Affordable, Safe Housing Based on Expanded Polystyrene Foam and Cementitious Coating

J. A. Lee 1, H. Kelly 1, A. Rosenfeld 2, E. Stubee 2, J. Colaco 3, A. Gadgil 4, H. Akbari 4, L. Norford 5, and H. van Burik 6
1 Federation of American Scientists Washington, DC, USA 2 Public Interest Energy Research, California Energy Commission Sacramento, CA, USA 3 CBM Engineers, Inc. Houston, TX, USA 4 Environmental Energy Technologies Division, Lawrence Berkeley National Laboratory Berkeley, CA, USA 5 Department of Architecture, Massachusetts Institute of Technology Cambridge, MA, USA 6 Shelter for Life Oshkosh, WI, USA

ABSTRACT

This paper describes an ongoing project to demonstrate an affordable, safe, and energy-efficient housing technology based on Expanded PolyStyrene (EPS) wall and roof panels covered with a cementitious coating. The three concepts being pursued and described in this paper are 1) EPS panels embedded with galvanized steel trusses, steel mesh welded or clipped to the protruding points of the trusses, and once the walls and roof are erected and connected, finished with a coating of cement plaster; 2) panels consisting of an inner and outer skin of fiber-reinforced cement board and a core of EPS, glued together with high-strength adhesive, dried under high pressure, and connected with splices of the same cellulose fiber cement board; and 3) EPS panels coated with a fiber-reinforced composite. The current scope of this project is to model energy flows, analyze construction costs, simulate seismic forces, test against environmental conditions and hazards, and build pilot houses initially in California for Native Americans and in Kabul, Afghanistan. Preliminary results from the energy flow analysis, cost modeling, and structural calculations are reported in this paper.

The main performance goals seek to address seismic safety considering wood shortages; energy efficiency in extreme temperatures to reduce both fuel required for heating and indoor air quality hazards; affordability and simplicity of construction in a post-emergency situation or low-income community, as well as ease of expansion for future development; local employment opportunities and small-scale, realistic capital investments; and finally, cultural acceptance through education and adaptation to traditional architecture.

KEYWORDS

EPS, energy-efficiency, wind, earthquake, affordable, composite, cement, wire, fiber, sustainable, Afghanistan, California

INTRODUCTION

Housing plays a central role in improving the quality of people's lives in both developing and developed countries. Safe and affordable housing provides personal, social, and economic benefits. Most directly, housing contributes to the health and safety of individual inhabitants. Housing re-anchors the homeless in the community and mobilizes those traumatized by a disaster, impacts especially important in a post-conflict situation. Housing also offers families a platform for economic recovery and is a means of employment generation, requiring intensive unskilled labor and local capital investment.

The approach of this housing project is to scientifically and objectively evaluate available housing designs on the basis of cost-effectiveness, seismic safety, energy-efficiency, and sustainability, in order to address the range of housing needs throughout the world. Though efforts have been directed towards demonstrating this new building technology in Kabul, Afghanistan, in partnership with Shelter For Life International (SFL), and in California for Native Americans, with funding from the California Energy Commission (CEC) and the Department of Energy (DoE), the guiding performance goals are framed for worldwide application.

According to the U.S. Energy Information Administration (EIA), the average U.S. household spent, in U.S. Dollars (throughout the paper all dollars are U.S. Dollars), about $1,300 on 101 million Btu of site energy, or the energy consumed within a housing unit, in 1997. Space heating accounted for 30% of that cost and half of that amount of energy. In the U.S., the EIA estimates an average growth rate of 1% per year in energy consumption for 2001-2025. By 2020, the projected residential energy demand in the U.S. is 24.5 quadrillion Btu. The CEC and the DoE are particularly interested in developing energy efficient housing in the U.S.

Afghanistan

Twenty-six years of almost continuous warfare coupled with major earthquakes in the past decade have damaged or destroyed much of the housing stock. Pressure on existing stock is growing rapidly as many of the six million Afghans that fled to Pakistan, Iran and other nations during the war begin to return. A population of 27 million is now struggling to accommodate the estimated 1.8 million refugees who returned in 2002 alone. While funding from the U.S. and other nations is woefully inadequate and unpredictable, some progress is being made. Funds typically go to non-governmental organizations (NGOs), like SFL, with facilities in Afghanistan to assist uprooted people in rebuilding their houses, infrastructure, and communities.

