the material property that defines the ease at which water vapor diffuses through it. The vapor permeability of many natural materials varies significantly with relative humidity. To use test data for 25mm thick cement-lime stucco as a reference, the permeability varies from about 100 perms (2 US perms) at 10-20%RH to over 400 perms (6.5 US perms) at 90%RH. While almost all finishes are sufficiently air impermeable to control airflow, their liquid water absorption and vapor permeability properties are highly variable and poorly known.

Stuccoes and plasters are quite impermeable to air flow, though they also need to be permeable enough to allow vapor diffusion to release any moisture trapped within. Porous hydrophilic materials tend to absorb liquid water (or “wick” water). During a rain event, water that is deposited on the surface of the exterior skin will be wicked into the stucco. This water can be stored in the stucco and may contact the straw at the bonded interface. The stored water can also be dried to the exterior or interior when heated by the sun (Straube, 2000:4). The permeability of a wall covering should be much greater than its ability to absorb moisture. As Straube stated “The ability of an exterior stucco to absorb and store water is critical since this water can then be transported inward to the straw-bales by vapor diffusion (and potentially by capillarity)” (Straube, 2000:2). To test this, Straube carried out experiments on the vapor permeability and water absorption of various different cement stucco and lime plaster mixtures, results are shown in Table 4.

<u>Table 4</u> – Vapor Permeance of Wall Covering Materials.

Sample	t	Vapour Permeance	Permeability	Water Absorption
Cement:Sand	[mm]	[ng/Pa•s•m2]	[ng/Pa•s•m]	[kg/m2•s1/2]
A - 1:3 datum	43.5	39	1.7	0.038
A1 - 1:3 elastomeric	39.5	40	—	0.0085
A2 - 1:3 siloxane	41	40	—	0.0004
Cement:Lime:Sand				
B – 1:1:6 datum	35	295	10.3	0.092
B1 – 1:1:6 linseed	36	223	8	0.067
B2 – 1:1:6 elastomeric	32.5	244	—	0.015
B3 – 1:1:6 siloxane	41	203	8.3	0.0006
B4 – 1:1:6 calcium stearate	53.5	81	4.3	0.101
B4 – 1:1:6 calcium stearate	44	142	6.2	0.083
B4 – 1:1:6 calcium stearate	53.5	41	2.2	0.093
B5 – 1:1:6 latex paint	36.5	203	—	0.02
B6 – 1:1:6 oil paint	40	41	—	0.014
Cement:Lime:Sand				
C - 1:2:9 datum	50.5	295	14.9	0.11
C1 - 1:2:9 linseed	50.5	259	13.1	0.105
Lime:Sand				
D – 1:3 Datum	33.5	565	18.9	0.127
D – 1:3 Datum	35.5	529	18.8	0.173
D1 – 1:3 Quicklime	32	459	14.7	0.161

(Straube, 2000).

A significant finding is that the vapor permeance of cement stucco is low, therefore its drying regime is relatively slow. The addition of lime was found to significantly increase the wall's vapor permeance (times 10), however, it also increased the walls ability to absorb water. An ideal wall covering for a straw-baled wall would be one with a high vapor permeance rating with a slow water absorption rate. Linseed oil assists in reducing a wall's water absorption while still remaining relatively vapor permeant. Its effect was minimal in this test, but it would be beneficial to see the effect from using a thicker coating of linseed oil. The most effective sealant seemed to be Siloxane (5% by weight solvent-based product - Sikagard 70 by Sika) and elastomeric (high-quality acrylic based product - Maxicyrl, by Sto Industries) treatments. They reduced the water absorption dramatically yet had little effect on the vapor permeance. Another interesting result was that that he found cement stucco to be ¼ as absorptive as lime plaster. This suggests that even though lime plaster may be a more absorptive material, its high level of vapor permeance allows the absorbed moisture to be readily released. It would have been interesting to compare earthern plasters' vapor permeance and ability to absorb water to these results. Perhaps this could be a future experiment.

IX. Moisture Migration and Accumulation in Building Envelopes Relative to Straw-Baled Walls

Moisture intrusion is a major concern for all building envelopes. Conventional wall systems, generally consisting of gypsum/fiberglass insulation/siding (or other such wood/cellulose/wood (or aluminum/plastic) combinations), require just as much attention to detailing and prevention of moisture intrusion as straw-bale/stucco building envelopes require. Regardless of building material used, it is important to prevent moisture accumulation (in liquid form) in any wall system, for when this phenomenon occurs, the deteriorating rate of any building material will accelerate. As Karagiozis explained, "Hygrothermal (combined heat-air and moisture) performance in building envelopes predominantly influences the durability and service life of a building envelope - and this may happen in all three states (liquid, vapor and ice) (1997:559). As the amount of available moisture increases so does the severity of degradation of construction materials. This deterioration may occur in many forms - surface damage, chemical damage (aging), structural (cracking), corrosion, and fungi and/or bacterial growth.

Conventional building envelopes require the use of vapor barriers to limit water (in liquid or vapor form) from penetrating the building envelope. Straw-bale buildings do not require the use of vapor barriers, due to their ability to "breathe."

This phenomenon is similar to the dynamic wall system explained by Taylor and Imbabi (mentioned later in this report) (1998:377-382).

X. **Forms of Moisture**

Moisture is water, and as we all know, it can appear in three forms - vapor, liquid, and solid. The amount of water present in the form of vapor is recognized as relative humidity and measured accordingly. Fluctuations in humidity and temperature levels will cause water vapor to move toward cooler surfaces due to the fact that warm air holds more water vapor than cold air. When warm humid air meets dew point, condensation will occur. Therefore, higher humidity levels increase the potential for moisture accumulation in walls. Warm air also has a higher vapor pressure than cold air. In the winter, vapor will move from the interior wall surface into the wall assembly toward the exterior, however during the summer vapor will move from the exterior wall surface into the wall assembly toward the interior. As the difference in temperature between the interior and exterior increases so does the pressure differential, consequently increasing vapor movement into the wall system. Houses heavily heated in the winter and cooled in summer are most susceptible to problems caused by vapor migration because the vapor will condense when it encounters cold air or cold surfaces (Swearingen, 1996).

Dew Point Factors:

- Air humidity outside the structure;
- Vapor production in the building;
- Volume of the building (smaller houses will more likely experience condensation problems);
- Air ventilation rate;
- Presence of air-drying elements inside the structure.

(Krarti, 1994:657).

Mitchell and colleagues found that as the relative humidity increases, so does the available water vapor molecules for adsorption increase, thereby concluding that an increase in the relative humidity or airflow rate from inlet air will increase the total amount of moisture accumulating in the wall system (Mitchell, 1995: Figures 6 & 7, 1593). Jen found that vapor pressure has more of an influence on moisture diffusion than temperature does; moisture has a positive influence on temperature yet a negative effect on vapor pressure (Jen, 1990:302-3). They also found that owing to Soret's effect and vapor pressure filtration, temperature and vapor pressure both have a positive effect on moisture diffusion (Jen, 1990:302). As mentioned earlier, an increase in temperature increases vapor pressure, and the greater the difference in temperature between the interior and exterior of a building, the greater pressure differential, thus increasing the amount of vapor entering the wall system. This of course is only dangerous to a building envelope when the vapor condenses into liquid.

Liquid moisture is also a major concern for buildings. Water often penetrates the building envelope from exterior sources, particularly via wind-driven precipitation (see exterior source section). However, interior leaks and pipe bursts can contribute greatly to moisture accumulation in a wall system. For this reason, it is important not to place any form of plumbing in a straw-baled wall (or any wall composing of cellulose material for that matter). Plumbing lines are often placed beneath the wall. Liquid moisture can also penetrate a wall system via capillary action through the foundation (see ground moisture section).

Solid moisture (ice) is obviously only a problem when liquid moisture has entered a wall system, and when the temperatures in the wall system are below freezing. First and foremost, it is important to prevent liquid penetration and accumulation in any building envelope, however if this does happen, freezing will expand the water that has accumulated, thus possibly breaking apart cellulose materials. This short-lived expansion will weaken materials, thereby reducing the durability of the wall.

XI. Sources of Moisture

There have been many contradicting experiments carried out to predict the main source of moisture intrusion in conventional building envelopes. Some have found that exfiltration of warm, humid indoor air is the main source of moisture accumulation in walls (Mitchell, 1995:1588). Other studies, such as one completed in 1996 for the Canada Mortgage and Housing Corporation, found that conventional homes in the coastal region of British Columbia were experiencing substantial problems due to water intrusion from exterior sources. They found that direct rain penetration contributed to 91% of all moisture problems (Ruest, 2000:1). Basically, moisture can penetrate from three main sources: exterior, interior, and/or ground.

Interior Sources

Interior sources of moisture seem to be in the form of vapor, and they tend to have two main sources; air leakage and diffusion. Air leakage - typically responsible for more than ninety percent of total vapor intrusion - through windows, doors, electrical outlets, ceiling and wall joints etc. - basically any point that has not been securely sealed. Air leakage is governed by air pressure and can be controlled by sealing leaky joints (when infiltration is the problem), and also by reducing dramatic pressure differences (e.g. opening windows when exfiltration is the problem). As Rob Tom from a Design Group/Atelier OCTO in Canada wrote: “Air leakage occurs through cracks usually found around junctions between dissimilar materials & components and penetrations of the building envelope... losses due to infiltration/exfiltration can account for ~50% of the space heating & cooling energy consumed by a well-insulated building. One of the many deleterious consequences of this leakage is that in heated buildings, condensation of exfiltrated moisture can occur in the envelope materials. In cold climates, this problem can be severe, often resulting in deterioration of the wall and/or roof materials, not to mention increased energy usage as a result of the lowered R-values; and as a result of the exfiltration losses; and that required to condition infiltrated air” (2001).

Diffusion on the other hand, is governed by vapor pressure where water vapor tends to move from areas of high concentration to areas of low concentration. The biggest vapor-intrusion risk in these climates usually exists during the heating season, when a much greater difference in temperature, humidity, and air pressure exists between the inside and the outside of the structure. When climates are colder, the water vapor will have a tendency to move from the interior to the exterior and when climates are warmer, the diffusion would occur from exterior to interior.

