Low-Cost Sustainable Wall Construction System

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ABSTRACT

Houses with no wall cavities, such as those made of adobe, stone, brick, or block, have poor thermal properties but are rarely insulated because of the cost and difficulty of providing wall insulation. A simple, low-cost technique using loose-fill indigenous materials has been demonstrated for the construction of highly insulated walls or the retrofit of existing walls in such buildings. Locally available pumice, in sandbags stacked along the exterior wall of an adobe house in New Mexico, added a thermal resistance (R) of 16 °F·ft^2·h/Btu (2.8 m^2·K/W). The total cost of the sandbag insulation wall retrofit was \$3.76 per square foot (\$40.50/m^2). Computer simulations of the adobe house using DOE 2.1E show savings of \$275 per year, corresponding to 50% reduction in heating energy consumption. The savings-to-investment ratio ranges from 1.1 to 3.2, so the cost of conserved energy is lower than the price of propane, natural gas and electric heat, making the system cost-effective. Prototype stand-alone walls were also constructed using fly ash and sawdust blown into continuous polypropylene tubing, which was folded between corner posts as it was filled to form the shape of the wall. Other materials could also be used. This inexpensive technique solves 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 people in many countries. The U.S. Department of Energy (DOE) has filed patent applications on this technology, which is part of a DOE initiative on sustainable building envelope materials and systems.

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. A part of a DOE initiative on sustainable building materials, the technology was demonstrated by constructing test walls of pumice, sawdust and fly ash. Energy simulation and economic analysis were performed only for the pumice wall. For new construction, the technology can provide a high-performance wall that is quick and easy to build. Depending on the material used, the wall may be either load-bearing or used for infill in a post-frame structure.

A manually bagged method was used to retrofit a wall of an existing adobe house using pumice as the fill material. The "QuickFill" wall technology is an advancement of the manually bagged method and uses machinery to blow the wall fill material into a geosynthetic fabric tube that is layered over itself to comprise the wall. The QuickFill technology was used to construct stand-alone test walls using fly ash and sawdust as the wall fill material.

Laboratory measurements confirmed the thermal characteristics of pumice, which were input into computer simulation using the DOE 2.1E program to show the impact on heating energy consumption of the adobe house retrofitted with the bagged pumice wall. The study did not address the effect on cooling; however, the insulation would make the house more comfortable in a climate with cool nights and hot days. Research, development and demonstration of the QuickFill wall are continuing.

The technology makes use of high performance construction materials -- woven and non-woven polypropylene fabrics, industrial strength geosynthetic textiles designed for civil engineering and soil construction use. Polypropylene is not affected by contact with earth or water and has no nutritional value so it will not attract bugs or rodents. The materials used are readily available and the wall assembly with 1 inch (0.025 m) of stucco facing should pass fire-resistance criteria of the building codes.

The insulated wall is inexpensive and simple to construct. The materials used are readily available, and expensive machinery and specialized equipment and skills are not needed. Other manufactured, natural or waste materials such as shredded leaves, expanded clays and shales, perlite and vermiculite can also be used as the wall fill material. The new technology solves the problem of insulating existing houses with solid walls, which are difficult and expensive to insulate using conventional methods. This technology can improve building energy efficiency, is environmentally friendly and promotes sustainable development.

Pumice Wall

Many houses in the Southwestern and Western United States, and in many other parts of the world, are built of indigenous materials, such as adobe and stone. Many Native Americans live in such houses on tribal lands, where 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-inch (0.25 m) thick adobe wall is only 3.5 $ft^2 \cdot h \cdot °F/Btu$ (0.6 $m^2 \cdot K/W$), which is similar to that of an 8-inch (0.20 m) thick cinder block wall, for which $R = 3$ $ft^2 \cdot h \cdot °F/Btu$ (0.5 $m^2 \cdot K/W$), or a non-insulated wood frame wall with 2x4 inch (0.05x0.10 m) studs, for which $R = 3.4$ $ft^2 \cdot h \cdot °F/Btu$ (0.6 $m^2 \cdot K/W$). 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 and to increase the thermal inertia, added insulation should always be placed on the exterior.