In an effort to use local resources and building traditions, as well as to save funds and take advantage of available skills, most of these projects rely on time honored Afghan construction methods, using handmade mud (adobe) bricks. Flat roofs are supported by wood beams covered by layers of branches, woven mats, and finally up to 40 cm of clay. Two-room houses can be built this way for less than $1,000.

Although inexpensive to build, these traditional homes present major long-term risks. Adobe structures are vulnerable in earthquakes and Afghanistan is one of the most active seismic regions of the world. More than 6,000 people died in two earthquakes four months apart which shook the Afghanistan/Tajikistan border in 1998 even though they measured only 6.1 and 6.9 on the Richter scale. An earthquake measuring 6.1 on March 25, 2002 and an aftershock of 5.1 in the Hindu Kush region in the northern part of Afghanistan left at least 1,000 people killed, several hundred injured, and several thousand homeless in Baghlan Province. At least 1,500 houses were destroyed or damaged at Nahrin and several hundred more in other areas of Baghlan Province. Houses in Afghanistan should be designed to meet roughly the same standards as in Los Angeles (4 m/s2 acceleration), but traditional methods founder at much lower levels. Brittle mud walls and roofs fail when shaken and their enormous weight causes disastrous injuries. Although earthquake mitigation measures as used by SFL in Afghanistan allow people more time to leave their adobe homes during seismic activity, alternative solutions need to be pro-actively explored.

Recent wood scarcities have made traditional construction more difficult. Many NGOs are forced to import wood from Pakistan, Russia, and other countries since decades of deforestation have devastated local timber supplies. Often, the wood for a roof accounts for half of the total construction costs for a house. Those not able to import wood are using inadequate and dangerous roof support structures.

Wood shortages also underscore the energy crisis facing the nation. Traditional Afghan homes are heated with wood or charcoal, but difficulty in obtaining traditional fuels has forced many to turn to expensive kerosene or imported coal. Kabul has an altitude of 1,800 m and nights are cool, but the winters are very cold (the average January temperature is 27°F or -2.8°C). These factors force a difficult choice between expensive fuel consumption and uncomfortable temperatures.

Traditional heating and cooking systems also lead to unhealthy air quality inside the homes. While the mud homes are not airtight, fires are not well vented, leading to dangerous buildup of combustion products. Lung and eye problems resulting from these pollutants have devastating effects, particularly on women who spend many hours indoors close to stoves and their nearby infants who are even more susceptible.

PROPOSAL

This housing project began with a rigorous list of performance goals intended to objectively evaluate available housing technologies. These specifications are applicable to both developed and developing countries in a range of environmental and economic settings.

Performance specifications

Affordable and cost effective for residents, including building cost, maintenance cost, life-cycle cost, and resale value.

Energy efficient and well insulated, offering higher comfort in extreme temperatures with minimal use of costly external energy sources.

Durable and safe under seismic activity and natural hazards such as strong winds, fire, pests, and moisture.

Well-designed to promote good indoor air quality, providing adequate ventilation and air flow.

Maximize local economic benefits, by requiring intensive unskilled local labor, realistic capital investments in region, and purchasing locally available materials.

Culturally acceptable and attractive to inhabitants.

Rapid implementation as a post-emergency shelter and competitive in quality and cost with winterized tents.

Adaptable to changing needs of growing families by easily transforming emergency shelters into larger permanent houses. Expandable when resources become available, especially in markets where loans and financing are unavailable.

Environmentally sustainable and resource efficient, using minimal or no wood and producing minimal waste.

Minimal or no proprietary technology, using simple housing design concepts in order to significantly reduce costs.

Ease of maintenance or minimal maintenance with readily available materials.

Reproducible in other markets, using materials available worldwide, minimal imports, and realistic capital investments in facilities employing local labor

Design Concepts

Expanded PolyStyrene (EPS) was found to be an attractive component in the designs. EPS begins as small pellets that contain a blowing agent like pentane or carbon dioxide. When heated to about 100°C, by steam for example, the expansion of the blowing agent creates a structure with millions of tiny air-filled cells. These pre-expanded pellets are then further expanded in a mold with steam or heat, which causes them to fuse together, creating a very strong and rigid foam structure.

The end result is a twenty- to thirty-fold increase in the original volume of the pellets, depending on the density desired. Toxicological tests by manufacturers have shown that fumes from burning EPS represent no greater toxic risk than fumes from natural materials, such as wood, cork, or wool. EPS is an excellent material for home construction because of its low thermal conductivity, moderate compressive strength, and excellent shock absorption.

