Thermal Performance of a Low-Cost Sustainable Wall Construction System

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ABSTRACT

Loose-fill pumice, fly ash, and sawdust have been used to construct insulated walls for retrofit or new construction of small residential buildings. Pumice in sandbags was demonstrated as exterior insulation for an existing adobe house in New Mexico. Such houses are rarely insulated because of the cost and difficulty of providing exterior insulation. Prototype stand-alone walls were also constructed using fly ash and sawdust blown into continuous polypropylene tubing, folded as it is filled to form the shape of the wall. Other materials could also be used. The construction requires no foundation or structural supports and only a small amount of lumber. These inexpensive techniques solve the problem of insulating solid-wall houses and constructing new houses without specialized equipment and skills, thereby saving energy, reducing greenhouse gas emissions, and improving comfort for millions of people. The U.S. Department of Energy (DOE) has received U.S. Patent #5,875,607 for "Low Cost Exterior Insulation Process and Structure."

INTRODUCTION

The U.S. Department of Energy (DOE) has developed a new technology that can insulate existing walls or construct insulated walls for new houses. Part of a DOE initiative on sustainable building materials, the technology was demonstrated by constructing test walls of pumice, sawdust, and fly ash. The materials used are readily available, and expensive machinery and specialized equipment and skills are not needed. The insulated wall is cheap and simple to construct. Other manufactured, natural, or waste materials, such as shredded leaves, expanded clays and shales, perlite, and vermiculite, can also be used. This technology can improve building energy efficiency, is environmentally friendly, and promotes sustainable development.

The new technology solves the problem of insulating existing houses with solid walls, which are difficult and expensive to insulate using conventional methods. For new construction, the technology can provide a high-performance wall that is quick and easy to build. The wall may be either load-bearing or used for infill in a post-frame structure.

Pumice was used to retrofit a wall of an existing adobe house, and fly ash and sawdust were used to construct stand-alone test walls. Laboratory measurements confirmed the thermal characteristics of pumice, which were used in DOE-2 simulations to show the impact on energy consumption of the adobe house.

PUMICE WALL

Many houses in the southwestern and western United States are built of indigenous materials, such as adobe and stone. In some of these areas, fossil fuels are not affordable or available and firewood is scarce. Although adobe, stone, and masonry have poor insulating properties, the walls are rarely insulated. For example, the thermal resistance (R) of a 10 in. (0.25 m) thick adobe wall is only 3.5°F·ft^2·h/Btu (0.6 m^2·K/W), which is similar to that of an 8 in. (0.20 m) thick block wall, for which R = 3°F·ft^2·h/Btu (0.5 m^2·K/W), or a noninsulated wood frame wall with 2 in. × 4 in. (0.05 m × 0.10 m) studs, for which R = 3.4°F·ft^2·h/Btu (0.6 m^2·K/W). As a result, these houses provide little protection against the harsh winters of the high Sierra. Adobe houses are generally quite airtight and are very small. Because of limited interior space, added insulation should be placed on the exterior. Also, the thermal inertia effect is beneficial for cooling when there are hot days and cool nights.

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Figure 1 *Pumice wall in construction.*

Figure 2 *Pumice wall after three years.*

To address this problem, in August 1995 the DOE constructed a prototype exterior wall insulation system using pumice on one wall of an adobe house in Santa Fe, New Mexico (Vohra 1997) (Figures 1 and 2). Pumice is a naturally occurring, lightweight volcanic ash that has a thermal resistivity of 1.0°F·ft^2·h/(Btu·in.) (7 m·K/W), as will be discussed below. However, when pumice is mixed with Portland cement to make masonry units or concrete, it loses over 90% of its thermal resistance. Moisture can reduce the thermal resistance of loose pumice by half. Therefore, it is important to use pumice alone as a dry, loose-fill material. Pumice is abundant in the Southwest, where adobe homes comprise 80% of the low-income housing stock in certain areas.