To address this problem, in August 1995 DOE constructed a prototype exterior wall insulation system using pumice on one wall of an adobe house in Santa Fe, New Mexico, that has 6016 Heating Degree Days [base 65°F] (3342 Heating Degree Days [base 18.3°C]). Pumice is a naturally occurring, lightweight volcanic ash with an oven-dry bulk density of about 25 lb/ft^3 (400 kg/m^3). Pumice is abundant in the Southwest, where adobe homes comprise 80 percent of the low-income housing stock.

Thermal Properties of Pumice

The U.S. Department of Energy's Oak Ridge National Laboratory has measured the properties of pumice under various conditions. The tests show that the thermal resistivity of pumice in its loose form, 1 $ft^2 \cdot h \cdot °F/(Btu \cdot in)$ (7 $m \cdot K/W$), at 5% moisture is an order of magnitude greater than that of pumice bound in a cement matrix, 0.09 $ft^2 \cdot h \cdot °F/(Btu \cdot in)$ (0.6 $m \cdot K/W$) [Wilkes, K. E.]. 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 by half [Stovall, T. K.] Therefore, to maximize its thermal resistance, it is important to use dry pumice alone as a loose-fill material.

Construction Technique

The retrofit insulation process began by installing 4x4 inch (0.10x0.10 m) pressure-treated wood posts in the ground at a depth of 2 feet (0.61 m) encased in concrete at the ends of the wall. 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, about 16 inches (0.41 m) in this case. A layer of crushed stone 6 inches (0.15 m) deep and 3 feet

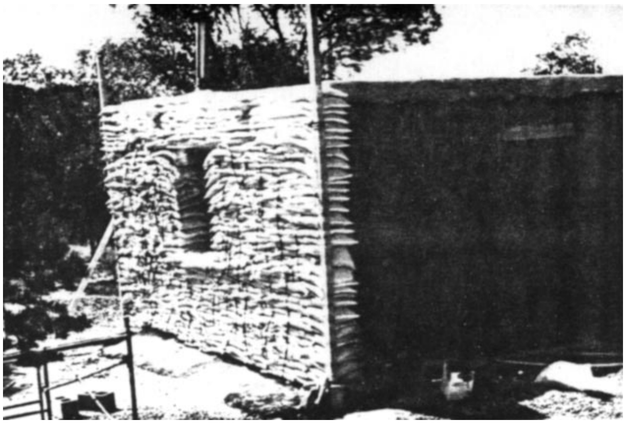

Figure 1. Pumice wall under construction

Figure 2. Pumice wall after two years.

(0.91 m) wide was wrapped above and below in geosynthetic felt fabric made of non-woven 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 and provides a hygroscopic break, preventing ground moisture from rising into the pumice bags and stucco skin.

Polypropylene sandbags. 18 inches (0.46 m) wide, were filled with 3/8-inch (0.01 m) graded pumice and stacked against the existing wall. The sandbags rested on the 6-inch (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-inch (0.01 m) wide were nailed to the wall with 6 inch (0.15 m) long spiral nails on a grid 2 feet (0.61 m) wide and 1 foot (0.30 m) high and tied around the bags. The straps provided the sandbags with some lateral support because of the limited pull out resistance of spiral nails in adobe brick. The bags were stacked up 12 feet high (3.66m) 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 2x12 inch (0.05x0.30 m) lintel above the window. The pumice bags supported themselves. The tops of the corner posts were tied together with polypropylene rope at the topmost layer of sandbags to provide retention of the bags to the adobe wall and maintain a square corner.

Stucco netting (heavy-gage "chicken-wire" mesh) was stretched the length of the wall and nailed to the corner posts. The sandbags supported the wire mesh when it was tied to the ends of the straps around the sandbags. It was anchored with 3-foot (0.91 m) long steel reinforcing rods woven through the lower 12 inches (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 3/4 inch (0.019 m), was troweled on 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.

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 pole with polypropylene rope to prevent the bagged pumice walls from pulling away from the house.

Construction Cost Estimates

All material costs are actual costs or retail value for donated materials.
Labor cost was provided by the Weatherization Coordinator for Open Hands Inc.