Use of EPS and a reinforced concrete coating circumvents the need for expensive wood in roof construction. In Afghanistan, pellets can be imported from Pakistan or India to expand in Kabul at a local steam facility, when a design is to be implemented on a larger scale. This would further the goal of employing local labor and reviving local industry. For Native American housing, EPS is widely available in California. EPS is lightweight and panels can be erected by hand without expensive equipment. Openings can be simply cut out of the EPS and fitted with windows and doors. The following are three building methods being analyzed for use as wall and roof panels.

1. Wire Mesh/Truss Panels - EPS panels are embedded with 10-gauge galvanized steel trusses and 14-gauge steel mesh is welded or clipped to the protruding points of the trusses. Once the wall and roof panels are erected and connected with wire clips, they are finished with two layers of cement plaster, resulting in a 1-inch (in.) coating. **(FIGURE 1)** Wire mesh houses have been built in Mexico, California, and Texas.

FIGURE 1: WIRE MESH/TRUSS PANEL

2. Pressed Cellulose Fiber Cement Board Panels - Panels consist of an inner and outer skin of cellulose-reinforced cement board (autoclaved fine-ground silica, cellulose, and cement) and a core of EPS, glued together with high-strength adhesive and dried under high pressure (12 psi or 83 kPa). Wall and roof panels are connected with splices of the same fiber cement board and screws. **(FIGURE 2)**

Cellulose-reinforced cement board is non-combustible; durable against precipitation, wind, or temperature extremes; able to maintain its shape; and impervious to decay and pests. This type of structure has been built in Puerto Panasco, Mexico; Washington State; Sholo, Arizona; Birmingham, Alabama; and Nashville, Tennessee.

FIGURE 2: PRESSED CELLULOSE FIBER CEMENT BOARD PANEL

3. Fiber-Reinforced Composite Panels - EPS panels are erected and connected with an adhesive in a tongue-and-groove scheme, then coated with a layer of adhesive and a 0.5-in. thick composite of polypropylene fibers, polymers, and concrete. **(FIGURE 3)** The composite recipe needs to be refined with further research and testing and is not ready for implementation at this time.

FIGURE 3: FIBER-REINFORCED COMPOSITE PANEL

Simulation and Testing

Experts from several fields are collaborating on this project, allowing independent evaluation of the three building methods in a systematic series of simulations and tests in order to determine which design, if any, best meets the required performance specifications. The method of assessment includes, in order,

Heat loss calculations to determine the optimal EPS thickness for the walls and roof, in order to maximize energy efficiency and minimize costs.

Cost modeling to provide an elemental comparison of the three design methods for two contrasting markets.

Structural calculations to determine gross behavior and stress and deflection patterns under gravity, wind, and seismic loads.

Three-dimensional finite element analysis of wall corners and openings, e.g. doors and windows, to provide detailed simulations of loads in regions more likely to fail.

Laboratory testing of actual panels for adhesion, shear stress, deformation, and deflection, using accelerated aging, chemical, thermal, and mechanical preparation techniques to simulate environmental conditions.

Laboratory development of fiber composite coatings for near future implementation.

Shake table testing of three-dimensional structures at the University of California, San Diego to simulate a recorded earthquake from the Northern Afghanistan area, with visual documentation and measurements of damage.

Building pilot homes in California on a seismically active Native American Reservation and in Kabul, Afghanistan.

Monitoring and documentation to educate and encourage participation by intended inhabitants.

And finally, capital investment and large-scale construction.

PROGRESS TO DATE

Indoor Air Quality and Energy Efficiency Modeling

Preliminary air quality and heat loss modeling assumed a typical SFL house, 65 m2 in gross area, or 42 m2 of living space in four rooms (see FIGURE 6 for similar floor plan); windows and doors insulated to half the level of the walls; the foundation insulated to a level that matches heat flow through walls, with a lower bound of 2.5 cm of EPS; an average of five occupants; a heating stove efficiency of 50%; an annual operating cost of $1/gal #6 oil; an EPS cost of $0.75/ft3; EPS cost annualized at 10% of total; and no charge for windows, doors, surface treatment, or foundation. Calculations were made for three levels of airflow per person: 7.5 Liters/second (American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) Standard 62), 5.0, and 2.5; and five levels of insulation thickness: 6.5 in. (wall) / 10 in. (roof), 6/8, 4.5/6, 3/4, and 1.5/2. Results are graphed in **FIGURE 4.** Note the shallow total cost minimum, indicating an initial specification of 6-in.walls and 8-in.roofs under the above assumptions. Somewhat less insulation, 4.5-in. walls and 6-in. roofs, is only slightly less attractive on a Life-Cycle Cost basis. More detailed energy calculations incorporating specific heating sources and fuels and ventilation methods will be performed to further this air quality and energy analysis.