Construction Technique

The retrofit insulation process began by installing 4 in. × 4 in. (0.10 m × 0.10 m) pressure-treated wood posts at the ends of the wall, so that the outer surface of the posts was at a distance from the surface of the wall equal to the width of bags filled with pumice, 16 in. (0.41 m) in this case. A layer of crushed stone 6 in. (0.15 m) deep and 3 ft (0.91 m) wide was wrapped in a layer of geosynthetic felt fabric made of nonwoven polypropylene and placed on grade against the base of the wall between the corner posts. The crushed stone was leveled and tamped down so that it settled. The geosynthetic fabric prevents the crushed stone from being washed away or moving.

Sandbags made of woven polypropylene were filled with 3/8 in. (0.01 m) graded pumice and stacked against the existing wall. The sandbags rested on the 6 in. (0.15 m) layer of crushed stone wrapped in geosynthetic felt fabric. The bags were patted down so that the pumice settled. Plastic straps 3/8 in. (0.01 m) wide were nailed to the wall with 6 in. (0.15 m) long spiral nails on a grid 2 ft (0.61 m) wide and 1 ft (0.30 m) high and tied around the bags. The straps provided the sandbags with lateral support. The bags were stacked up to the top of the wall. In addition to the corner posts that defined and supported the ends of the wall, the only lumber used was a 2 in. × 12 in. (0.05 m × 0.30 m) lintel above the window. The insulation bags supported themselves. The tops of the corner posts were tied together with polypropylene rope at the topmost layer of sandbags.

Stucco netting (heavy-gage "chicken-wire" mesh) was stretched the length of the wall and nailed to the corner posts. The wire mesh was supported by the sandbags by tying it to the ends of the straps around the sandbags. It was anchored with 3 ft (0.91 m) long steel-reinforcing rods woven through the lower 12 in. (0.30 m) of mesh and then driven into the ground. A layer of glass-fiber reinforced Portland cement stucco with a minimum thickness of ¾ in. (0.019 m) was applied to the wire mesh. The stucco was forced into intimate contact with the polypropylene bags. This eliminated voids where air could circulate and degrade the thermal resistance of the system. After the entire wall was stuccoed and allowed to cure, it was waterproofed with a thin coat of a synthetic acrylic-based stucco. Because the fabric bags have a tight weave, they do not allow wicking of moisture from the wet stucco to the pumice.

Due to time constraints, only one wall was insulated using this method. In the future, to finish all the walls using this technology, the top of each corner post would be tied to the adjacent post with polypropylene rope to prevent the bagged pumice walls from pulling away from the house. The bagged pumice wall cannot fall inward because the existing wall will prevent this from happening.

Measurement of Thermal Properties of Pumice

A national laboratory (ORNL) has measured the properties of pumice under various conditions. The tests show that the thermal resistivity of pumice in its loose form, 1°F·ft^2·h/(Btu·in.) (7 m·K/W), is an order of magnitude greater than that of pumice bound in a cement matrix, 0.09°F·ft^2·h/(Btu·in.) (0.6 m·K/W) (Wilkes 1996).

The thermal properties of pumice were measured using heat flow meter apparatuses (HFMA) and a guarded hot box. The HFMAs are small-scale laboratory instruments that conform with ASTM C 518. In a heat flow meter apparatus, the specimen is placed between two isothermal plates. For the data reported here, the plates were maintained at constant

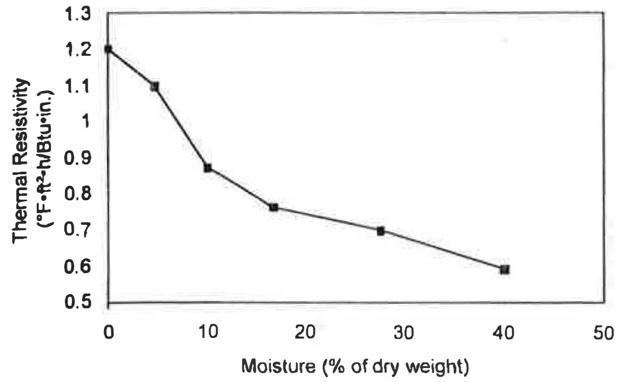

Figure 3 *Thermal resistance of loose pumice by moisture content.*

temperatures of 55°F (13°C) and 95°F (35°C), giving a mean specimen temperature of 75°F (24°C).