Wall Area	= 17 feet wide X 12 feet high (including parapet)	
	= 204 square feet - window (2 feet X 2 feet) = 200 sq feet	
Pumice wall volume	= 200 square feet X 16 inches	=9.9 cubic yards
Pumice [@ $23.50 per ton (1 ton = 2 cubic yards) including delivery]		=$123
Stucco netting (Wire Mesh) and rebars		= $ 50
Labor		= $400
Polypropylene Bags [@ 22 cents each]	= 520 bags	= $114
Polypropylene felt fabric for base [@ 50 cents per square yard]	= 18 ft long X 6 ft wide	= $ 6
Corner Post [4 X 4 inch, 14 ft long]		= $ 20
Window lintel [2 inch X 12 inch X 4 ft]		= $ 7
Stucco, 200 sq ft X 3/4 inch thick		= $ 32

[Stucco mix: 1 cubic foot cement, 0.1 cubic foot lime, 3 cubic feet sand. Cost: Portland cement $7/cu ft or 94 lbs; Sand $20/ton or 3/4 cu yd; Lime $5/cubic foot]

TOTAL COST for 200 square feet .... = **$752**
COST PER SQUARE FOOT .... = **$3.76**

The retrofit cost was $3.76 per square foot ($40.50/m^2) of wall face, of which $2.00 per square foot ($21.50/m^2) was labor. It is estimated that the QuickFill technology would reduce the retrofit cost by $100.00 by using a pneumatic or mechanical conveying method to transport the pumice and a gunite machine to apply stucco. Use of a continuous polypropylene fabric tube, 18 inches (0.46 m) wide at 12¢/foot ($0.39/m) filled to a height of 6 inches (0.15 m), instead of bags, would provide an additional saving of $64; for an **overall cost saving of about $164 or 22% and a reduced cost of $3.00 per square foot ($32.30/m^2).**

The key cost-saving ideas in this process are that it may need no foundation (depending on the soil type) or structural supports (depending on the fill material) and may need a very small amount of lumber. Since the retrofit wall is not load-bearing, the pressure on the ground is moderate. Depending on the soil type, 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. The retrofit can be accomplished by using manual labor and standard construction trade skills. Expensive machinery and specialized equipment are not essential.

Economic Analysis

The finished wall area of 200 square feet, not only insulates the house at less than half the cost of conventional exterior insulation systems, it also prevents a deteriorating wall from falling apart. The demonstration wall provides insulation with thermal resistance (R) of 16 ft^2·h·°F/Btu (2.8 m^2·K/W), at 5% moisture content, based on a 16 inch (0.41 m) thick core wall. The total wall R-value is increased from 3.5 to 19.5 ft^2·h·°F/Btu (0.6 to 3.4 m^2·K/W).

Conventional exterior insulation systems use expanded plastic foam insulation boards that are nailed to the walls and then covered with a fiber glass mesh and acrylic-based coatings. A system using 3 inch (0.08 m) thick extruded polystyrene board that adds the equivalent insulating value of the Pumice wall, about R= 16 $ft^2 \cdot h \cdot °F/Btu$ (2.8 $m^2 \cdot K/W$), is estimated to cost $7.44 per square foot for materials and labor [Means Building Construction Cost Data, 202.]

A DOE 2.1E computer simulation [McDiarmid, M.] was performed on the demonstration house, with the assumption that all four walls are insulated with the pumice system. This simulation shows that the energy savings is 27 million BTU (28.5 GJ), or 296 gallons (1120 L) of propane plus 150 kWh of electricity for the furnace fan (see Fig. 3). In rural New Mexico, wood is the most widely used heating source, followed by propane. Since fuel content, efficiency and cost data for propane (but not for wood) are readily available, the simulation assumes propane for heating at $0.95 per gallon and 74.1 percent heating efficiency and electricity for the furnace fan at $0.0924/kWh, the costs in rural New Mexico in July 1996. The projected propane heating and furnace fan electric cost savings per square foot of wall is $0.28 per year (see Fig. 4), and the annual heating cost (propane plus electric) is reduced from $570 to $275, for a saving of about 50%. Equivalent carbon dioxide savings, converted to tonnes of carbon is about 0.5 t_c per year. The lifetimes of stucco and polypropylene are over 30 years.