In a study conducted by the Canada Mortgage and Housing Corporation, they found that condensation moisture, caused by consistent indoor relative humidity levels above 30% caused 10-15% of all moisture problems in conventional buildings (Ruest, 2000:3). Vapor barriers are usually used in conventional buildings to limit this diffusion, however as David Eisenberg from Development Center for Appropriate Technology explains, this is not a significant concern:

Now what all of the "experts" I've talked with are in absolute agreement about is that the permeability of typical wall finish materials on the interior is almost insignificant in relation to the amount of moisture that will pass through the material. The critical source of water vapor migration into walls in heating climates is gross air leakage, through holes in the finishing system such as at electrical boxes and fixtures, around windows and doors, at the connections of the walls and the ceiling and floor, etc., Bob Platts [founder and a principal at the consulting firm Scanada Ltd, now with Fibrehouse Ltd] said in Canada in dozens of studies that were done, they proved that, although the guideline of having the exterior finish system five times more permeable than the interior finish system is a good idea, in a building that has all the air leaks sealed, it is virtually impossible to get enough moisture migrating through the wall finish to cause moisture failure of a wall system.

Heating and Ventilating magazine indicates that the modern life of a family of four can easily generate 150 pounds, or more than 18 gallons, of water per week into the household air (see Table 5).

***Table 5.* Household vapor accumulation**

Household Activity	Water Vapor Produced
Cooking (3 meals)	1 kg per day (2.2 lb)
Dishwashing (3 meals)	0.5 kg/day (1.1 lb)
People (family of 4)	5 kg/day (11 lb)
Bathing (shower)	0.25 kg each time (.55 lb)
Bathing (tub)	0.05 kg each time (1.76 oz)
Clothes washing	2 kg each time (4.4 lb)
Clothes drying	12 kg each time (26.46lb)

(Canadian Homebuilders Association:1998)

The same report also states “that one tiny crack creates a six-fold increase in water vapor intrusion.” A one-inch square puncture in a Vapor Diffusion Retarder per ten square feet will only increase vapor permeance by 1/1440 (Canadian Homebuilders Association: 1998).

It has been suggested that the most important barrier of concern in straw-bale construction with regard to moisture is the Air Barrier System. The Air Barrier is not a single piece of material, but a system which may consist of several common building elements: interior floor/wall/ceiling materials; weather-stripping; caulking; gaskets; etc., all working together to prevent the leakage of the moisture-laden air inside the house into the walls. Gaps in the interior finishes around electrical outlets, overhead fixtures, window and door frames, plumbing, floors and ceilings, etc., should be sealed and work together as a whole system to prevent vapor movement from the interior of the house into the walls. It's also common good practice to use small active ventilation systems in humid areas such as bathrooms and kitchens to remove much of this concentrated vapor at the source.

Exterior Sources

Liquid moisture is a concern for building envelopes that are exposed to either direct rain penetration or the migration of ground water into the building envelope through poor foundations or from poor drainage systems. Direct liquid moisture penetration via wind driven rain or horizontal wetting seems to be a predominant source of moisture in building envelopes according to Karagiozis (1997:560). Karagiozis stated "wind-driven rain (in liquid form) can increase the amount of moisture present in the structure by more than one hundred times that due to vapor diffusion" (Karagiozis, 1997:559). Karagiozis and colleagues found that wind-driven rain is an important contributor to the total amount of moisture entering the structure - particularly in masonry walls (1997:560). They found that wind speed has more of an effect on moisture distribution patterns than rainfall intensity does (Karagiozis, 1997:570). This is understandable, for it is the wind that drives the rain into the wall systems. If the wind speed were minimal, then the rainfall would both fall more vertically and possess significantly less driving force. It seems obvious then that these two factors combined (wind speed and rainfall intensity) would have the most dramatic influence on building envelope saturation. Karagiozis and colleagues also found that when westerly winds were present during rain events, the western walls received the highest amount of wind-driven rain. It is interesting to note that the upper top sections of walls also received higher amounts of wind-driven rain, which makes one wonder if overhang size (or lack of) influenced this finding. It would seem that the buildings sampled in Karagiozis' study were both high-rise and mid-size city buildings, which would more often than not lack any substantial overhangs. Also, surrounding buildings could have been blocking the majority of wind-driven rain from hitting the lower surfaces of the building envelope, due to their close proximity and height. These results may be significantly different for detached, isolated build.

Figure.19. House No.1 southwest wall

The main exterior source of moisture accumulation in straw-bale buildings according to many studies is precipitation (Lacinski, 2000:47). This seems to be the largest source of water intrusion in buildings, not specifically to straw-baled buildings. A study completed in 1996 for the Canadian Mortgage Housing Corporation found that conventional homes located in the coastal region of British Columbia were experiencing substantial problems due to water intrusion from exterior sources (Ruest, 200:1). They found that direct rain penetration contributed to 91% of all moisture problems (Ruest, 2000:1). When precipitation hits plastered surfaces, the water moves via capillary action through the plaster and into the straw (amounts varying with moisture absorption of different plasters). In conventional buildings, a moisture barrier is usually used to prevent water from soaking into the wood. Moisture barriers also trap water that may have penetrated the wall system from a crack, poorly detailed sill, or other imperfect areas that may be vulnerable to moisture intrusion (which is another factor that could have affected the results in this study). In a 1997 Alberta study they found that most of the problems experienced from exterior sources occurred at window and door perimeters and decks (Ruest, 2000:2).

The plastering material can also significantly affect moisture intrusion into straw-bale building envelopes. Different stuccoes/plasters have different vapor permeability and water absorption qualities. Straw-bales are very vapor and water permeable and therefore rely on the wall coverings to control the moisture from entering. Stuccoes and plasters are quite impermeable to air flow, although they also need to be permeable enough to allow vapor diffusion to release any moisture trapped within. Porous hydrophilic materials tend to absorb liquid water (or “wick” water). During a rain event, water that is deposited on the surface of the exterior skin will wick into the stucco. This water can be pulled through the stucco to the straw at the bonded interface. It is also possible for the stored water to be pulled by solar radiation and escape as vapor to the exterior (Straube, 2000:4). The permeability of a wall covering should be much greater than its ability to absorb moisture. Due to the high permeance rating of a straw-bale/stucco building envelope, these walls could and would be considered a form of dynamic insulation as described by Taylor and Imbabi (particularly when the surface of bales are plastered with earth or lime). Taylor and Imbabi defined dynamic insulation as a "breathing wall," one "which allows movement of air and moisture through the external walls" (Taylor, 1998:377). The permeability of the stucco material contributes greatly to the breathability of the entire building envelope.

Figure 20. A simplified example of an infill gravel foundation system

Ground Sources

Like the movement of rainwater penetrating wall systems, ground sources of moisture also move via capillary action. Cement is a porous material that encourages water molecules to move through its pores via capillary action. Moisture barriers are materials that prevent water intrusion because their pore sizes are too small for water molecules to fit through them, hence the recommendation for using moisture barriers on concrete foundations -- to prevent wicking moisture from penetrating bales. The only problem with this is that if moisture were to penetrate the wall system from a higher source, it may accumulate at the base of the wall, where it would be restricted from exiting due to the presence of a moisture barrier. This point has been proven by straw-bale builder and researcher John Swearingen after building a test wall in California, finding that "rigid insulation under the bales had also trapped water, resulting in the undersurface of the bottom bales to rot (Swearingen, 1996).

An alternative footer system may be to use an in-fill gravel system where gravel is spread between two ties, so that if water were to penetrate the wall system, it would have a means to escape. The pores between gravel pieces are too large to encourage the wicking of ground moisture through capillary action.

It is also a waste product that can be re-used at much less expense to the owner than cement footers. It is interesting to note also that concrete readily wicks water up from the ground, even when it is the wall-covering (stucco) coming into contact with the ground. Due to concrete's wicking nature, Tsongas has recommended that concrete should not come in direct contact with straw-bales (Tsongas, 1995:10).

Prevention of liquid water intrusion into wall systems.

i. Protect materials during construction;
ii. Build substantial overhangs (two feet);
iii. Incorporate the use of verandahs;
iv. Use splash-back protection - either gravel on ground to diffuse water molecules, a garden, or moisture barrier on the lower wall section;
v. Drip-edge window sills;
vi. Adequate sealant for windows;
vii. Maintenance of stucco and sealants.

Figure 21. Overhangs

The purpose of larger overhangs is to protect the southwest wall from direct precipitation influence. Note: Walls are undesirably plastered all the way to the ground.

XII. <u>Methodology</u>

House Descriptions

Three different straw-bale houses were sampled for their moisture content. At the time, these were the only three houses in Athens County that had been built with straw-bales. I believed these three houses were a good representation for variety in size and structure in straw-bale homes. The sampling locations were similar on all three houses, although House No.3's locations vary slightly. Areas susceptible to moisture intrusion and accumulation were the locations sampled and compared to those less likely to accumulate moisture (e.g. below window locations compared to above window locations. All three houses were south facing, allowing for passive solar heating, lighting and drying of walls.

i. House No. 1

Figure 22. Southern and western walls of House No.1.

Note unplastered section.

Figure 23. The window section sampled – eastern wall, House No.1.

House number one is owned and was built by Grant Gilcher in March of 1997. The south-facing house is located on a wooded lot on Tick Ridge Road in Amesville, Ohio. The two-hundred square foot residency used approximately seventy two-string wheat straw-bales to complete load-bearing construction. Each of the bales cost approximately $3.00 and were delivered from a local Athens County farm. The bales were laid flat with the cut side facing the exterior to assist the successful application of cement stucco (with lime) to the exterior. Chicken wire was used to wrap the bales, with diamond lath used for reinforcement around the windows. Rebar was used for the first course of bales, followed by bamboo pinning for the remainder of bale courses. Number thirty roofing felt was used as a moisture barrier around the doors and windows and in the ceiling. Caulking was used as a sealant for all windows and doors. The largest moisture protection feature on this house is the foundation. The house is located on a platform deck 20 inches above grade supported by nine posts cemented 24 inches below grade. The 24” overhangs on the north and southern gable ends and the 20” overhangs on the eastern and western walls also add extra protection to the straw-baled walls. No mold/fungi or insect problems have occurred since the structure was built in 1997.