The HFMA tests were performed both on loose pumice and on pumice that was bonded with Portland cement to form bricks. Loose pumice, with an oven-dry bulk density of about 25 lb/ft^3 (400 kg/m^3), comparable to that in the walls, was loaded into a thin frame to a thickness of about 1.75 in. (0.044 m) and was tested in a HFMA having 12 in. (0.3 m) square plates. Thin plastic sheets were placed between the pumice and the plates to help avoid scratching the plates, and thermocouples were placed in contact with the specimen to measure the temperature difference that was used in calculating the thermal resistivity. Since the as-received pumice was moist, it was measured as received and then after various stages of drying in an oven at 250°F (120°C). Figure 3 shows that the thermal resistivity increased from about 0.6°F·ft^2·h/(Btu·in.) (4.2 m·K/W) to about 1.2°F·ft^2·h/(Btu·in.) (8.3 m·K/W) as the specimen was dried from the as-received moisture content of 40% by weight (on an oven-dried-weight basis) to the oven-dried condition.

The Portland cement-bonded pumice bricks were also tested in an HFMA. The bricks had dimensions of 3 5/8 in. × 3 5/8 in. × 15 ½ in. (0.092 m × 0.092 m × 0.394 m) and densities of 96 to 104 lb/ft^3 (1540 to 1670 kg/m^3). Since they were wet from rain when received, they were dried in an oven at 250°F (120°C) for 12 days. The weight loss due to drying was 5% to 7%. After drying, they were placed in the laboratory and were allowed to come to moisture equilibrium, which was about 1 weight percent moisture. They were then tested in an HFMA that had 24 in. (0.61 m) square plates. A 3/8 in. (0.0095 m) thick sheet of foam rubber was laid on the bottom plate to provide thermal contact between the plate and the bricks and also to protect the plate from damage. Three bricks were then laid side by side on the rubber sheet in the center of the plate, and the space around the edges of the bricks was filled with fiberglass insulation. Thermocouples were taped to the top and bottom of the center brick to measure the temperature difference across the specimen. Another sheet of foam rubber was laid over the bricks and the top plate was lowered to make contact with the assembly of bricks, insulation, and foam rubber. The heat flux through the center 3 in. × 9 in. (0.076 m × 0.23 m) area of the center brick was measured using three 3 in. (0.076 m) square heat flux transducers in each of the two plates. The average heat flux temperature difference across the brick and brick thickness were used to calculate the thermal resistivity, which was found to be 0.09°F·ft^2·h/(Btu·in.) (0.6 m·K/W). These tests showed that forming the pumice into high-density bricks with Portland cement lowers the thermal resistivity by about a factor of 10 compared with loose, dry pumice.

Thermal Testing of the Pumice Wall System

The pumice wall system for testing was constructed by filling sand bags that are 16 in. (0.41 m) wide and 3 in. (0.076 m) thick and 24 in. (0.61 m) long. Each bag contained approximately 2/3 ft^3 (0.02 m^3) of pumice, and the bags were stacked in front of a 1 in. (0.025 m) thick plywood sheet. A 6 in. (0.15 m) long length of each bag was left unfilled and was placed under the next filled bag. A mason's level was used to determine if the bags were flat and level. A layer of four sheets of newspaper was placed on top of every third layer of sandbags to reduce potential convective current effects. Three layers of sandbags were strapped together with plastic strapping and attached to the plywood. The straps provided some stability by holding the bags to the plywood substrate that was used as interior sheathing. The edge of the pumice wall was held in place with 2 × 4 wood framing. The overall dimensions of the test wall were 9.8 ft (3 m) high by 9.0 ft (2.7 m) wide.

Stucco netting was nailed to one end of the test wall and stretched horizontally across the length of the wall. The wire mesh was tied to the pumice bags with the plastic strapping. Portland cement stucco, about 1 in. (0.025 m) thick, was applied to the wire mesh to provide a solid weatherproof exterior surface. After the construction was completed, the wall system was allowed to dry for 30 days prior to testing.