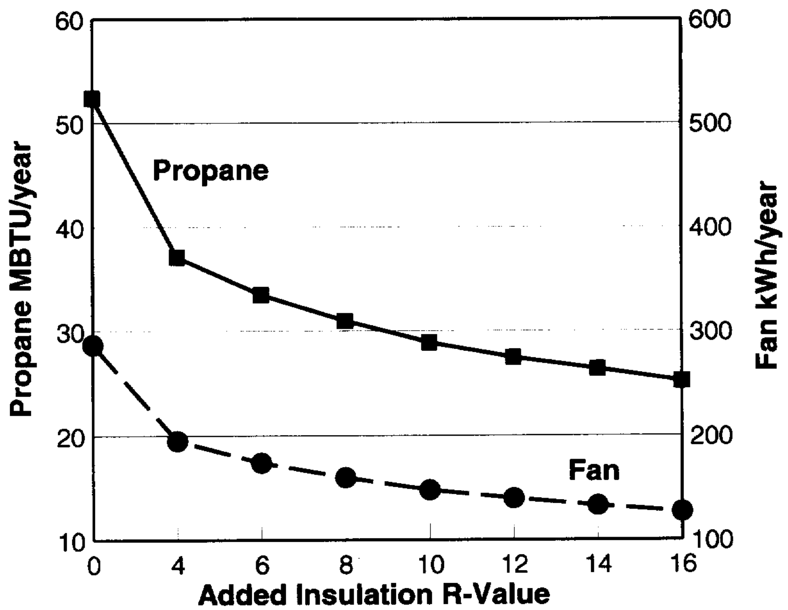

Figure 3. Annual propane heating energy consumption and furnace fan electrical consumption with added insulation R-value.

The house used for the demonstration is not typical of adobe houses because it has an unfinished cellar and the living space is 2 feet above grade. The cellar is not heated. The heat loss per unit wall area through the above-grade part of the unheated cellar walls is assumed to be 50% less than that through the walls of the heated living space. However, the construction cost of the pumice wall is the same for both parts of the exterior wall.

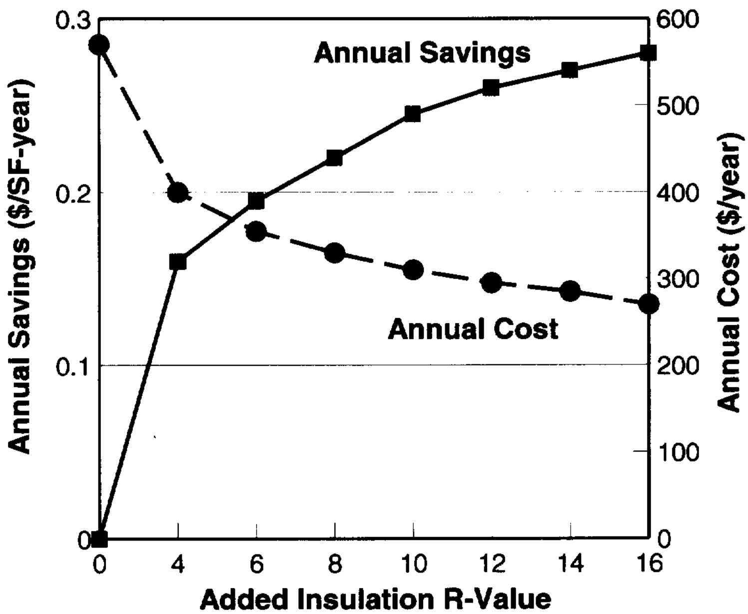

Figure 4. Annual savings in propane heating cost per square foot of wall ($/SF-year) and annual heating cost ($/year) at a propane cost of 95¢/gallon and a furnace efficiency of 74%.

Table 1 gives two familiar economic ratings, Cost of Conserved Energy (CCE) and Savings to Investment Ratio (SIR), but these are in no way independent, in fact they are reciprocal. CCE is discussed in "Policy Implications of Greenhouse Warming 1992", and SIR is discussed in NISTIR 85. CCE and SIR are defined as follows:

$$CCE = \frac{Annualized\ investment\ (\$/year)}{Annual\ energy\ saved\ (energy\ units/year)} \tag{1}$$

and

$$SIR = \frac{Unit\ Price\ of\ Energy}{CCE}$$

In turn,

$$SIR = \frac{Present\ value\ of\ energy\ saved}{Cost\ of\ Pumice\ wall} = \frac{PV}{\Delta\$} \tag{2}$$

To calculate PV we must choose 3 parameters,
a service life, t = 30 years (3)
a real discount rate, d = 4.1% per year (4)
a real escalation rate, e for fuel price (real = net of general inflation)
e = 1.0% per year for propane, etc. (tabulated on the bottom row of Table 1.) (5)

$$P V = A_0 \sum_{t=1}^{30} \left(\frac{1+e}{1+d} \right)^t \qquad (6)$$

where A_0 = base year annual fuel $ saved, including the furnace fan saving.
Thus for propane (per square foot of wall), PV = $0.28/year x 20.5 years = $5.74
And for the first row of Table 1 (actual house)

$$SIR = \frac{PV}{\Delta\$} = \frac{\$5.74/square\ foot}{\$3.76/square\ foot} = 1.52$$

The values of d (Equation 4), e (Equation 5) and the sum (Equation 6) come from the National Institute of Standards and Technology Report [NISTIR 85-3273-10, 18, 41.]