Level of activity in home:

i. Average number of hours spent indoors per week: 160-200hrs;

ii. Average number of showers per week: 10-12shwrs/wk;

iii. Average hourly usage of stove per week: 5-8hrs/wk.

ii. House No. 2

Figure 24. House No.2.

House number two is owned and was built by Bill Worrell in the summer of 1997. The south-facing house is located on an open field on Lower Allison Road in Athens County. The 732 square foot (450sqft in straw-bale section) house is load-bearing on three walls. The south wall had been framed to support the installation of large windows. The straw-bale construction took one hundred two-string wheat bales stacked flat and an extra seventy for roof insulation. The bales were bought for $3.00 a piece delivered from a farm in northeast Ohio. Chicken wire was used to wrap the bales, bamboo pins to stabilize and a 3-1-1 (sand, cement, lime) mix was used as the wall covering. Three coats were applied to the interior and only one to the exterior. Moisture barriers were used on the lowest course of bales and upon the tar painted railway tressel gravel in-filled footers. Roofing paper was also used around the doors and windows. On the northern wall, plastic and roofing paper was used between the straw and brick interior covering in attempt to protect the wall from any moisture intrusion from the interior water cistern located adjacent to the north wall. The majority of the northern and half of the eastern walls have been exposed since 1997. A large porch protects half of the northern wall and most of the western wall. An eighteen-inch overhang protects the remainder of the north wall, whereas the south and east walls possess a smaller six inch overhang. The total cost of the house thus far has totaled $7,000. There have been no reports of mold/fungi infiltration, yet there has been a strong influx of insects living in the straw-bales - mainly the eastern and northern walls that have yet to be sealed.

Level of activity:

i. Average number of hours spent indoors per week: 112hrs;

ii. Average number of showers taken per week: 3/wk;

iii. Average hourly usage of stove/week: 2hrs.

iii. House No. 3

Figure 25. Sampled windows on House No.3 southern wall

Figure 26. House No.3 western wall with more appropriate overhang length

Matt Glass and friends built House No. 3 in 2000. Like House No. 1, chicken wire was used to wrap the bales and rebar was used to pin the first course of bales, then bamboo was used to pin the remainder of bales. A 1-3-3 cement, sand, lime mix was used to enclose the exterior walls and a 1-3-4 combination was used for the interior surfaces. One large difference to note in House No. 3 compared to the Houses No.1 and No. 2, is that House No. 3 did not make use of any moisture barriers. At the beginning of testing, the windows on the south wall did not possess any sills, though after the first two months of sampling, sills were installed and caulking was used for sealing. A Frank Lloyd Wright rubble trench foundation was used with plastic roof cement used between the footer and the bales. It is also important to note that this house, as with House No.2 have stuccoed all the way to the ground, allowing water to be readily wicked by the cement stucco, particularly after heavy rains. Overhangs on this house are approximately 12" on the south and north walls, with large porches protecting the eastern and western walls.

Level of activity:

Average number of hours spent indoors per week: *60-100hrs;*

Average number of showers per week: *No shower yet;*

Average hourly usage of stove per week: *40hrs/wk.*

Instrumentation

The instrumentation used for testing the moisture content of the straw-bales within these houses was a Delmhorst F2000 bale moisture meter. The New Jersey based company has been producing moisture meters for various materials since 1946 and is currently the market leader in moisture meter production. The F2000 moisture meter operates on the principle of electrical resistance - the moisture content of a material and its conductivity. Moisture is an effective conductor of electricity and straw is a good insulator, thereby allowing a more accurate reading to be taken. The "reading" is made between the two metal contacts located at the tip of the eighteen inch probe. The F2000 possesses a micro-controller circuit that can take moisture readings between 8-40%. It is a digital meter possessing a built-in calibration check and a temperature stable circuit. The unit was calibrated at 80 degrees Fahrenheit. Temperature differences can affect the accuracy of a reading; therefore the data collected has been altered accordingly.

For each 20-degree difference approximately 1% should be added when the temperature is lower, and subtracted when the temperature is higher. Other factors that can affect moisture content readings include: moisture distribution, crop variety, and temperature of the bale, bale maturity, bale density, and climatic conditions. For example, denser bales may yield readings that are 1-2% higher where looser bales may yield readings 1-2% lower. Delmhorst suggests that stacked bales may actually yield readings that are 2-3% lower than the actual moisture content. This may affect the accuracy of readings taken within the houses because the bales have all been stacked, though it seems it may actually have the opposite effect, considering that bales stacked and sealed may in fact have a higher density - only on-site density test could determine this.

Sampling procedure

It is important to acknowledge that the density of bales may differ significantly. The research subjects chosen were inhabited residences, externally and internally coated with cement. It was therefore only possible to drill a limited number of holes into the wall structures to sample moisture content levels. The same bale in the different walls had been probed on a weekly basis for ten months. A conscious effort was made during every sample, to access the walls' interiors with the moisture probe at a different angle from the previous sampling day. Differing probing angles provided access to denser sections of the bales, thereby ensuring peak accuracy in every moisture content reading.

Secondary sub-research experiments were necessary to perform in order to invalidate or substantiate moisture diffusion rates previously assumed. I have found that within a healthy bale (relatively dry) moisture distribution does not vary greatly. From the bales sampled, the readings did not vary more than 3% per position sampled. The moisture distribution in a wetter bale however, varies greatly. Water seems to run through a bale without actually distributing the water evenly through the entire bale. It is therefore possible for water to be intruding a section of a wall without distributing the moisture to surrounding bales.

Sampling points were selected on the basis of their vulnerability to moisture intrusion. Houses No. 1 and No. 2 were sampled in the same areas. House No. 3 however was not sampled on the eastern wall, due to its added porch protection. Extra readings were taken on the southern wall, where the majority of windows were located.

Areas tested that were considered to be vulnerable to moisture intrusion

- Under windowsills;
- Southwest walls - exposed to wind-driven rains;
- Northeast walls - shaded from sunlight;
- Low-lying bales - vulnerable to moisture wicking from earth;
- Top bales - vulnerable to vertical wetting from precipitation;
- Above shower - vulnerable to indoor moisture intrusion.

Monitoring Depths *- (external to internal wall surface):*

- *Exterior surface (1-2 inches);*
- *Mid-bale (7-8 inches);*
- *Interior surface (16-18 inches).*

Monitoring Height

- *Top course of bales;*
- *Mid course of bales;*
- *Bottom course of bales.*

Data Collection Locations

i. Southwest Wall Section

Southwest section - exposed upper section of wall, cement-stucco coated bales lie beneath. Rain is predominantly driven in southwest direction. Nine readings taken within southwest section:-

- *Three samples taken 2-5 inches above the base of the lowest bale -* ***SWB*** *(interior, middle, and exterior bale moisture readings).*
- *Three samples taken midway up the wall -* ***SWM*** *(interior, middle, and exterior bale moisture readings).*
- *Three samples taken 2-5 inches below the top surface of the highest bale* ***- SWT*** *(interior, middle, and exterior bale moisture readings).*

ii. Northeast Wall Section

Directly opposite the southwest location, the northeast wall area receives minimal sunlight, yet sufficient precipitation accesses the walls' surface. Nine readings taken within the northeast section:-

- *Three samples taken 2-5 inches above the base of the lowest bale - NEB (interior, middle, and exterior bale moisture readings).*
- *Three samples taken midway up the wall - NEM (interior, middle, and exterior bale moisture readings).*
- *Three samples taken 1-2 inches below the top surface of the highest bale - NET (interior, middle, and exterior bale moisture readings).*

iii. Eastern Wall Section

The eastern walls were included in the research to provide moisture reading comparatives between wall sections with windows and without. Subjects sampled sindow is located -6 readings:

- *Three samples taken 1-2 inches above the base of the lowest bale - WB (interior, middle, and exterior bale moisture readings);*
- *Three samples taken 2-5 inches above the window buck – WT (interior, middle, and exterior bale moisture readings);*

Figure 27. House No.3 southwest below window sampling point.
When not being sampled, the hole is plugged.

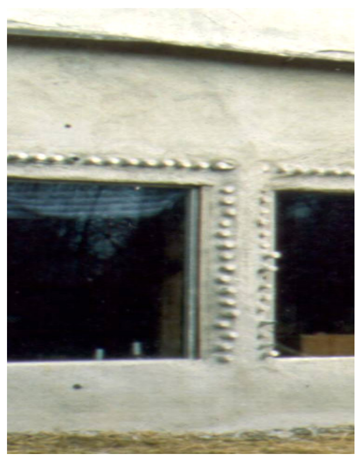


Figure 28. House No.3 south-mid-wall
- above window and below window sampling points.

iv. House No. 3 Alterations

House No. 3 had an array of windows located within the southern wall, thereby differing from the eastern wall windows of Houses 1 & 2. Three samples taken on the southwest wall below window with sill (interior, middle, and exterior bale moisture readings):-

a) *Three samples taken on the south mid wall below window* ***– WB*** *(interior, middle, and exterior bale moisture readings);*
b) *Three samples taken on the southwest wall below window -* ***SWB*** *(interior, middle, and exterior bale moisture readings);*
c) *Three samples taken on the south mid wall above window –* ***WT*** *(interior, middle, and exterior bale moisture readings).*

Data collection began in December 2000 and continued until the end of September 2001. During the first three months, samples were taken three times per week. Beginning in March 2000 sampling days were reduced to once per week. All readings were written in table form in a laboratory book - then transferred to an excel database. Readings were taken at various times of the day, times, temperature, and relative humidity were recorded for that particular time.

XIII. Data Analysis

The weather data used for this investigation was collected from Scalia Laboratory at Ohio University. Weather data is collected by the university daily using sophisticated weather monitoring technology. The supervisor of the laboratory, Dr Isaac, informed me that the weather monitored at the university could be used to accurately represent weather throughout Athens County. All moisture content data collected from the three houses was entered into a Microsoft Excel spreadsheet. As stated in the previous section, its manufacturers had calibrated the Delmhorst moisture meter at 80 degrees F. It was therefore necessary to manipulate the data 1% for every 20-degree F difference to accurately represent true moisture content (>1% if temp <20deg.F; >2% if temp <40deg.F, <1% if temp >by 20deg.F etc.) Accurate graphing and data analysis was accomplished using the Microsoft Excel program and the SPSS statistical analysis program.