Measurements of the wall system's R-value were carried out in accordance with *ASTM C 236-89, Standard Test Method for Steady-State Thermal Transmission Properties of Building Assemblies by Means of a Guarded Hot Box* using ORNL's rotatable guarded hot box. The wall system was evaluated at metering and climate chamber air temperatures of 100°F and 30°F (38°C and −1°C). The measured surface-to-surface thermal resistance was 9.82°F·ft^2·h/Btu (1.73 m^2·K/W). When the resistances of stucco and plywood are subtracted, this corresponds to a thermal resistivity of 0.53°F·ft^2·h/(Btu·in.) (3.71 m·K/W) for the pumice. The pumice received was wet, with a moisture content at the time of the hot box test of approximately 20%, which is higher than what it would be in practice. Figure 3 shows that the measured thermal resistivity of pumice with a nominal moisture content of 7% is 0.85°F·ft^2·h/(Btu·in.) (6.05 m·K/W) and this would give a surface-to-surface resistance of 16°F·ft^2·h/Btu (2.8 m^2·K/W). The small sample of pumice used in the measurement of thermal resistance may not be representative of the pumice in the whole wall because the size distribution could be different, i.e., more or less fines. Also, since the test wall had plywood on one side, air pockets at the layers of the bags could affect R-values, as could moisture movement in the whole test wall. The ASTM C 236-89 guarded hot box procedure does not require additional calculations of mass transfer in the wall.

The dynamic thermal performance of the pumice wall system was analyzed based on a dynamic guarded hot box test. The same wall configuration discussed earlier was exposed and modeled with dynamically changing boundary conditions. The finite difference computer code, Heating 7.2, was calibrated using the steady-state test data. The validation of the model for dynamic boundary conditions was made by comparing model heat flow predictions to the hot box measured heat flow when exposed to a step change dynamic boundary condition. Good agreement was found between test and computer modeling results (simulated heat flux was within 5% of test results).

The dynamic test consists of the three basic stages: a steady-state stage (steady temperatures on both sides of the wall), a thermal ramp (rapid change of the temperature on one side of the wall), and a stabilizing stage (wall is kept under the second set of steady boundary temperatures until steady-state heat transfer occurs). During the initial stage, temperatures on both sides of the wall were stabilized and the experiment was continued until steady-state heat transfer occurred. Air temperatures on the metering and climate chamber sides of the wall were stabilized at 100°F and 30°F (38°F and −1°C), respectively. During the second stage, a rapid change of the climate side air temperature was performed (thermal ramp). The climate side air temperature was increased from 30°F to 60°F (−1°C to 16°C). During the third stage, the meter and climate air temperatures were stabilized at approximately 100°F and 60°F (38°C and 16°C), respectively.

Measured air temperatures and velocities in the metering and climate chambers were used as boundary conditions for dynamic modeling of the pumice wall. The computer program reproduced all recorded test boundary conditions (temperatures and heat transfer coefficients) in one-hour time intervals. The pumice wall internal geometry was numerically described to create the Heating 7.2 input file. Surface film coefficients were determined from the experimental measurements of air and surface temperature and heat flux. The following thermal properties of materials were used for dynamic modeling (with 20% moisture content):

- thermal conductivity of stucco, 10.0 Btu·in./h·ft^2·°F (1.4 W/m·K);
- thermal conductivity of plywood, 0.80 Btu·in./h·ft^2·°F (0.12 W/m·K); and
- thermal conductivity of pumice, 1.67 Btu·in./h·ft^2·°F (0.24 W/m·K).

Values of heat flux on the surface of the wall generated by the program were compared with the values measured during the dynamic test. Computer program predictions reproduced the test data very well. For the first 100 hours of the test, the average discrepancy between test-generated and simulated heat fluxes was approximately 1%. For the last 160 hours of the test, the average discrepancy between test-generated and simulated heat fluxes was about 5%. The experimental accuracy of the ASTM C 236-89 Standard Test Method is 8%.