The cost of conserved energy was calculated to be 30% lower than the actual price of propane. If the DOE 2.1E results for the demonstration house are modified to represent a typical adobe house that is built with the floor on grade with no cellar, the economics of the pumice wall becomes even more favorable. The wall becomes 2 feet shorter and the cost of conserved propane drops 45% below the price of propane. The first cost for the whole house drops from $4820 to $3783 (27%), but the heat savings drops by 5%, so the SIR rises by only 22%.

Table 1. Cost of Conserved Energy (CCE) for three fuels, and Savings to Investment Ratio (SIR). Both CCE and SIR are calculated with 4.1% annual real discount rate and 30-year wall life and the tabulated annual fuel price escalation. Both CCE and SIR take into account the tabulated heating efficiency.

	Source of Heat					
	PROPANE		NATURAL GAS		ELECTRICITY	
HOUSE VERSION	CCE ($/Gal)	SIR	CCE ($/Therm)	SIR	CCE (¢/kWh)	SIR
Actual house with unheated cellar	0.62	1.52	0.56	1.1	4.36	2.12
Typical house with no cellar	0.52	1.84	0.47	1.33	3.6	2.57
Typical house, with QuickFill wall	0.41	2.3	0.39	1.66	2.87	3.22
Residential Energy Price (1997)	0.95		0.62		9.24	
Heating efficiency assumed	74.1%		74.1%		100%	
Annual real fuel price escalation	1.0%		0.9%		0.7%	

As shown in the table above, the cost of conserved energy for propane drops to $0.62 per gallon ($0.22/L), which is below the actual price of $.95 per gallon, and even lower with improved construction techniques (QuickFill wall). The cost of conserved energy for natural gas and electric heating is also below the actual respective price in all three cases.

The pumice wall has proven to be structurally successful and has gone through three winter seasons with no evidence of significant defects. This new technology also preserves the structural integrity of the original wall, and requires no further maintenance such as the need to resurface the adobe walls every 3 years or so.

QuickFill Wall - Improved Construction Technology.

We have done the economic analysis only for the bagged pumice wall, but in addition to using individual sandbags, DOE has further developed an improved construction technology called the "QuickFill" wall. A Quick-fill wall consists of a layered geosynthetic fabric tube with an insulating material blown or mechanically conveyed into it and then covered with chicken wire and hand plastered or gunited. The technology can be adapted for application in any part of the world by using available natural, manufactured, recycled, or waste materials with insulating properties such as sawdust, fly ash, pumice, shredded leaves, expanded clays and shales, perlite and vermiculite. This technology would have a lower cost for both materials and labor, as stated above in the section on Construction Cost Estimates.

Quick Fill Fly Ash Prototype Wall

A QuickFill wall was built using fly ash as the wall fill material with the cooperation of Allegheny Power at the fly ash disposal site adjacent to the Hatfield Power Station in Masontown, Pennsylvania. The wall was constructed to a height of about 4 feet (1.2 m) during a two-hour period in October 1997.

The fly ash material was blown into a long 18-inch (0.46 m) wide, woven polypropylene fabric tube placed between corner posts placed 10 feet (3.0 m) apart. A 4-inch (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 six inches (0.15 m). The top surface of the layer was leveled in both directions with a "rolling pin." A 4 foot long and an 8 inch long bubble levels were taped to a plank, at right angles to each other and were placed on the surface to check the level. 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 is being constructed, the fabric tube is filled with material in a continuous winding around the corner posts. For just one wall, the fabric tube is layered over itself, the U-bends at the ends of the layers are tied to the corner posts and the process is repeated. Each layer is tied to the layer above with cord, every 2 feet (0.61 m). The fill process is continued until the desired wall height is reached, limited to about 12 feet (3.7 m) high. Further structural testing would dictate the maximum wall height. Vertical framing for door and window openings are treated as wall ends, a lintel is placed over the opening and layering continues over the lintel. Wire mesh and stucco or gunite is applied on the outer side for retrofit and on both sides for new wall construction.