XIV. Results

Individual Data Collected

***Table 6.* House No.1 Monthly Average Moisture Content Readings**

House No. 1									
	SWT	**SWM**	**SWB**	**WT**	**WB**	**NET**	**NEM**	**NEB**	**Total Av.**
December Av.	12.74	12.49	12.30	12.02	11.54	12.38	11.64	11.77	12.10
January Av.	11.87	11.82	12.25	12.29	11.24	11.68	11.25	11.46	11.73
February Av.	11.35	11.33	11.35	11.61	10.71	11.01	10.94	10.98	11.16
March Av.	11.46	11.31	11.15	11.44	10.88	11.58	10.84	11.19	11.23
April Av.	10.49	10.36	10.15	9.98	9.67	10.93	10.23	10.73	10.32
May Av.	11.09	10.89	9.89	10.14	9.37	11.51	10.11	10.01	10.38
June Av.	12.50	11.94	11.28	10.70	10.16	12.40	10.62	10.59	11.27
July Av.	13.33	12.45	11.24	10.59	10.57	13.17	10.53	10.93	11.60
August Av.	14.67	13.21	12.09	12.05	11.95	13.73	11.75	11.91	12.67
September Av.	15.13	14.03	12.57	11.78	12.35	14.35	12.01	12.58	13.10
Total Wall Av.	12.43	11.93	11.33	11.18	10.76	12.26	10.92	11.15	11.55

***Table 7.* House No.2 Monthly Average Moisture Content Readings**

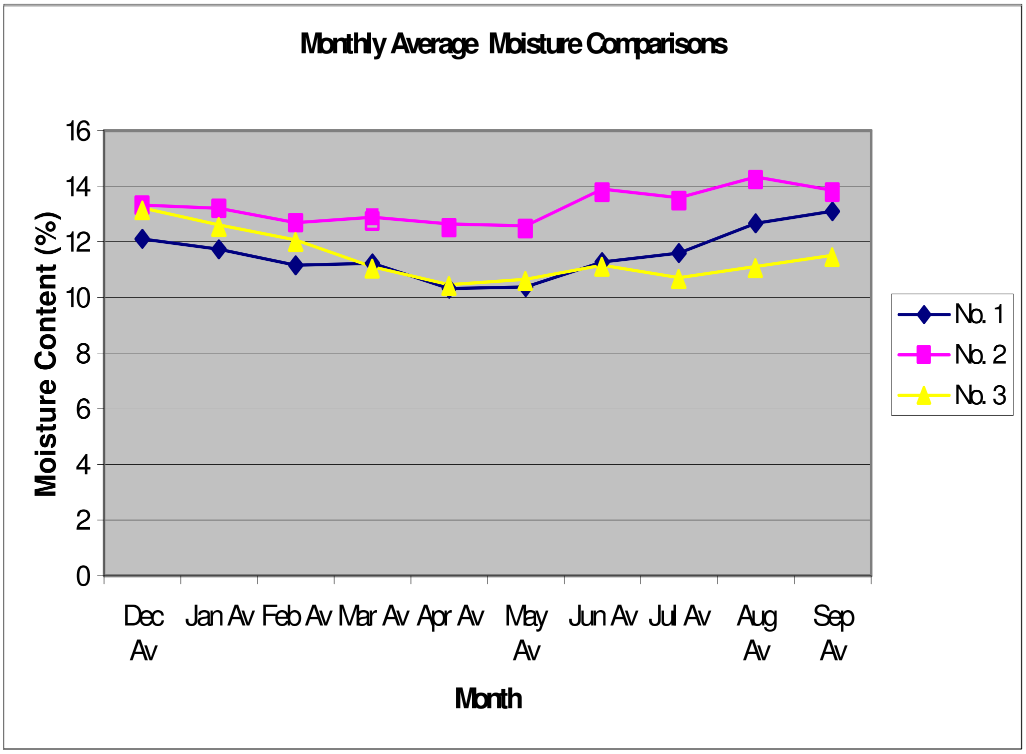
House No. 2									
	SWT	**SWM**	**SWB**	**WT**	**WB**	**NET**	**NEM**	**NEB**	**Total Av.**
December Av.	11.24	11.48	17.13	11.39	17.68	11.48	11.88	14.22	13.31
January Av.	10.79	11.34	16.34	11.29	18.06	11.53	11.85	14.42	13.20
February Av.	10.33	10.70	16.02	10.64	17.70	11.14	11.29	13.67	12.69
March Av.	10.43	10.50	14.57	11.14	19.11	11.38	11.52	14.38	12.88
April Av.	9.65	9.86	15.39	10.15	19.78	10.00	10.66	15.63	12.64
May Av.	10.79	9.44	14.30	10.29	20.07	10.46	10.74	14.40	12.56
June Av.	12.60	10.38	16.41	10.47	22.94	10.63	10.49	17.19	13.89
July Av.	12.61	9.47	15.08	10.34	23.48	10.13	10.97	16.56	13.58
August Av.	13.69	10.17	17.17	10.64	23.88	10.64	10.99	17.45	14.33
September Av.	14.88	10.13	18.10	10.53	18.18	10.95	11.10	16.95	13.85
Total Wall Av.	11.70	10.35	16.05	10.69	20.09	10.83	11.15	15.49	13.29

<u>Table 8.</u>* *House No.3 Monthly Average Moisture Content Readings

House No. 3							
	SRB	**AW**	**SMB**	**NET**	**NEM**	**NEB**	**Total Av.**
December Av.	15.23	11.88	17.57	11.47	12.65	12.10	13.21
January Av.	13.26	11.06	15.50	11.37	12.25	12.27	12.61
February Av.	11.34	10.10	17.20	11.14	11.54	12.01	12.07
March Av.	10.53	10.07	12.08	10.82	11.43	11.90	11.10
April Av.	9.38	9.12	11.71	10.28	10.94	12.09	10.46
May Av.	9.89	9.20	12.76	10.39	10.48	12.07	10.65
June Av.	10.93	9.29	13.29	10.49	11.13	12.31	11.16
July Av.	10.92	10.05	11.88	9.18	10.33	12.62	10.70
August Av.	10.83	9.60	13.08	9.79	10.76	12.55	11.10
September Av.	11.71	10.25	13.58	10.38	11.43	11.78	11.52
Total Wall Av.	10.98	9.86	13.45	10.43	11.14	12.18	11.34

Monthly Averages Comparisons

***Graph 1*. Monthly Average Comparisons for Houses 1, 2 & 3.**



With exception of House No. 3 (due to the two - three month high window readings) the trend line seems to slightly increase throughout the latter part of the ten-month period of sampling, illustrating higher moisture content readings during the last three - four months of sampling than what were found earlier in the year. A noticeable increase occurs in May/June and continues until September. From these results (tables 6-8 and graph 1), it is obvious that House No. 2 has significantly higher moisture content readings than that of House No. 1 or House No. 3 - particularly when comparing the lower sections of the house. The largest difference can be seen when comparing below window readings from all three houses. The average window reading (WB) from House No. 2 was 20%, compared to 10.7% and 13.4% from House No. 1 and No. 3 respectively. The first two months of no windowsill or other window protection affected the overall average below window readings for House No. 3. During the first two months of sampling below window readings were 15.5% and 17.2% for January and February respectively. After caulking the seals and installing a drip sill, the average monthly moisture readings fell to between 11-13% (see section D – Wall Altitude Comparisons for more information). The high moisture content readings of House No. 2 may be caused by drainage problems and/or foundation problems. It is difficult to pinpoint one specific cause when it probably has multiple causes, such as:

- The foundation;
- The lack of sealing of the window;
- The holey tarpaper wrapping the first two courses of bales;
- Poor drainage;
- Exposed bales.

Figure 29. Northwest wall section of House No.2
- remains unfinished for 3yrs now.

House No.1's highest monthly reading came in September – on the southern upper wall section. This had been a gradual increase since April, although the moisture content levels do not appear to be abnormally elevated nor are the differences significant. There are varying opinions on the healthy moisture content level for bales – from 13.5%-20%. Therefore, levels below the lowest suspected healthy moisture content level of 13.5% should be regarded as safe. Four of the eleven monthly average readings exceeded that of 13.5%. House No.1 and No. 3 did not exceed 13.5% during any of the given monthly averages. However, during December, January, February, House No.3 exceeded the 13.5% moisture content level at the southern mid-wall section below the window. This was solely the result of early year highs found underneath the unprotected window located on the southern center lower wall. House No.2 exceeds 13.5% on many of its monthly average moisture content readings for the reasons stated earlier in this section – all bottom wall sections show severely elevated moisture content levels – high enough to be of great concern.

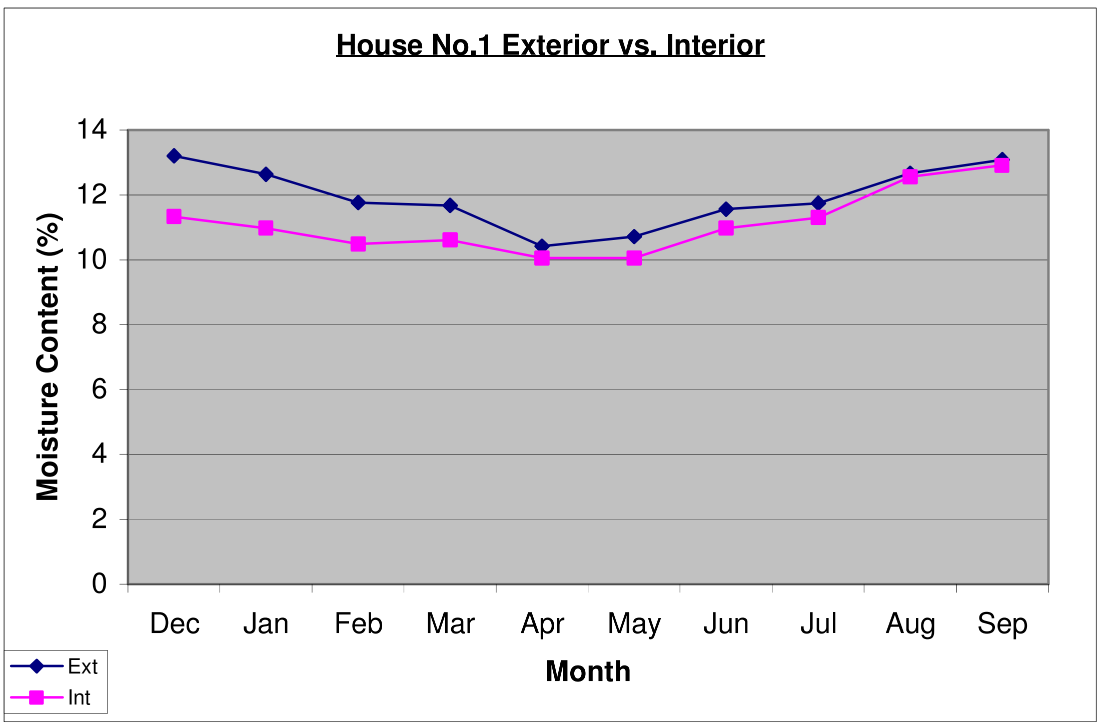
Although significant differences can be seen in the monthly average moisture content readings between all three houses (particularly that of House No.2) at any point throughout the ten-month sampling period, the percentage of difference between the houses did not exceed 4%. When viewing the figures for August (the month in which greatest variance occurred), House No.1 held a monthly average moisture content reading of 12.67%, House No.2 – 14.33% (the highest monthly average in this study), and House No.3 with 11.10%. The difference between House No.2 and House No.3 being 3.23% - the greatest found between the monthly average readings of all three houses during the ten-month sampling period. Further evaluations are necessary to understand how and what contributed to the monthly average moisture content readings and why they illustrated the pattern seen in Graph 1.