The model for the pumice wall system was then used in DOE-2.1E, a whole building thermal performance computer model. The DOE-2.1E computer code was used to simulate a single-family residence in six representative U.S. climates. To normalize the calculations, a standard residential building elevation was used. The standard elevation selected for this purpose is a single-story ranch-style house that has been the subject of previous energy-efficiency modeling studies. The space heating and cooling loads from the residence with massive pumice walls were compared to an identical building simulated with lightweight wood-frame exterior walls. Nine lightweight wood-frame walls with R-values ranging from 2.3 to 29°F·h·ft^2/Btu (0.4 to 5.1 m^2·K/W) were simulated in six U.S. climates. The heating and cooling loads generated from these building simulations were used to estimate the R-value that would be needed in conventional wood-frame construction to produce the same total heating and sensible cooling loads as the pumice wall system in each of the six climates. The resulting R-value is a steady-state R-value for the pumice wall multiplied by the DBMS (dynamic benefit for massive systems) (Kosny et al. 1997). This factor accounts not only for the steady state R-value but also the inherent thermal mass benefit of the wall system. DBMS is a function of climate, building type, and base envelope system (i.e.,conventional 2 × 4 wood-frame wall system). DBMS values for the pumice wall were obtained by comparison of the thermal performance of the pumice wall and conventional lightweight wood-frame walls, and they should be understood only as an answer to the question, "What R-value would an identical house with wood-frame walls need to obtain the same space heating and cooling loads as a pumice house?" There is no physical meaning for the product of R-value × DBMS.

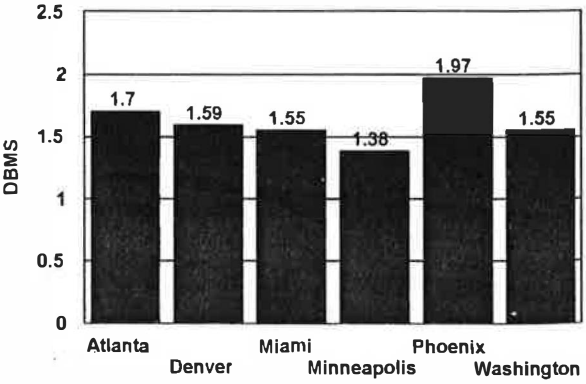

Figure 4 DBMS values for the pumice wall system.

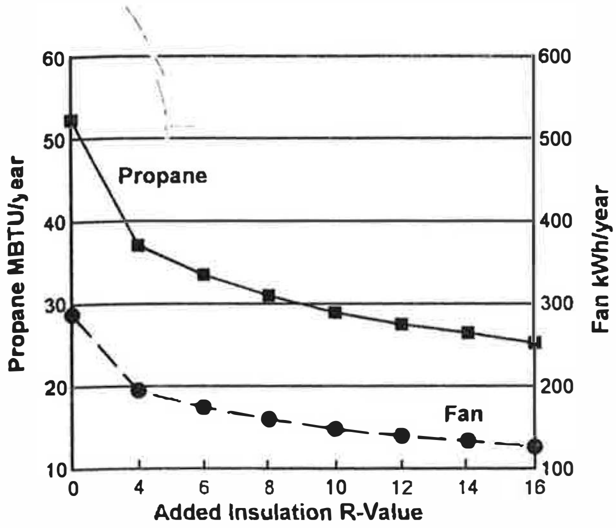

Figure 5 *Annual propane heating energy consumption and furnace fan electrical consumption with added insulation R-value.*

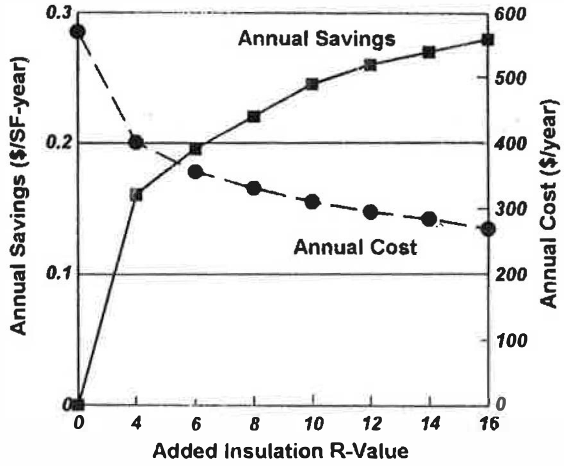

Figure 6 *Annual savings in propane heating cost per square foot of wall ($/SF-year) and annual heating cost ($/year) at a propane cost of 95¢/gallon and a furnace efficiency of 74%.*