The thermal performance of the fly ash wall is better than the pumice wall, as the R-value is 1.1 per inch and the density is 72 pounds per cubic foot, [Stovall, T. K.] compared to 1.0 and 25 respectively for pumice.


Figure 5. QuickFill fly ash wall before it is covered with wire mesh and stucco.

Figure 6. QuickFill sawdust wall. Sawdust is sucked out of the trailer and blown into the fabric tube.

QuickFill Sawdust Prototype Wall

A QuickFill wall using sawdust as the wall fill material was built in Franklin, WV, using sawdust from a nearby sawmill and the help 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.

The fabric tube was layered over itself and the process was repeated. Each layer was tied to the layer above with cord, every 2 feet (0.61 m). The U-bends of the layers were tied to the posts. To prevent the wall from bowing, a horizontal stiffener, fashioned roughly as a ladder, made of scrap wood was placed between two tiers of fabric tubes about halfway up the wall. It consisted of two parallel lengths of 1x6 inch (0.025x0.15 m) planks, 11 feet (3.4 m) long, with rungs nailed every 2 feet (0.61 m) and 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 feet (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.

The thermal performance of the sawdust wall is much better than the pumice wall, as the R-value is 2.5 per inch and the density is 15 pounds per cubic foot, [Gabbard, A.] compared to 1.0 and 25 respectively for pumice.

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 used for infill, depending on the material used. Since the pumice wall retrofit saves 50% of the heating fuel, as mentioned above, we save about 0.5 tonnes of carbon emissions for propane fuel [DOE/EIA-0573, 98] per house. This technology has the potential to significantly reduce carbon dioxide emissions and global warming.

In Russia, East European, Central Asian and war torn countries, the millions of sandbags left over from the Cold and recent wars, could be put to good use by utilizing this technology to make their citizens warm and comfortable. In South Africa, electric space heaters that are only used for an hour or two on cold evenings by poor people strain the capacity of the electric utility. This technology could keep poor consumers warm with reduced electric bills, and reduce the need to build additional power plants.

In Nepal, mountains have been stripped of trees that were used for firewood. Before the trees were burned, cow manure was used as a natural fertilizer, but now it is dried and burned as it is the only fuel available. Because the hillsides are bare and unprotected, the heavy monsoon rains wash the valuable topsoil into the rivers. Agricultural productivity suffers and people go hungry. The riverbeds get choked with the soil runoff. Consequently, the rivers flood vast areas of Nepal, India and Bangladesh. The floods ruin crops and drown livestock and dozens of people every year. Application of this technology to insulate houses with indigenous materials such as straw or pine needles could correct these problems and allow reforestation programs to succeed, as much less firewood would be needed.

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, this innovative construction technology has the potential to reduce greenhouse gas emissions, global warming and climate change.

The most important benefits of the QuickFill wall are:

1. Lowest life cycle cost of most comparable technologies. This innovation can use manufactured, natural, waste, recycled and resource-efficient materials and/or low cost materials. It uses bulk loose fill material in a dry form that can be blown into place. Since the material is not mixed with cement, mud or adobe to form blocks, plaster or concrete, it does not lose its thermal resistivity. Since there are no metal connections from the inner to the outer surfaces, there are no thermal bridges. Because the wall contains about 16 inches (0.41 m) of wall fill material, materials with moderate resistivity can be used to give a reasonably high R-value.
2. A concrete foundation may not be needed, due to the large footprint of the wall, depending on the soil type. Depending on the wall fill material, the system may need no structural supports and only need a very small amount of lumber. For new construction it can be either load bearing or used for infill, depending on the material. For retrofit, it does not add any additional structural loads to the existing wall and can preserve a deteriorating house from falling apart.
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. Since the pumice wall retrofit saves 50% of the heating fuel, as mentioned above, we save about 0.5 tonnes of carbon emissions for propane fuel per house. This new technology can improve building energy efficiency, is environmentally friendly, promotes sustainable development and can improve the quality of life for millions of people around the world.

The system still has to go through structural tests and code approval. DOE has filed patent applications for this technology with the U.S. Patent Office.

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