Cost Analysis

Cost estimation was performed in order to evaluate and compare the affordability of the three building methods, and in addition, a proprietary and commercially manufactured fiber-reinforced composite coating. Calculations include building materials, capital investment, and labor in both Afghanistan and California (Sacramento area) with available data from contacts in Afghanistan, published U.S. residential construction handbooks, and quotes from local suppliers. The two locations illustrate the differences in costs for materials and labor in developing and developed countries. EPS costs are for 4-in. wall and 6-in. roof panels in California; 10-cm wall and 15-cm roof panels in Afghanistan. Costs in Afghanistan are for a 35.5-m2 starter **(FIGURE 5)** and a 72-m2 expanded house **(FIGURE 6)**; and in California, a 408-ft2 starter and an 828-ft2 expanded house (floor plans similar to FIGURES 5 and 6).

These floor plans are based on houses that SFL has built in Afghanistan so that structures will be similar in appearance to traditional adobe homes. The starter house can be expanded easily as the resident family grows or achieves the financial capability for expansion. Other details of cost are difficult to quantify precisely (e.g. transportation to site), but effort was made to determine a relative (not absolute) comparison between designs. For example, foundation costs have not been included, based on assumptions that the four building methods would use the same foundation. (In Afghanistan, the cement necessary to add to a dug-hole foundation filled with rocks costs approximately $30) Capital costs per house are based on simple division of total estimated cost by 10,000 planned houses. A more sophisticated accounting of capital costs per house will be performed later. Costs are summarized in **TABLE 1.**

The costs of some of the systems are difficult to determine because the figures depend on some proprietary information. Based on reasonable assumptions, the non-proprietary fiber composite panel design is the least expensive; however, it is not as fully developed as the other methods. There may be additional polymers necessary to prevent cracking and ease application. Although this composite is not ready for implementation at this time, further research and testing should be pursued because of its potential affordability. The commercially available composite is the most expensive compared to the other designs, because it is a proprietary technology. In Afghanistan and other developing countries, where labor rates are lower, more labor intensive methods appear to be appropriate, in order to keep costs low and stimulate the local economy. In California and other developed countries, where labor is relatively more expensive and materials like cellulose cement board are readily available, the pressed cement board technology is more suitable, with most of the assembly completed in a factory.

FIGURE 5: AFGHANISTAN STARTER HOUSE, 35.5 M2

FIGURE 6: AFGHANISTAN EXPANDED HOUSE, 72 M2

Structural Calculations

Linear calculations were performed for loads under worst case assumptions for the floor plan in FIGURE 5. The simulations consisted of three types of loads (gravity, wind, and seismic) applied to the four systems: wire mesh, pressed cement board, fiber composite, and the proprietary composite. Gravity loads included dead loads (material weight), live loads, and Afghanistan snow loads. Wind loads used American Society of Civil Engineers (ASCE) Code 7-2002. The seismic load design followed the 2003 Universal Building Code, using a seismic importance factor of IE = 1.0, seismic use group I, a site soil classification of Class D, seismic design category E, R=2, SS >1.25g, and S1> 0.75g. **TABLE 2** lists the specific design criteria used in the calculations and **TABLE 3** outlines the results.

CONCLUSIONS

Future work on this project beyond modeling energy flows, analysis of construction costs, simulation and testing of seismic forces, environmental conditions, and hazards, and building pilot houses in California and Afghanistan, includes application in other regions of the world and other building types (e.g. schools, hospitals, community centers). Another important application of EPS and reinforced concrete is retrofit or addition of roofs to damaged houses, as they are the least stable component of a building in an earthquake. It will be important to involve global companies with the ability to implement new building technologies in the future of this project. This project is ongoing and continued research and development will be required to work towards meeting all the performance specifications.

References:

BASF. (2001), Styropor Technical Information, [CD-ROM], 2001 edition, BASF, Germany.

Central Intelligence Agency (CIA). (1 August 2003), CIA - World Factbook Afghanistan, [Online], Available from: [9 September 2003].