As shown on Figure 4, the most effective application of the pumice wall system for the climates we analyzed is in Phoenix, where the comparative R-value that would be needed in conventional wood-frame construction to produce the same loads as the pumice wall system is 97% higher than the steady-state R-value of the pumice wall. Minneapolis is the location where the effectiveness of the pumice wall system is lowest; however, even in Minneapolis, wood-frame construction would require an R-value 38% higher than the pumice wall system to produce the same heating and cooling loads. Although there would be additional benefits from solar gain and storage, as well as cooling benefits from thermal inertia, these were not considered in this analysis.

Computer Simulation for Energy Savings of Adobe House

Simulation with the DOE-2.1E computer model shows that, for nearly dry pumice 16 in. (0.40 m) thick with thermal resistance of 16°F·ft^2·h/Btu (2.8 m^2·K/W) added to all four walls of the adobe house, the annual heating energy consumption of the house would be reduced by 50% in Santa Fe, N.M. (McDiarmid 1996). In dry climates, such as that of the Southwest, pumice has a thermal resistivity of 1°F·ft^2·h/(Btu·in.)(7m·K/W), as shown by Figure 3. The energy savings is 27 million Btu (28.5 GJ), or 296 gal (1120 L) of propane, with a corresponding savings in carbon dioxide emissions of about 2 tons (1800 kg) per year. Based on propane at 95 cents per gallon (25 cents per L), the heating cost of this house would be reduced by $295 per year, or about 28 cents per square foot ($3.00 per m^2) of wall face. Simulation results are shown in Figures 5 and 6.

Construction Cost

The finished wall not only insulates the house at less than half the cost of conventional exterior insulation systems, but it also prevents a deteriorating wall from falling apart. Assuming nearly dry pumice, the demonstration wall provides insulation with thermal resistance of 16°F·ft^2·h/Btu (2.8 m^2·K/W), increasing the total R-value from 3.5 to 19.5°F·ft^2·h/Btu (0.6 to 3.4 m^2·K/W). The retrofit cost less than $4 per square foot ($43 per m^2) of wall face. Conventional exterior insulation systems use plastic foam insulation boards that are nailed to the walls and then covered with a fiberglass mesh and acrylic-based coatings that cost $5 to $12 per square foot ($54 to $129 per m^2) for R of 8°F·ft^2·h/Btu (1.4 m^2·K/W).

The key cost-saving ideas in this process are that it may need no foundation or structural supports and needs a very small amount of lumber. Since the retrofit wall is not load bearing, the pressure on the ground is very low. No digging or pouring of a reinforced concrete footer is needed. The insulation supports itself and the weight of a stucco skin and does not add any additional structural loads to the existing house wall. Expensive machinery and specialized equipment are not needed. Standard construction trade skills are used. Polypropylene bags are not affected by contact with earth or water and have no nutritional value so they will not attract bugs or rodents. The materials used are readily available and should easily pass fire-resistance criteria of all the building codes.

FLY ASH AND SAWDUST WALLS

In addition to using individual sandbags, DOE has also tested the feasibility of constructing a prototype wall by blowing loose insulating materials into a long, woven polypropylene fabric tube layered upon itself. Fly ash and sawdust have been tested.

Fly Ash Wall

A demonstration using fly ash was conducted with the cooperation of a utility at the fly ash disposal site adjacent to a power station in Masontown, Pennsylvania. A wall was constructed to a height of about 4 ft (1.2 m) during a two-hour period in October 1997.

The fly ash material was blown into a long 18 in. (0.46 m) wide woven polypropylene fabric tube placed between corner posts that were 10 ft (3.0 m) apart. A 4 in. (0.10 m) fill pipe was inserted through a slit cut in the top layer of the fabric tube and pushed in all the way to the corner post. A blower conveyed the material through the fill pipe into the fabric tube. The fill pipe was pulled out of the slit gradually as the fabric tube filled up with material to a height of about 6 in. (0.15 m). Then the top surface of the layer was leveled, the fabric tube was folded over itself, and the process was repeated to make another layer. In actual practice, after the desired wall height is reached, the wall would then be finished with chicken-wire mesh and stucco on the outer side for retrofit, similar to the pumice wall, and on both sides for new wall construction.

If a new house were being constructed, the fabric tube would be filled with material in a continuous winding around the corner posts. For just one wall, the fabric tube would be layered over itself, the U-bends of the layers would be tied to the corner posts, and the process would be repeated. Each layer would be tied to the layer above with cord. The fill process would be continued until the desired wall height was reached, limited to about 12 ft (3.7 m) high. Wire mesh and stucco or gunite would be applied on the outer side for retrofit and on both sides for new wall construction.

Sawdust Wall

In another test, a prototype wall was made by blowing sawdust into a fabric tube layered upon itself. The test was conducted in Franklin, W.V., using sawdust from a nearby sawmill and with the cooperation of volunteers from the Mountain Institute, Youthbuild, and Habitat for Humanity. The arrangement of the woven polypropylene fabric tube and the filling technique were similar to that used in the fly ash test, with changes in the blower and fill tube to compensate for the difference in materials (see Figure 7).

The fabric tube was layered over itself and the process was repeated. Each layer was tied to the layer above with cord, every 2 ft (0.61 m). The U-bends of the layers were tied to the posts. To prevent the wall from bowing, a stiffener consisting of two parallel lengths of 1 in. × 6 in. (0.025 m × 0.15 m) planks, 11 ft (3.4 m) long, with rungs nailed every 2 ft (0.61 m), was placed on the wall about 4 ft above the ground. It was tied to the filled layers above and below it. The stiffener could also be made from plywood or wafer board.

The test was finished when the wall was 9 ft (2.7 m) high. The next steps to complete the wall would be to stretch and nail chicken-wire mesh to the end posts, tie it to the cords wrapped around adjacent layers, and apply stucco.

POTENTIAL IMPACT ON GLOBAL WARMING AND CLIMATE CHANGE

Although the technology was demonstrated in the United States using pumice, fly ash, and sawdust, it could be developed for use in any other part of the world. Indigenous insulating materials such as straw (baled and sheaves), shredded leaves, expanded clays and shales, perlite, vermiculite, and other natural or waste materials could be used. For new construction, the new technology wall can be either load bearing or be used for infill, depending on the material used.

CONCLUSIONS

Adequate and reliable supplies of affordable energy, obtained and used in environmentally sustainable ways, are essential to economic prosperity, environmental quality, and political stability around the world. Since houses insulated in this manner will use significantly less fuel for heat, these innovative construction technologies have the potential to reduce greenhouse gas emissions, global warming, and climate change and to improve the thermal comfort of millions of people around the world.

The most important benefits of these technologies are as follows:

1. Bulk loose-fill material is used in a dry form that can be manually placed or blown in place. Since the material is not mixed with cement to form blocks or concrete, it does not lose its insulating value. Because the core material of the wall is about 16 in. (0.41 m) thick, materials with moderate insulating properties can be used to create walls with high thermal performance. Also, since there are no thermal bridges in the wall, the steady-state R-value for the wall can be easily calculated by adding the thermal resistance of the individual layers.

Figure 7 *Sawdust wall under construction.*

2. Depending on the soil type, a concrete foundation may not be needed due to the large footprint of the wall. For retrofit, it does not add any additional structural loads to the existing wall. Load-bearing materials need a very small amount of lumber for either new construction or retrofit. Non-load-bearing materials can also be used for infill with post beam structure for new construction; for retrofit, minimal structural support for the stucco skin would be needed.
3. The materials used are readily available, and expensive machinery and specialized equipment and skills are not needed. It is cheap and simple to construct.

The system still has to go through structural tests and code approval. The DOE has received U.S. Patent #5,875,607 for "Low Cost Exterior Insulation Process and Structure."

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