Exterior readings vs. Interior readings

***Table 9*. House No.1 interior vs. exterior averages**

	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep
EXT	13.20	12.64	11.76	11.68	10.42	10.72	11.56	11.74	12.67	13.09
INT	11.33	10.98	10.49	10.61	10.05	10.06	10.98	11.30	12.56	12.91

***Graph 2*. House No.1 Interior vs. Exterior Comparisons**

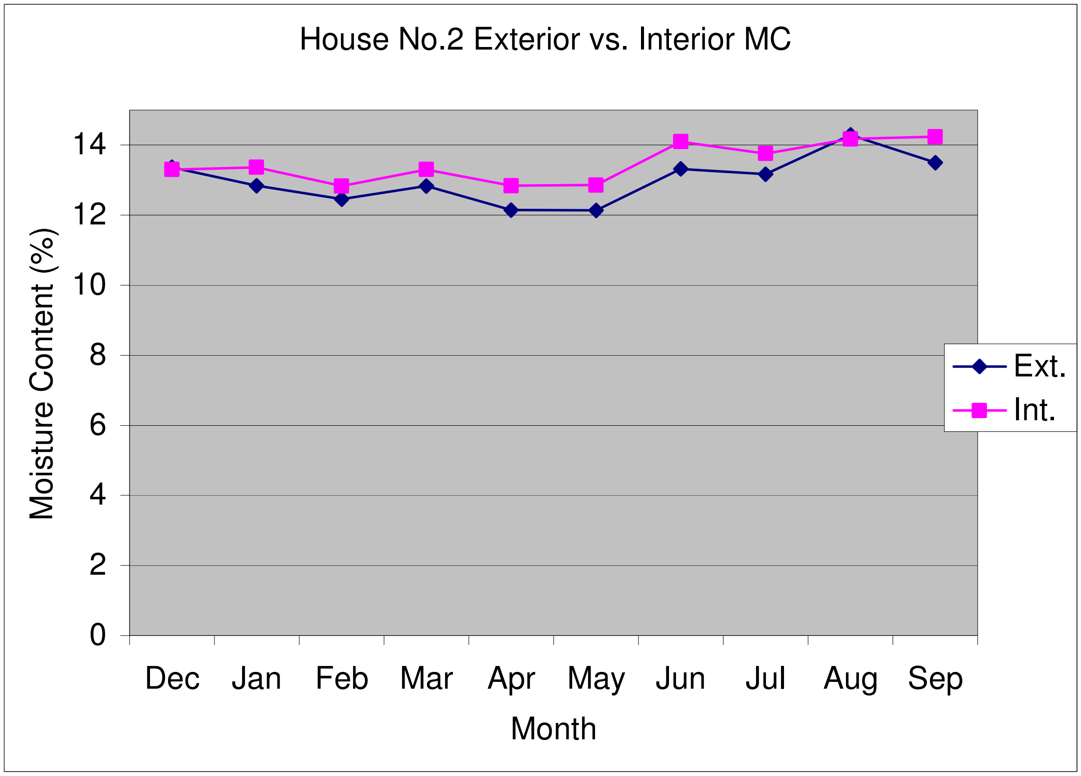


House No.1's interior and exterior moisture content levels appear to be closely correlated throughout the ten-month sampling period. Both interior and exterior readings fell during the first few months, reaching an all time low during the mid months of April and May. Both the interior and exterior moisture content levels began to rise again immediately after the dip, and continued to rise during the latter months. The exterior readings remained steadily higher than the interior readings throughout the year; however, the difference never exceeded 2%. Both exterior and interior readings remained closely correlated, particularly during the latter months. This graph shows that the wall system of House No.1 seems to be quite secure – protecting the bales uniformly well. Interior and exterior moisture content readings remained between 10% and 13.2% - never varying more than 2.2%during any one month.

***Table 10*. House No.2 Interior vs. Exterior**

	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep
EXT	13.36	12.84	12.46	12.83	12.14	12.14	13.32	13.17	14.29	13.49
INT	13.30	13.36	12.83	13.30	12.84	12.86	14.09	13.76	14.17	14.23

Graph 3. House No.2 Interior vs. Exterior



It is interesting to note that interior moisture content levels exceed exterior moisture content levels during every month (except January and August where they overlap). This may be to the high sun radiation in the area surrounding House No.2. The high level of sun exposure is able to quickly dry the exterior section of the bales, whilst also perhaps able to dry the interior section of the bales as quickly and/or thoroughly. No significant difference between the two readings suggests that the moisture penetrating the exterior wall surface is in fact seeping into the interior section of the bales in a somewhat uniform manner as it also may be drying in a uniform manner.. House No.2 also shows a dip, falling during the first few months to be its lowest during April and May, then rising again during the latter months as does House No.1 illustrated in Graph 1. The differences between the interior and exterior moisture content readings within House No.2 are actually so similar that a different scaling procedure was necessary to illustrate the comparison clearly. In fact, the greatest difference found between House No.2's interior and exterior readings during any monthly average was found in September, when exterior – 13.49% and interior – 14.23% - showing the maximum difference to be 0.78%

From observing the dramatic changes of moisture content in House No.3 after the first two months, it is obvious that the sealing of the windows is of utmost importance in preventing moisture intrusion into the exterior and interior section of the bales. The percentage of moisture continue to drop, like seen in both House No.1 and 2, House No.3 shows a dip occurring during April and May for both interior and exterior.

Table 11. House No.3 Exterior vs. Interior

	Jan	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**
EXT	14.49	12.69	11.84	10.79	10.13	10.62	10.85	10.28	10.75
INT	12.11	11.88	11.26	10.73	10.21	10.78	11.2	10.91	11.22

The rise that occurs in House No.1 and 2 cannot be seen here in House No.3, probably due to the fact that the higher earlier readings were solely due to the unprotected window. Only a slight rise occurred, hardly significant enough to mention.

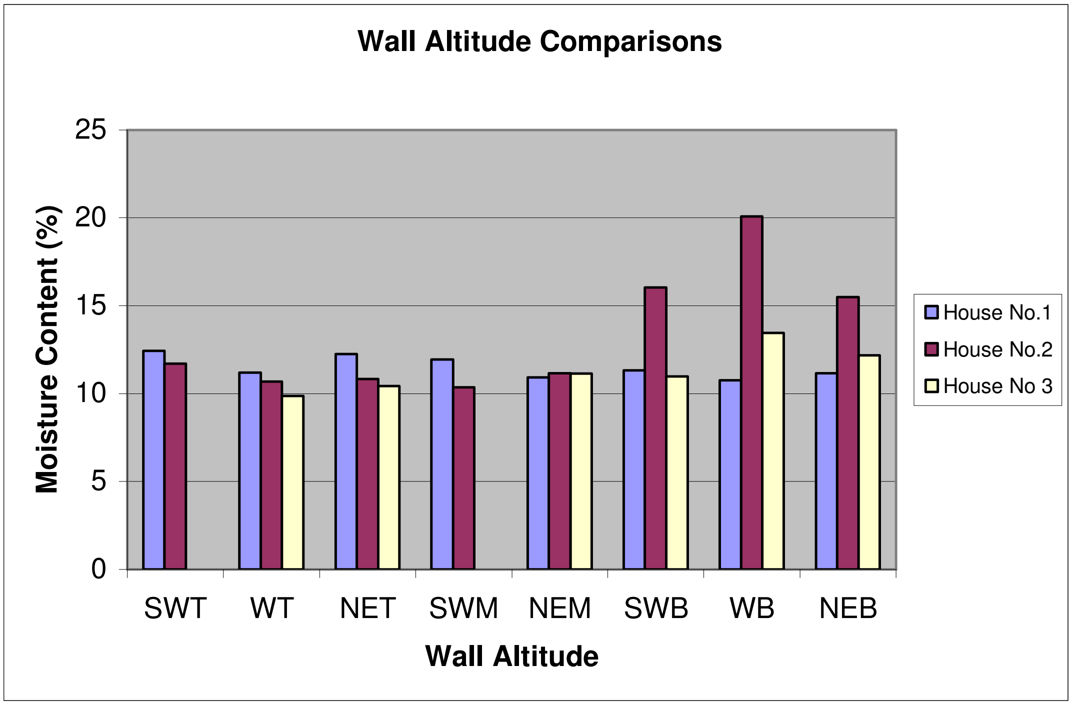
House No.3 proved to have the greatest difference between the exterior and interior readings during a particular month, and that month was January. The exterior surface gave a moisture content reading of 14.49% while the interior surface gave a reading of 12.11%, a difference of 2.38%. As mentioned earlier, the cause for the dramatic difference could have been the precipitation soaking the exterior section of bale which lay below where the unprotected window. During the latter six months the interior and exterior readings showed no significant difference.

Wall Altitude Comparisons

Table 12*. *Wall Altitude Averages

	SWT	WT	NET	SWM	NEM	SWB	WB	NEB
House No.1	12.43	11.18	12.26	11.93	10.92	11.33	10.76	11.15
House No.2	11.70	10.69	10.83	10.35	11.15	16.05	20.09	15.49
House No.3	N/A	9.86	10.43	N/A	11.14	10.98	13.45	12.18

***Graph 4*. Wall Altitude Comparisons (Column)**



SWT – Southwest Top **WT** – Window Top **NET** – Northeast Top

SWM – Southwest Medium **NEM** – Northeast Medium

SWB – Southwest **WB** – Window Bottom **NEB** – Northeast Bottom

i. Top Wall Sections

House No.3 sustained lower moisture content levels in all the higher wall positions sampled, perhaps due to short northern and southern overhangs positioned on the house, thereby exposing the higher wall sections to a greater amount of drying sunlight. This finding and suggested theory would definitely concur with the results from House No.1 also. House No.1 shows slightly higher readings for all top wall sections than either House No.2 or No.3. The larger overhangs on House

No.1 may have in fact prevented solar radiation from hitting those higher surfaces and therefore slowing the drying process of bales that lie beneath precipitated cemented stucco.

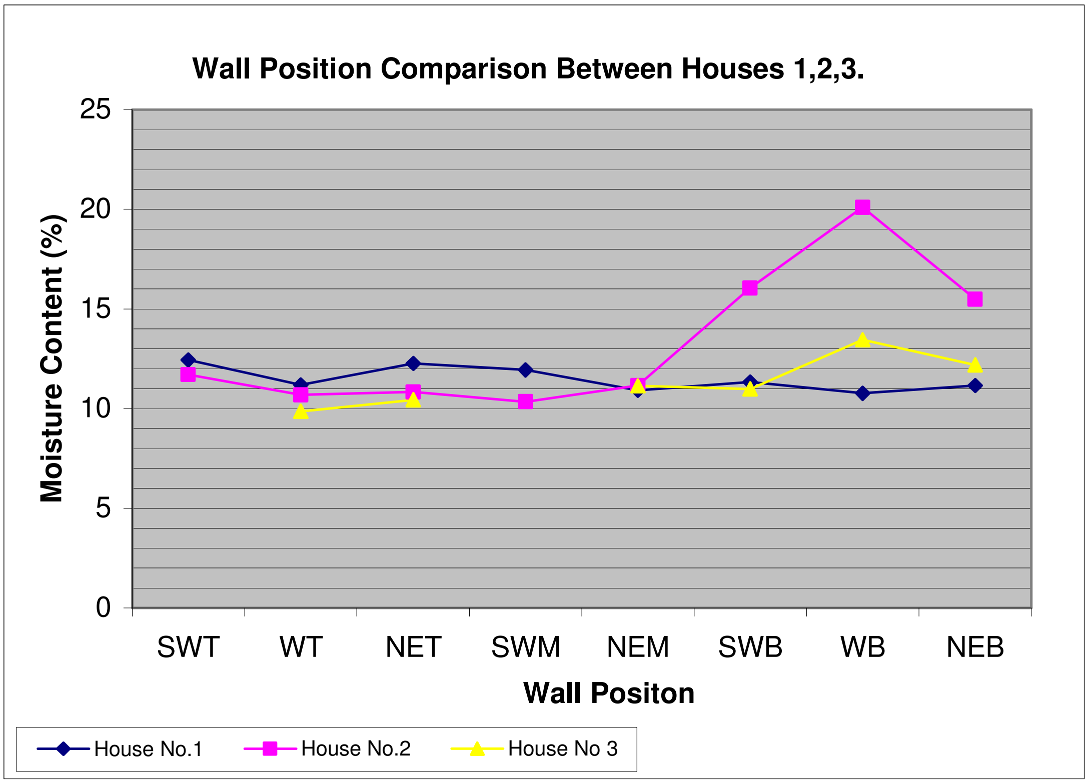
ii. Mid Wall Sections

There are no significant findings from analysis of the mid-wall sections between the sampled houses, although House No.1 held a slightly higher moisture content level on the southern mid-wall section whereas House No.3 showed to have an insignificantly higher mid-wall level of moisture content within its northern wall.

iii. Bottom Wall Sections

The most significant difference between wall sections appears within the lower wall sections, particularly for House No.2. House No.2's moisture content levels greatly exceed those of House No.1 and No.3. This finding is of no surprise due to House No.2's unfinished plastering of the lower bales that not only extend into the moist ground but are also encompassed with tarpaper, allowing moisture to accumulate within the lower course of bales. As suggested earlier, this house may have some serious drainage problems, or the backsplash is becoming trapped behind the tarpaper that encompasses the lower bales. House No.3 also appears to have higher lower wall readings, particularly below the window. These readings however were generally higher during the first two months of sampling, before caulking and installing a drip sill. There is no significant variation between top and bottom readings for House No.1 - probably due to the house being situated three feet above grade.

Graph 5*. *Wall Position Comparison (Line Graph)



XV. Weather Data Analysis

***Table 13.* Monthly Average Weather Data**

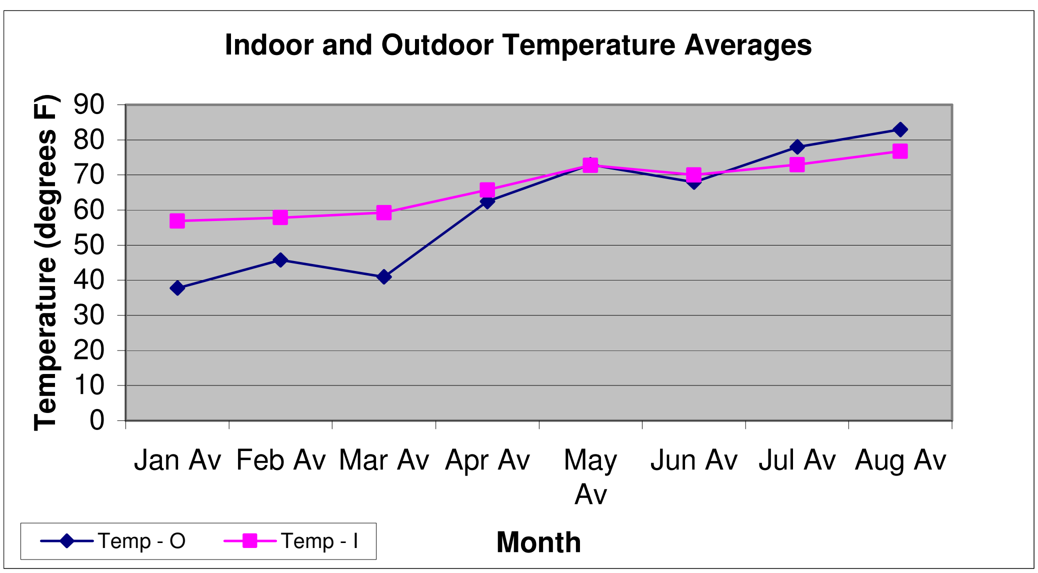
	Temp - O	Temp - I	RH - O	RH - I	RH – O - max	Precip inches
Jan Av	37.8	56.9	68.2	49.3	93.1	2.1
Feb Av	45.8	57.9	53.3	49.1	86.5	1.3
Mar Av	41	59.3	50.8	42.5	77.8	2.9
Apr Av	62.5	65.8	58	46.3	94.8	4.1
May Av	73	72.8	64.6	59.8	98.6	6.5
Jun Av	68	70	61.5	65	99	5.2
Jul Av	78	73	58.3	66.8	97.5	3.6
Aug Av	83	76.8	53.8	71.2	98.4	2.3
Sep Av	70	69	72.5	72	98	0.8

Temperature

Indoor temperatures and relative humidity readings were gauged using a thermometer and hygrometer placed within House No.1. Both indoor and outdoor temperatures rose somewhat steadily throughout the year – from an indoor low of 56.9deg.F, average January reading, and an outdoor low of 37.8deg.F, also the January average. Temperature was important in the correct calibration of the Delmhorst moisture meter (as mentioned in Section XIII – Data Analysis). July and August experienced the highest monthly average temperatures, both outdoor and indoor. It was during these two months that the outdoor temperatures exceeded the indoor temperatures by 5-5.2deg.F. Temperature seems to have an insignificant effect on the moisture content of straw-bales from any of the houses sampled in this study.

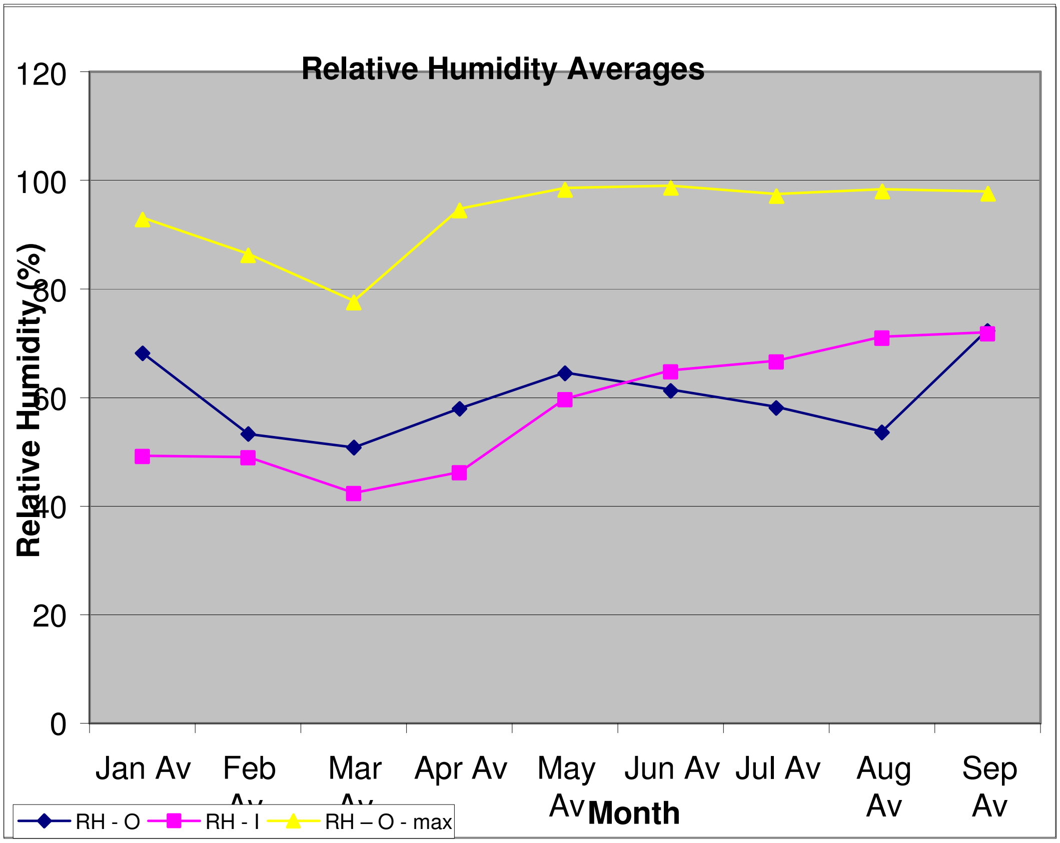
Houses No.2 and No.3 show a closer correlation with temperature than House No.1, however the trends seem to be contradictory to each other. House No.3 showed its highest moisture reading during the coldest day (note: this high reading could have been during the first two months of sampling when the south walls' window was unprotected). It is also interesting to note that Houses No. 1 and 2 showed their lowest moisture readings when the temperature remained between 60 - 70 degrees Fahrenheit. In general, strong correlations could not be made between temperature and moisture content.

<u>Graph 6</u>. Monthly Average Indoor and Outdoor Temperatures



Relative Humidity - moment and maximum

***Graph 7*. Outdoor, Indoor, and Maximum Average Monthly Relative Humidity**

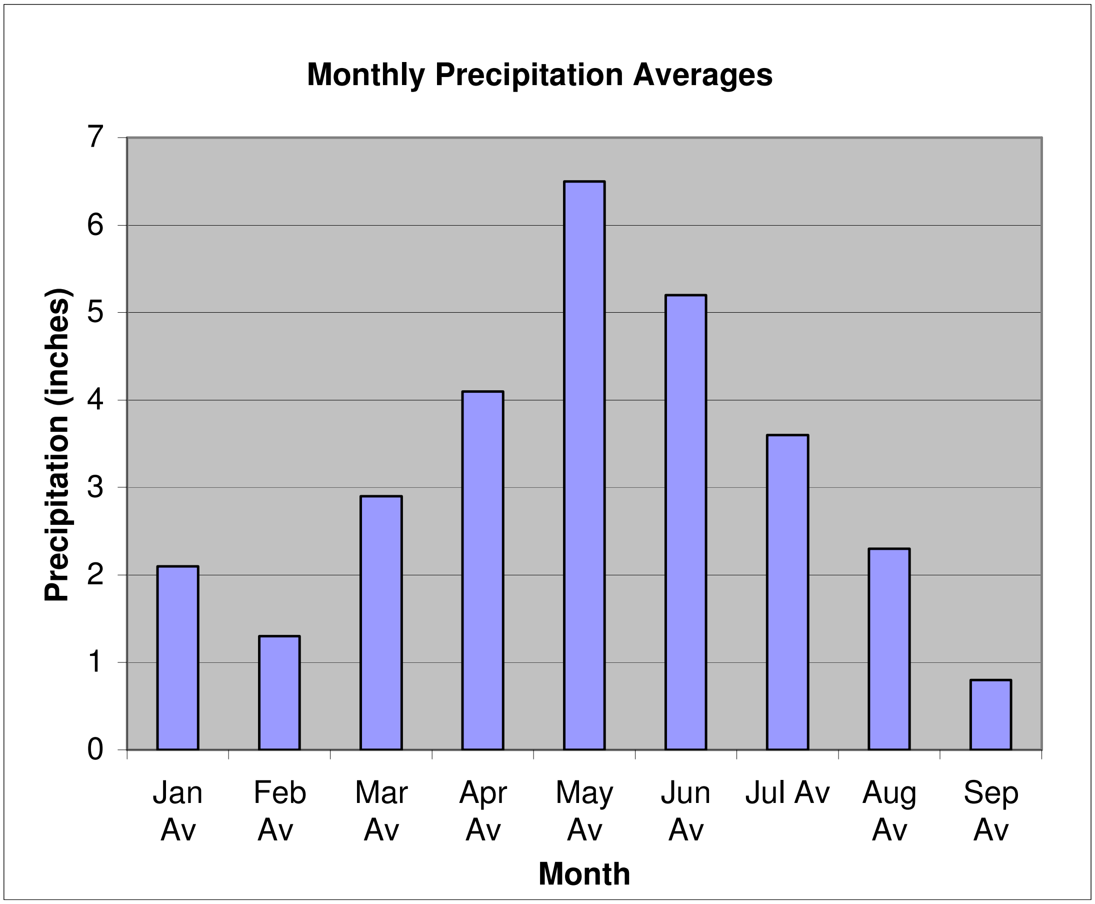


Closer correlations can be seen between relative humidity and moisture content than all other weather data, however correlations remain insignificant. All graphs show a positive linear regression (except House No.3 when correlating moisture content with RH-max). An almost perfect linear correlation can be seen between RH - max and House No.3 until relative humidity exceeds 93%. Houses No.1 and 2 showed their highest and lowest readings when the maximum relative humidity was 98%. This may suggest that relative humidity may in fact have a marginal effect on the moisture content of bales in a house. An interesting pattern can be seen when comparing graph 7 with graph 1. There is an obvious “dip” in both graphs. Graph No.7 experiences this dip in its outdoor (both max and at time of sample) and indoor readings during the three-month period from January through till and including March. In April, the relative humidity figures begin to rise again. When examining graph No.1, a similar pattern can be observed, although the “dip” occurs at a later stage – during the three-month period of March, April and May. It may be suggested that the lower relative humidity experienced during the earlier three-month period of January, February and March may have possibly bee experienced by the straw-bale wall system during the following three-month period – March, April, May. An observation of speculation suggests that further studies could find more conclusive evidence find the specific role of relative humidity in the moisture content of straw-bale houses.

Precipitation

From the monthly data collected, it seems that precipitation has no effect on the moisture content of bales within the three homes tested. In fact, the linear trend shows moisture content of bales actually decreasing when rainfall increases. This suggests that maybe these homes have been sufficiently protected from rain. However, this would be a difficult argument to defend considering House No.2 kept half of the exterior surface of the home unstuccoed with insufficient overhangs. The result from this analysis was unexpected and remains quite perplexing. It seems that an increase in rainfall would almost undoubtedly increase the moisture content of bales, but this does not seem to be so. Rainfall can greatly vary from day to day, perhaps monthly averages do not accurately represent the true effect rainfall has on the moisture content of straw-bales.

***Graph 8*. Monthly Precipitation Levels**



XVI. Conclusion

All three houses sampled in this study exhibit monthly average moisture content readings below 13.5%. According to previous research findings and the educated opinion of straw-bale experts, bales existing within an enclosed wall system exhibiting moisture content readings below 14.5% are safe from moisture related deterioration (within the wall systems' straw-bales). Bales with less than

14.5% moisture content readings are considered quite healthy – this of course, is referring to monthly average readings. The moisture content levels within individual locations cannot be viewed lightly. As we observed with House No.2 – its lower walls are severely affected by moisture accumulation from precipitation and ground water sources – particularly at its below window (WB) location. Due to the lack of attention to detail and specified straw-bale constructional knowledge, the house will inevitably endure severe future deterioration – particularly within its wall system (and foundation).

From my original research, practical experience, and theoretical knowledge, I strongly believe that straw-bale homes built in the high precipitation and high humidity environment of southeast Ohio are not only safe, but appropriate when built by a person/group knowledgeable not only of general construction, but specifically skilled in working with and understanding the different requirements needed for a meticulously detailed and therefore successful straw-bale home.

According to the results found here, straw is a viable building material for houses in southeastern Ohio. It is important, however, that the house is built with great attention to detail, particularly around the windows and doors. Anywhere cracks or joints within the building envelope are points prone to intrusion. An efficient drainage system and foundation are also vital to keep a dry home. When paying attention to these details, straw seems to be a viable building material to use for homes in southeast Ohio.

Southeast Ohio has experienced massive environmental destruction over the past two centuries due to mining and logging. Housing demand is the single largest economic force impacting national forests, accounting for more than three-fourths of the world's voracious appetite for wood (Roodman, 1994:22). Straw is an under-used, low-energy, non-toxic, renewable material, which could be used as an alternative to over-used, and energy intensive products such as plastic, wood and cement. Conservative figures show that Ohio harvests enough straw to construct more than two hundred 2,000 square foot homes every year. Environmentally, the use of straw for constructional purposes seems to be one appropriate response to the current building crisis- to using a waste material to provide affordable housing. It is important to note however that both monetary and environmental costs would be dramatically reduced, not only by constructing with straw, but by making it a priority to use low energy input, renewable, sustainable, non-toxic, re-used, recycled local products.

It has been estimated that straw-bale homes require less than a third of the energy requirements for heating and cooling than conventional homes, in terms of costs these energy savings can be significant (Wilkins, 1995:7). Buying a house is the largest single investment most middle-class Americans will make in their lifetime (Miner, 1995:4), one that many people living in Appalachian Ohio cannot conceive. Per capita income in Appalachia Ohio stands at $12,500, that's 20% below the state average. In 1989, Athens County per capita income was at $9170, less than 50% of the U.S. average. The houses sampled cost between $10-$30 per square foot. These figures are less than half the price of an average stud framed house at $65-$75 per square foot. It has been shown that the most efficient means to reduce the cost of a straw-bale home is to cut labor costs – participate in the building process. To lower costs does not simply mean building with straw, but modifying and simplifying the way we live, so that simpler and more practical structures can cater for such lifestyles without dramatically impacting the earth or our health. By doing this we could also reduce both energy and monetary expenditures, build community and house the needy, while minimizing the negative impacts we have on the earth. It would seem that southeast Ohio (like many other areas) would greatly benefit, financially and environmentally, with the use of straw-bales as building materials.

There are many people and organizations that do not particularly like change. It has been difficult to pass building code restrictions in many states. The areas where these homes were built were not governed by building codes. If research continues to prove that straw-bale homes are as safe (if not more so) than conventional buildings, we may see an increasing interest in such a progressive movement. I would particularly like to see more research carried out on earth plasters and the benefits they bare over cement stuccoes.

XVII. <u>Discussion</u>

Athens County, Ohio experiences a variety of temperatures, rainfall and humidity levels. We experience freezing temperatures, high humidity levels, and a relatively high amount of rainfall. It is very important for buildings in this area (or any area for that matter) to detail according to the environment. Generally, during the summer months in Athens, air conditioners are often used in buildings. This decreases the temperature inside the building while the temperature outside the building remains high. The opposite phenomenon happens during the winter months when people often use central heating to increase the temperature inside, while the temperature outside remains low. The greater difference in temperature (from inside a building to the outside) increases vapor pressure and increases the potential for moisture accumulation in wall systems - particularly when the building has not been built specifically to deal with such problems. This often occurs via air leakage from cracks in walls and incomplete sealing. It has been found that very little moisture accumulates in building envelopes via diffusion. This would suggest that perhaps the high relative humidity levels in this area may not have a positive effect on the moisture content of straw-baled walls, and the data analyzed in this report supports this hypothesis.

It is also important to prevent liquid moisture penetration, particularly in an environment experiencing relatively high levels of precipitation. My data analysis does not support the findings of other building envelope studies which have suggested that rain influences moisture accumulation in straw-bale building envelopes more so than any other form or source of moisture. Observing and analyzing data on a monthly basis definitely generalized daily data. The simplest way to prevent liquid moisture accumulation in straw-bale building envelopes is to pay attention to detail (sealing), build sufficient overhangs, and incorporate an effective drainage system. These preventative measures should be taken when building within a moist environment, regardless of the building materials used. We have observed the importance of window sealing, given that rain penetrates the unsealed window sections to the lower course of bales. Observations made during sampling found that with rain came higher moisture content readings on the southern walls of House No. 2 and No.3, and below the windows. As John Straube said “Many of the same considerations that need to be given to other super-insulation techniques need to also be given to straw-bale construction. A properly designed and constructed straw-bale house will last as long as any "standard" house; and an improperly executed straw-bale structure will fail just as miserably as an improperly executed stick house.” (2000:4).

The lower wall sections in House No.2 seemed to be the only area exceeding healthy moisture levels. These moisture levels are caused by a number of factors. House No.2 had below window problems earlier in the sampling period, however, repairs were made early enough to prevent any long-term harm. The differences observed between interior and exterior surfaces were relatively consistent yet insignificant. Differences observed between top and bottom readings were significant in Houses No.2 and three. Another observation that may have also affected the lower course of bales in houses No. 2 and 3 was the cement stucco touching grade. Due to cement stuccoes’ wicking qualities (see stucco section), this may have contributed to higher moisture content readings in the lower sections of the walls in House No.2 and House No. 3.

References

Alexander, C. April, 1965. "A city is not a tree." Architectural Forum. No. 122:118-131.

Anink, D., Boonstra, C., Mak, J. 1996. Handbook of Sustainable Building. James and James, London.

Bainbridge, David. March 2000. "Straw-bales Stack Up for Buildings". American Society of Agricultural Engineers. Vol.7, No.3, pp9-10.

Bolman, Robert. Winter 1994. "It Stacks Up!" The Last Straw. No.9.

Builders' Guide to Energy Efficiency in New Housing: 2nd Edition. 2001. Canadian Homebuilders Association/Ontario Ministry of Energy/HUDAC.

City of Tucson and Pima County Arizona Building Code. Appendix Chapter 72. Straw-bale Structure. Center of Excellence for Sustainable Development. (www.sustainable.doe.gov/codes/azstraw.htm).

Daniel Smith & Associates Architects. July 20, 2000. "Straw-bale FAQ." Berkeley, California. (www.dsaarch.com).

Department of Agriculture. 2001. Ohio Agricultural Production Annual Report.

Doxsey, Laurence. 2000. "Green Buildings." Center of Excellence for Sustainable Development. (www.sustainable.doe.gov/buildings/gbintro.htm)

Edmninster, Ann. 1995. Investigation of Environmental Impacts: Straw-bale Construction. Design AVEnues, California. p127.

Eisenberg, David. 1998. Post to Crest-sponsored Straw-Bale Construction E-mail Listserve. Co-Director Development Center for Appropriate Technology (DCAT).

Environmental Building News. May/June, 1995. "Straw: The Next Great Building Material?" Vol.4, No.3. (www.buildinggreen.com/features/straw/straw.html)

Everett, George. October, 1993. "Straw Homes." Mother Earth News. No.140:54-61.

Gould, Addie. February, 2001. Personal Interview. 4455 Rhoric Road, Athens.

Hill, Duncan. August 1997. "Field Investigations of Indoor Environment and Energy Usage of Mid-Rise Residential Buildings." CMHC Research Highlights. Technical Series 98-100.

Hofmeister, Kemble, Macdonald, Perry, and Myhrman. Spring, 1994. "House of Straw - Straw-bale Construction Comes of Age." The Last Straw. No.15. (ww.eren.doe.gov/EE/strawhouse/)

Hofmeister, 1994:15 Table 3 - Outline Range of Straw-bale Construction Costs Per Square Foot.

Holmes, Stafford., and Wingate, Michael. 1997. Building with Lime in Building: a Practical introduction. Intermediate Technology Publications. London.

Jen, M.H., Yang, K.H., Kung, H.K. June 1990. "The Temperature Distribution Influenced by Moisture and Vapor Pressure in a Multilayered Composite Wall." Applied Math Modelling. Vol.14. 296-303.

Karagiozis, Achilles., Hadjisophocieous, George., Cao, Shu. 1997. "Wind-driven Rain Distributions on two Buildings." Journal of Wind Engineering and Industrial Aerodynamics. Vol.67 & 68, pp559-572.

Krarti, Moncef. 1994. “Heat Loss and Moisture Condensation for Wall Corners.” Energy Conservation Management. Vol.35, No.8, pp651-659.

Lacinski, Paul., Bergeron, Michel. 2000. Serious Straw-bale - A Home Construction Guide for All Climates. Chelsea Green Publishing Company, Vermont.

Marshall, Terry. 1990. “Atlantic Canada Wood Framing Moisture Survey.” Research and Development Highlights, Canada Mortgage and Housing Corporation. Technical Series 90-225.

McCabe, Joseph. March, 1993. “History of Straw-bales Used for Construction.” The Thermal Resistivity of Straw-bales for Construction.

Miner, Rod. Fall 1995. “The Socially, Ecologically, and Financially Affordable House.” The Last Straw. No.12, pp4-6.

Mitchell, D.R., Tao, Y. -X., Besant, R.W. “Air Filtration with Moisture and Frosting Phase Changes in Fiberglass Insulation - I Experiment.” Int. J. Heat Mass Transfer. Vol.38, No.9, pp1587-1596.

National Low Income Housing Coalition. September, 2000. Out of Reach - Ohio. Washington, D.C. www.nlihc.org.

Platts, Bob. 31 May, 1997. "Pilot Study of Moisture Control in Stuccoed Straw Bale Walls". Report to Canada Mortgage and Housing Corporation. Fibrehouse Limited.

Quirouette, R.L. 1998. "The Difference Between a Vapour Barrier and an Air Barrier." NRC Building Practice. No.54, pp1-10.

Roodman, D.M., and Lenssen, N.A. 1995. "Building Revolution: How Ecology and Health Concerns are Transforming Construction." World Watch Institute. Washington D.C.

Roodman, David and Lenssen, Nicholas. November, 1994. "Our Buildings, Ourselves." World Watch Magazine. Vol.4, No.6, pp21-33.

Ruest, Ken. 2000. "Wall Moisture Problems in Alberta Dwellings." Canada Mortgage and Housing Corporation. Technical Series 2000-112.

Smith, Maf., Whitelegg, John., Williams, Nick. 1998. Greening the Built Environment. Earthscan Publications Ltd., London.

Solomon, Nancy. May 1995. Architecture. Pp 155-185.

Straube, J.F., and Acahrya, V. "Indoor Air Quality, Healthy Buildings, and Breathing Walls." Oikos Library. (http://oikos.com/library/breathingwalls/index.html)

Straube, John. 2000. Moisture Properties of Plaster and Stucco for Straw-bale Buildings. Technical Series Issue 100-132. Report to CHMC.

Straube, John. Spring 1998. "Moisture and Straw - Not a Dry Topic." The Last Straw. No.22, pp4-5.

Swearingen, John. 1996. "What Happens When You Let The Water In." The Last Straw. (www.strawhomes.com/main/back/15_34.html).

Swearingen, John. "Moisture Barriers in Straw-bale Construction." (http://www.skillfulmeans.com/moist5.htm).

Swearingen, John. Spring 1996. "Breathing Wall." The Last Straw.

Taylor, B.J., Imbabi, M.S. 1998. "The Application of Dynamic Insulation in Buildings." Renewable Energy. Vol.15, pp377-382.

Tsongas, George. May/June 1995. Environmental Building News. Vol. 4; No.3, Pp10-20.

U.S. Census Bureau. 1997. State and County Quick Facts.

U.S. Department of Energy. April 1995. “House of Straw - Straw Bale Construction Comes of Age.” Energy Efficiency and Renewable Energy. DOE/G010094-01.

Volhard, Franz. 1995. Leichtlehmbau: alter Baustoff - nueu Technik:Light straw-clay construction: old material - new technique. 5th Edition, C.F. Muller.

Wackernagel, M., and Rees, W. 1996. Our Ecological Footprint. New Society Publishers. British Columbia.

Watts, Chris Dr. Fall 1994. “Maritime Moisture Measurements.” The Last Straw. No.8, p13.

Wilkins, Francis., Sharon, Kass., Barbara Ruben. Summer 1995. “House for Bale.” Environmental Action. Vol.27. No.2 pp7-8.

Wilson, Alex. April 1998. “Thermal Mass and R-value: Making Sense of a Confusing Issue.” Environmental Building News. Vol.7, No.4.

Working Group Reports. September, 1993. "Roots and Revival." Plastered Straw-bale Conference. Arthur Nebraska.