Chandler, Howard M. (ed.) (2002), Residential Cost Data 2003, Robert S. Means Co., ISBN 0876296835.

CNN.com. (28 March 2002), Day of mourning for Afghan quake victims, [Online], Available from: [9 September 2003].

CountryWatch.com. (14 September 2003), Afghanistan Countrywatch.com, [Online], Available from: [14 September 2003].

Energy Information Administration (EIA). (November 1999), A Look at Residential Energy Consumption in 1997, DOE/EIA-0632 (97), EIA, Washington, DC.

Energy Information Administration (EIA). (18 July 2003), Annual Energy Outlook 2003 with Projections to 2025 - Overview, [Online], Available from: [9 September 2003].

Monotech. Monotech International, Inc., [Online], Available from: [9 September 2003].

One World Living Systems. (2003), One World Living Systems, [Online], Available from: [9 September 2003].

Ruiz, Hiram. (29 May 2003), World Refugee Survey 2003: News: South and Central Asia: 1.8 Million Afghans Return Home, But International Community Fails to Deliver Promised Aid, Security, [Online], U.S. Committee for Refugees (USCR), Available from: [9 September 2003].

Thermapanel. ThermaPANEL Building Systems, [Online], Available from: [9 September 2003].

United States Geological Survey (USGS). (28 October 2002). USGS Earthquake Hazards program: Significant Earthquakes of the World for 2002, [Online], Available from: < http://neic.usgs.gov/neis/eqlists/sig_2002.html> [9 September 2003]. United States Geological Survey (USGS). (7 April 2003), USGS Earthquakes Hazards program: Earthquakes with 1,000 or More Deaths from 1900, [Online], Available from: [9 September 2003].

Tables:

Table 1: Cost Comparison of the Four Building Methods:

		Wire Mesh	Pressed Cement Board	Fiber Composite	Proprietary Composite
Afghanistan, Starter House, 35.5 m^2	EPS	$300			
	Materials	$680	$1,390	$170	$2,960
	Labor/Capital	$160	$100	$150	$150
	Total	$1,140	$1,790	$620	$3,410
	$/m^2	$32	$50.40	$17.50	$96.10
Afghanistan, Expanded House, 72 m^2	EPS	$530			
	Materials	$1,120	$2,260	$300	$5,130
	Labor/Capital	$270	$120	$250	$250
	Total	$1,920	$2,910	$1,080	$5,910
	$/m^2	$26.70	$40.40	$15.00	$82.10
California, Starter House, 408 ft^2	EPS	$710			
	Materials	$1,680	$1,670	$530	$3,090
	Labor/Capital	$2,430	$1,670	$2,280	$1,800
	Total	$4,820	$4,050	$3,520	$5,600
	$/ft^2	$11.80	$9.90	$8.60	$13.70
California, Expanded House, 828 ft^2	EPS	$1,250			
	Materials	$2,950	$2,900	$930	$5,460
	Labor/Capital	$4,570	$2,870	$3,850	$3,460
	Total	$8,770	$7,020	$6,030	$10,170
	$/ft^2	$10.60	$8.50	$7.30	$12.30

Table 2: Design Criteria:

		Wire Mesh	Pressed Cement Board	Fiber Composite	Proprietary Composite
Dead Load		1.46 kN/m^2	0.50 kN/m^2		
Live Load		0.96 kN/m^2			
Snow Load		0.96 kN/m^2			
Wind Load (ASCE 7-2002)	Windward	0.50 kN/m^2			
	Leeward	0.36 kN/m^2			
	Roof	0.90 kN/m^2			
Base Shear		100.97 kN	34.69 kN		

Table 3: Calculations of Stress Levels at Certain Points:

			Wire Mesh	Pressed Cement Board	Fiber Composite	Proprietary Composite
At base of wall panel	Bending stress	Wind	218 kPa	655 kPa		
		Seismic	1,551 kPa	1,641 kPa		
	Shear stress	Wind	19 kPa	56 kPa		
		Seismic	132 kPa	140 kPa		
	Diaphragm Force	Wind	22 kPa	66 kPa		
		Seismic	104 kPa	108 kPa		
At roof panel	Bending stress	At coating	744 kPa	1,517 kPa		
	Shear stress	At foam	32 kPa	21 kPa		
	Deflection	At mid-span	19 mm	19 mm		

Table 4: Preliminary Heat Loss Calculation Results: