Improving Building Efficiency in Developing Countries: Case Study of Insulation for Northern Pakistan

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ABSTRACT

There is a need to improve building envelopes in many parts of the developing world. In cold climates, scarce fuel is consumed in an attempt to maintain reasonable indoor temperatures. In Northern Pakistan, traditional houses are made with stone walls while newer buildings, houses and schools, use uninsulated concrete block that has even lower thermal resistance. Evaluation and improvement of these buildings were undertaken with a regional non-governmental organization. Measurements were made of the thermal resistance of typical exterior walls. An energy analysis showed that using 1.0 kg of straw in an insulation board would save about 5 kg of firewood over a winter in a Pakistani school.

Recent research has focused on development of an insulation that can be retrofitted over existing walls. The insulation board must be sufficiently strong to support itself during construction and resist damage at its surface. Several methods of containing and binding straw were examined; the most promising adhesive was commercially available methane di-isocyanate. Good mechanical properties were obtained at resin contents as low as 2% by weight. At densities of 128 and 160 kg/m^3 (8 and 10 lb/ft^3), these boards have thermal conductivities of 0.039-0.041 W/m-K (R-values of 3.7 and 3.45 per inch), respectively. The boards have an estimated materials cost per unit thermal resistance that is roughly half the delivered cost of competing insulations available in Pakistan. Straw insulation boards have the added advantage that they can be made on site with semi-skilled local labor and local materials.

Introduction

There is a need for inexpensive thermal insulation in many parts of the developing world. In cold climates, the wood, charcoal, peat or dung used for heating fuel may be scarce, and insulation for the dwellings would conserve resources and would better living conditions; in hot climates, thermal comfort could be greatly improved by the use of insulation under the roofs of the houses. This paper[1] describes our effort to develop a rigid insulation board for use in such developing countries as Pakistan, where firewood is burned to heat houses and schools are made of uninsulated stone or concrete block. Our goal is an insulated board that can be made locally from wheat straw, using simple machinery and requiring little energy to manufacture. The board would be fastened to the inside of the concrete or earth block walls and roofs, and could receive a plaster finish coat. Loose fill insulation, by contrast, is inappropriate for almost all buildings, due to the absence of cavity walls. The only rigid insulation material available is expanded polystyrene, which has been used sparingly due to its high cost. Our target insulation will not have the thermal performance of foams filled with low conductivity gas, but must insulate well enough to justify the effort and material going into it.

[1] A fuller description of the work can be found in Charlson [1997], Harvey [1997], Charlson *et al.* [1998], and Norford *et al.* [1998].

This paper reviews the cost and performance of currently available insulations; presents thermal, structural and cost data for the straw-insulation panels we have developed; and describes the economic benefits of using such an insulation in Northern Pakistan.

Insulations Used Today

Table 1 gives approximate 1996 retail prices for common insulation materials. In Pakistan, prices for expanded polystyrene are in the range of 8.6-14.3 ¢/(m²-k/W)-m² (4.5-7.5¢/R-ft²) [Sullivan 1995].

Insulating Material	Density kg/m³ (lb/ft³)	Conductivity W/m K (R per inch)	Cost \$/(m² K/W)-m² (¢/R-ft²)
wood fiber insulation board	272 (17)	0.051 (2.8)	not available
fiberglass batt	24 (1.5)	0.045 (3.2)	0.027 (1.4)
cellulose attic	35 (2.2)	0.040 (3.6)	0.019 (1.0)
cellulose wall	56 (3.5)	0.041 (3.5)	0.030 (1.6)
expanded polystyrene	16-32 (1-2)	0.036 (4)	0.076 (4)
rigid fiberglass	80 (5)	0.036 (4)	0.19 (10)
extruded polystyrene	29 (1.8)	0.029 (5)	0.12 (6.5)
polyurethane foam	29 (1.8)	0.022-0.026 (6.5-5.6)	0.099 (5.2)
phenolic foam		0.021 (7)	0.11 (6)

Table 1. Density, thermal resistance and cost of current insulation [Harvey 1997].

Adhesives and Straw

Using the unguarded flat-screen heater described below, we tested loose straw to establish the thermal value of the material, as shown in Table 2. We shredded straw in two ways, with a leaf shredder and with a hammer mill, consisting of blunt blades rotating in a vertical plane. Shredded oat straw was screened with a 4.3 mm (0.17 in.) screen, so that we had three products to test; unscreened, screened (larger pieces), and the fines (smaller pieces) that were separated out in the screening. The fines have a natural settled density of about 96 kg/m³ (6 lb/ft³), so we measured them at that density.

We measured the thermal conductivity of insulation boards in an unguarded flat-screen heater, consisting of a nichrome screen heated by electric current, sandwiched by insulation boards 38 x 64 cm (15 x 25 in.) and no more than 38 mm thick (1.5 in.). Chromega-constantan thermocouples were placed on the screen and on either side of the samples, one of which was a reference sample of known conductivity. Aluminum plates, 6 mm thick (0.25 in.) were placed on the outer surface of each sample to provide a nearly isothermal surface. Design of the conductivity tester was based on Hager [1985] and McElroy [1985] and is described more fully in Harvey [1997]. Theoretical analysis of heat transfer in straw insulation boards is presented in Charlson *et al.* [1998a, b].

Initial efforts were made with three readily available, non-hazardous, water-soluble glues: PVA, sodium silicate, and wheat paste. We ran side by side tests to see which of these three representative binders worked best. At the same time we tried different straw grinds; uncut, shredded, milled, with and without screening. The method of applying the adhesive was likewise varied from spraying to foaming and dipping. We produced some boards with fair to good structural qualities, but using large amounts of adhesive, so that the estimated cost per insulating unit was too high 9.5-19 ¢/(m^2-k/W)-m^2 (5-10 ¢/R-ft^2). Efforts with less adhesive produced fragile, flake-prone, incohesive samples. This may have been because we did not have an effective technique for finely distributing the water-adhesive mixture over the straw pieces.

Straw	Density kg/m^3 (lb/ft^3)	Conductivity W/m-K (Btu-in/Rft^{2}F)$^{-1}$
Unscreened	87 (5.4)	0.038 (3.83)
Screened	87 (5.4)	0.041 (3.52)
Fines	95 (5.9)	0.041(3.48)

Table 2. Thermal resistance of loose straw.

MDI Straw Boards

Our recent work focused on one promising adhesive, diphenylmethane diisocyante (MDI). We made 42 50 x 70 cm (20 in. x 28 in.) hammer-milled wheat-straw boards at the research plant of a manufacturer of MDI. For most of the tests we used the complete straw furnish (the output of the hammer mill), with no fines screened out. For two blender loads we used furnish that had been screened in a commercial, rotating sifter with a 0.4 cm (0.16 in.) screen. We used the coarser pieces, rejecting the approximately equal volume of fines. The furnish was placed in a rotating blender and sprayed for 10-15 minutes with a predetermined quantity of resin from a fine nozzle. We then placed a measured amount of furnish in a form, lifted off the form, and hot pressed the mat to a one inch thickness. The upper and lower platens of the press were maintained at 190°C (375°F). After a dwell time of eight minutes in the press, the resin was fully cured, and the boards were removed.

We fabricated boards with densities of 64-240 kg/m^3 (4-15 lb/ft^3), and with resin content of 1-11% by mass. Generally speaking, the strength follows density; the 192 and 240 kg/m^3 (12 and 15 lb/ft^3) boards are strong enough for trial installation, and the 160 kg/m^3 (10 lb/ft^3) boards are nearly so, although further tests and refinements are needed. The 128 kg/m^3 (8 lb/ft^3) boards in general need some structural improvement to be usable, and the 96 kg/m^3 (6 lb/ft^3) boards would need major reinforcement. Resin content had little impact on thermal resistance and compressive strength, while increased resin modestly increased the modulus of rupture, a measure of bending strength [ASTM 1994]. The impact of resin content at specific board densities is included in Figures 1-3, discussed below; the figures show as-manufactured (or actual) board densities, as distinguished from the target densities.

The use of screened versus unscreened straw particles had no consistent effect on thermal resistance over a range of densities. Screening out the fines significantly boosts both compressive strength and bending strength. The compressive strength gain was on the order of 20% for the 160 kg/m^3 (10 lb/ft^3) boards, and by nearly a factor of two for the 128 kg/m^3 (8 lb/ft^3) boards. The modulus of rupture nearly doubled for boards of both densities.

Density has a strong effect on thermal conductivity, as shown in Figure 1. For a given material we wish to minimize the conductivity. Since expanded polystyrene at 0.036 W/m K (R4/inch) is available, we would like to at least approach that value. At densities above 160 kg/m^3 (10 lb/ft^3), thermal resistance drops off. Our 128-160 kg/m^3 (8-10 lb/ft^3) density boards, which have 0.041 W/m-K (R3.5/inch) conductivity, match the thermal value of foams that aren't filled with a low conductivity gas, meaning 0.036-0.048 W/m-K (R4-R3 per inch). This is typical for the better air-based insulations such as fiberglass, cellulose, and expanded polystyrene. One important question is whether or not straw boards at these densities are strong enough, or can be made strong enough. Figure 2 shows compressive strength as a function of density for unscreened boards at all resin contents. Included are points for five other kinds of board that we tested. Our 128 kg/m^3 (8 lb/ft^3) boards, at 28-55 kPa (4-8 lb/in^2) pressure for 10% compression, have greater strength in compression than such widely used boards such as expanded polystyrene 32 kPa (4.6 lb/in^2), and rigid fiberglass, 11 kPa (1.6 lb/in^2).

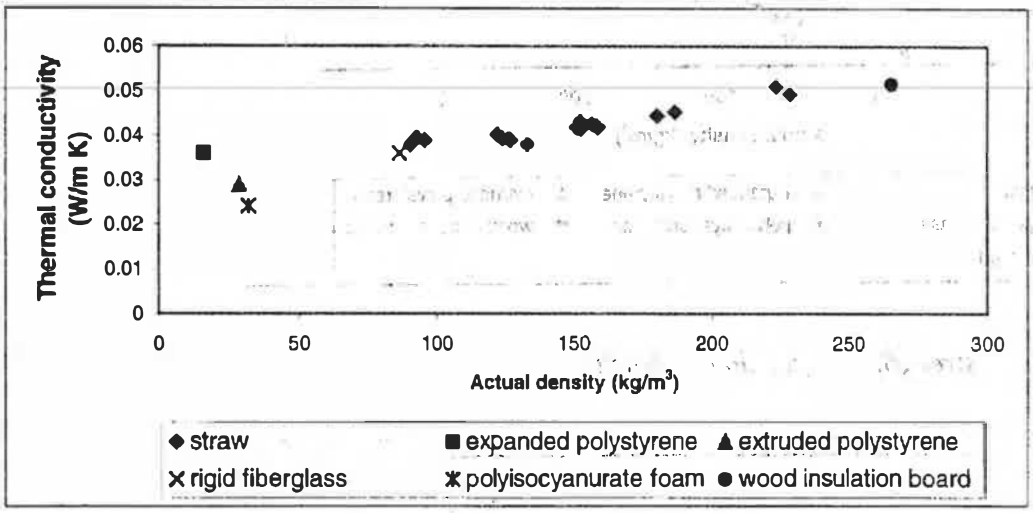

Figure 1. Thermal conductivity as a function of density.

The strength of the boards in bending, which involves compression on one face, and tension on the other, also provides a meaningful structural criterion for our purposes, giving a sense of how well the boards can span studs or rafters, and how easily they can be carried. Figure 3 reveals that modulus of rupture (MoR) for our straw boards increases substantially with density. The 160 kg/m^3 (10 lb/ft^3) straw boards have an MoR equivalent to extruded polystyrene, which has remarkable structural properties and is used in forming concrete foundations. On the other hand, the foamed plastic boards are clearly superior to the straw boards in resisting flaking or dog-earing.

Figure 4 provides cost data, based on a Pakistani straw price of 11.7¢/kg (5.3¢/lb), and an international MDI price of $2.20/kg ($1.00/lb) for the heat cured resin. So far we have only achieved acceptable structure in boards of 128-160 kg/m^3 (8-10 lb/ft^3) or greater. We take 3.8¢/(m^2 K/W)-m^2 (2¢/R-ft^2) as a rough upper limit for materials cost, so that with the added expense of labor, overhead, retail markup, etc., the boards should still cost less than the polystyrene currently available for 11.4¢/(m^2 K/W)-m^2 (6¢/R-ft^2). Several boards depicted in Figure 4 clearly meet this cost criterion, although the 160 kg/m^3 (10 lb/ft^3) boards at 1% resin are structurally unacceptable. Boards with density of 160 kg/m^3 (10 lb/ft^3) and 2 or 4% resin meet the cost criterion, have moderate thermal performance, and are strong enough, or could be made so with minor improvement.

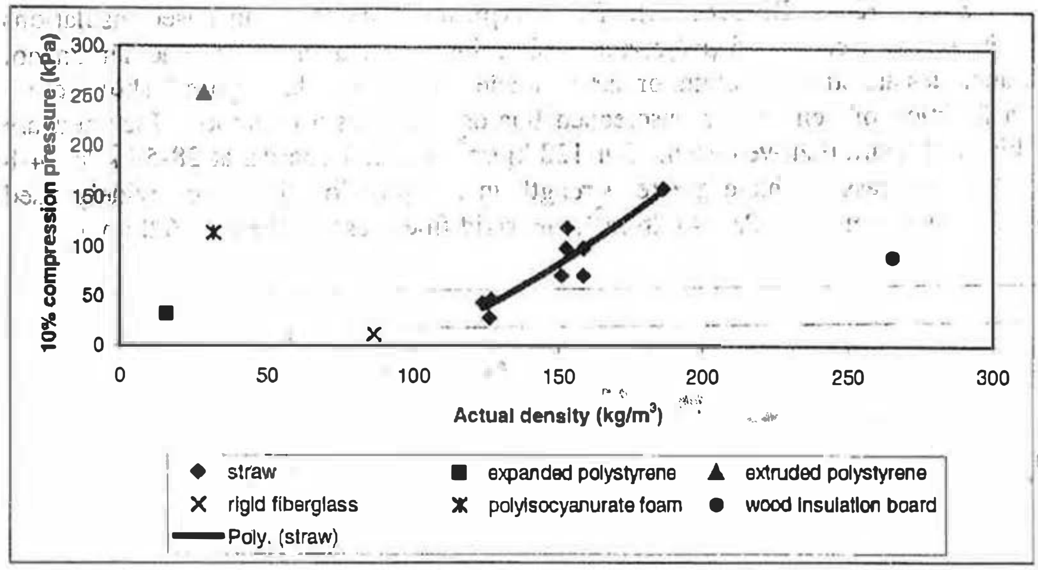

Figure 2. Compressive strength as a function of density.

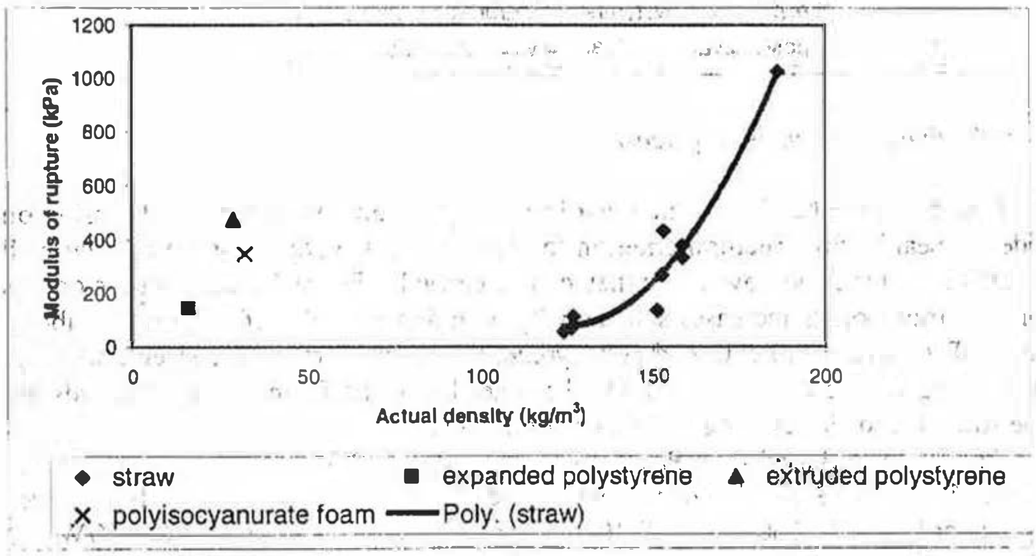

Figure 3. Modulus of rupture as a function of density.

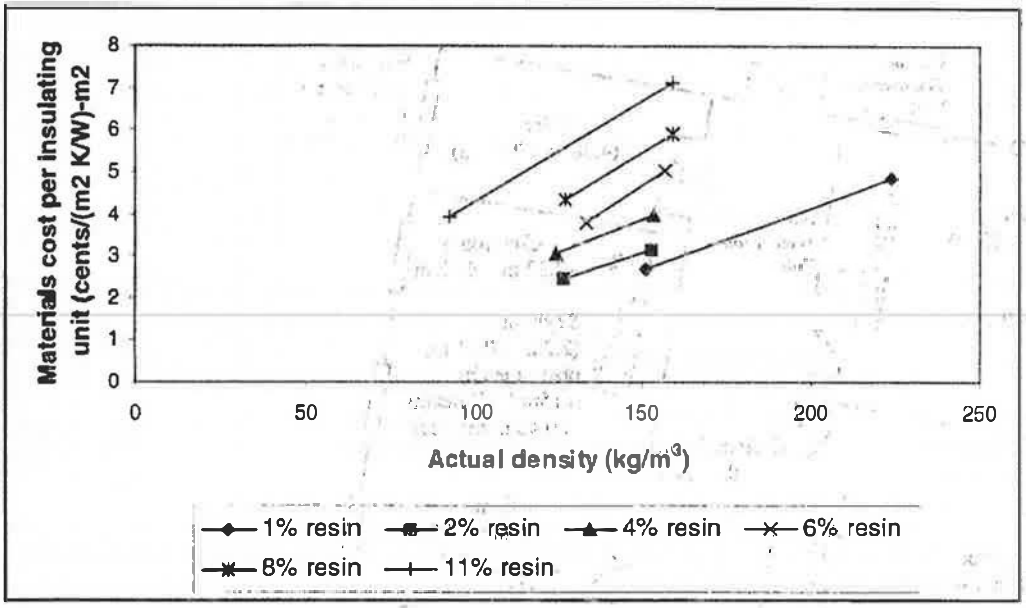

Figure 4. Material cost as a function of density and resin content for straw boards.

Economic Benefits of Insulation for Buildings in Pakistan

To assess the benefits of thermal insulation, we surveyed and then simulated the energy performance of four schools, covering three designs and three wall constructions. The location and a brief description of the schools are as follows:

1. Danyore, in the Gilgit valley of the Northern Areas. This school has seven classroom blocks radiating from a central core block. The walls are made of hollow-core concrete blocks and the flat roof is made of concrete blocks placed on T beams.
2. Ahmedabad, in the Hunza valley of the Northern Areas. This school has the same construction as the school in Danyore, but has four rooms with a central corridor (Figure 5).
3. Ghakuch, in the Gilgit valley. The walls are made of semi-dressed stone, the pitched roof is comprised of plywood, a reed-like insulation, and corrugated iron, and the school has four rooms.
4. Parvak, in Chitral. This school is identical to that in Ghakuch but the walls are of cement-reinforced earth, known as terracrete.

For reference, the Gilgit climate has about 1700 heating degree days, base 18 °C, as estimated from monthly mean temperature data [Pakistan Meteorological Dept. 1993].

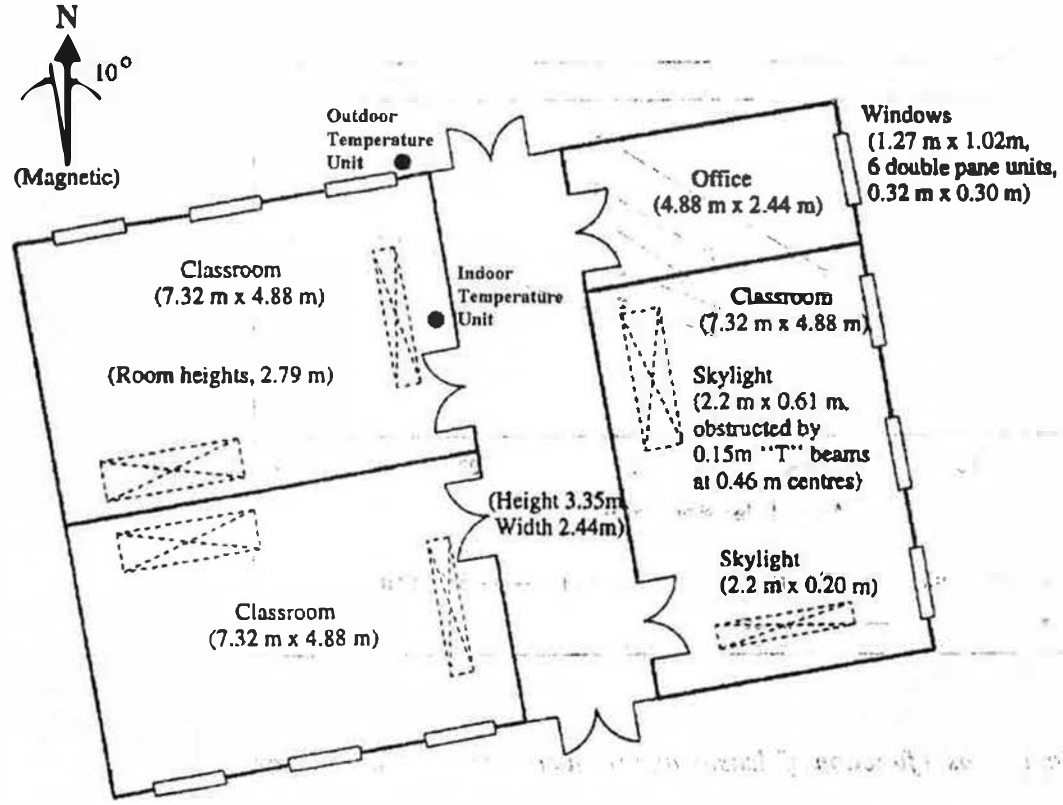

Figure 5. Orientation of Ahmedabad School

On-site survey work, conducted in November 1995, included occupant surveys, measurements of thermal resistance and density of building materials, illuminance measurements, and air-tightness measurements using a blower door. Long-term temperature measurements from portable data loggers supplemented the on-site work. The schools were too cold to be usable for 6-8 weeks in winter. Measured indoor temperatures were often only 2 °C warmer than outdoor temperatures, and modest use of wood stoves in some schools typically boosted temperatures by no more than an additional 2 °C. Densities and thermal resistances for wall materials are shown in Table 3. Table 4 shows the insulation placement scenarios that were simulated and then compared with the baseline, uninsulated case. Scenarios 3 and 6 both involve insulating the roofs of the occupied rooms and do not have favorable payback periods for Ghakuch and Parvak schools, the roofs of which are already insulated. Simulations 5-A and 7 were performed for the Ahmedabad school and simulations 3-D, 7 and 7-D were performed for the Danyore school.

The SERI-RES/PC V1.2 program [Haves 1987], an hourly simulation that adequately models thermal-mass effects, was used for thermal simulations. The occupied-period indoor temperature was set to 17 °C, a reasonable target given the lower temperatures now experienced. The efficiency of wood stoves was estimated to be 50%. Classroom occupancies noted in the site surveys were incorporated in the simulations. Infiltration rates, estimated from measured air tightness and available wind-speed data, ranged from 1.4-1.9 ACH. Ground heat loss was based on ground temperatures estimated to be mean ambient dry-bulb temperatures three months in advance of the month in question and ground resistance calculated from a perimeter heat-loss model. Estimates of material costs and heating fuel costs ($0.07/kg) were provided by Pakistani colleagues [AKHBP 1996].

Material	Density kg/m^3	Thermal resistance m^{2}K/W (w/o boundary layer)
hollow-core concrete block	2272 measured in Gilgit	0.33 measured at Danyore and Ahmedabad, 203 mm thick
semi-dressed stone (granite)	2466 measured at Ghakuch	0.23 measured at Ghakuch, 381 mm thick
terracrete	2253 measured at Parvak	0.30 measured at Parvak, 300 mm thick
flat concrete roof (block on T-beams)		0.44 measured at Ahmedabad
pitched roof[1]		2.32 measured at Ghakuch

1. The pitched roof construction has a ceiling layer of 12.5 mm plywood, a 200.0 mm layer of sirkander grass (reed) insulation, and an outer layer of 24 gauge corrugated galvanized iron sheet.

Table 3. Densities and thermal resistances of wall materials, as measured on-site by authors.

Scenario	Insulation Placement
1	Inside surface of the external walls for the occupied rooms.
2	Inside surface of the external walls for the occupied rooms except for the walls which face the Southeast direction.
3	Inside surface of the external walls and the ceilings of the occupied rooms.
3-D	Inside surface of external walls for occupied rooms and all of the ceilings.
4	Inside surface of all walls for occupied rooms except for those shared with another occupied room.
5	Inside surface of external walls for occupied rooms, the occupied side of the walls shared between occupied rooms and the corridor, and half the given insulation on each side of the walls shared between two occupied rooms; i.e. for the case where external walls are insulated a material with a resistance of 0.88 m^2 K/W, 0.44 m^2 K/W is placed on each side of the walls shared between occupied rooms.
5-A	Inside surface of external walls for occupied rooms and the full amount of insulation on both sides of the walls shared between two occupied rooms
6	Inside surface of external walls for occupied rooms, the occupied side of walls shared between an occupied room and the corridor, half the given insulation on each side of the walls shared between two occupied rooms, and the ceilings of the occupied rooms.
6-A	Inside surface of external walls for occupied rooms, half the given insulation on each side of the walls shared between two occupied rooms, and the ceilings of the occupied rooms.
7	Inside surface of the external walls of the occupied rooms, the occupied side of all walls shared with the corridor, and the ceilings of the occupied rooms.
7-D	Inside surface of the external walls of the occupied rooms, the occupied side of all walls shared with the corridor, and all of the ceilings.

Table 4. Thermal insulation scenarios compared with the baseline model.

Figure 6 shows estimates of the delivered energy required for heating one building at the Ahmedabad school. The results show a 25% energy reduction, relative to the uninsulated base case, for Scenario 2, with 0.88 m^2 K/W (R-5) of insulation applied to all of the external occupied walls except the southeast wall. There is a 37% reduction for Scenario 1 (insulating all the external walls) and a 41% reduction for Scenario 4 (insulating all the walls of occupied rooms except those shared with another occupied room), in both cases for 0.88 m^2 K/W (5.0 hr ft^2 °F/Btu, or R-5) of insulation. Because the roof and walls are both made of uninsulated concrete in Ahmedabad, it is necessary to insulate both the roof and walls to achieve the optimal benefits. This effect is observed in the last four data points on the graph. These scenarios give a tight range of 67%-68% reduction. When the insulation is doubled to 1.76 m^2 K/W (10.0 hr ft^2 °F/Btu, or R-10), energy reductions are 30, 44 and 47% for Scenarios 2, 1, and 4, respectively. When insulation is added to the roof, the range of reductions jumps to 76%-79%.

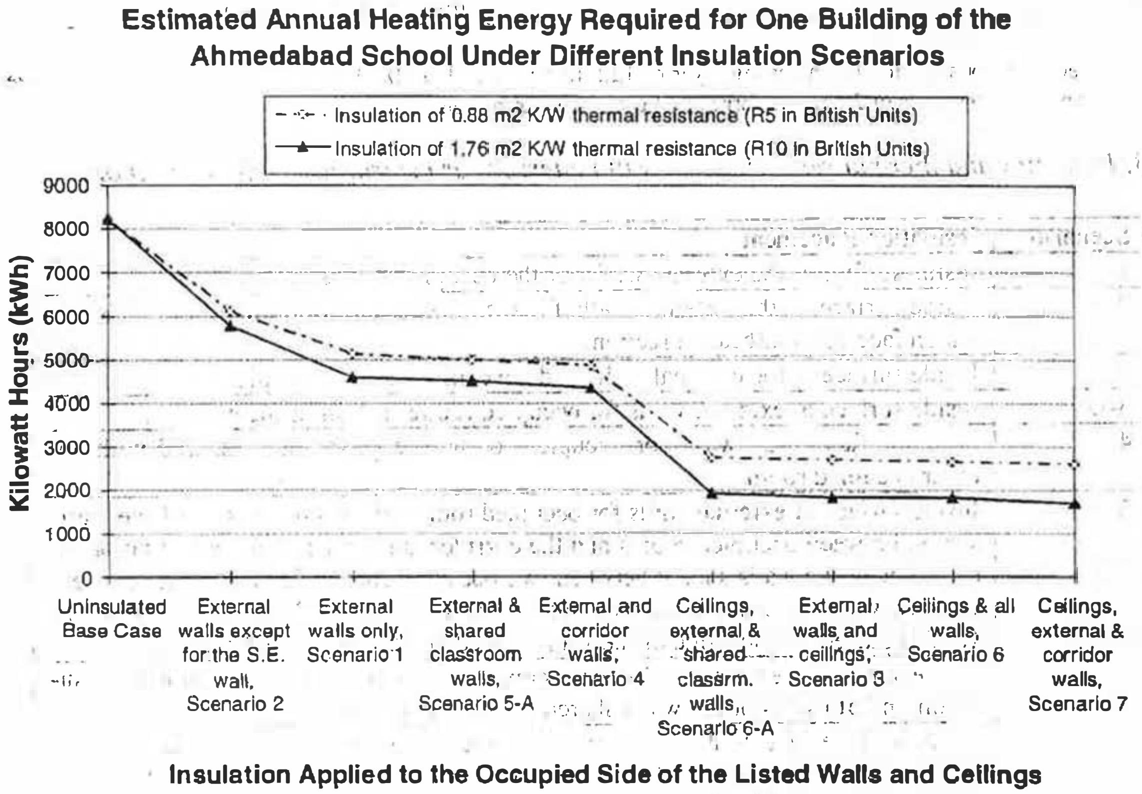

Figure 6: Annual heating energy requirements for the Ahmedabad school.

Figures 7 and 8 summarize the payback periods for two optimal insulation placement scenarios at each school using straw insulation material and expanded polystyrene, respectively. The results are given at both the 0.88 m^2 K/W (5.0 hr ft^2 °F/Btu, or R-5) and the 1.76 m^2 K/W (10.0 hr ft^2 °F/Btu, or R-10) insulation quantity levels. For each school, the payback period is charted for the insulation material itself as well as the combined material, installation, and surface finish costs. Labor costs for manufacturing the straw boards were not considered in the payback analysis and could increase the board cost by as much as 24%. With the addition of the labor, which could in practice be donated, the cost of straw-MDI boards is still 48% below the cost of expanded polystyrene rigid insulation. Payback periods based on material usage (mass of straw required for insulation, returned in avoided heating-fuel

Payback Periods* for the Initial Investment in Straw Insulation

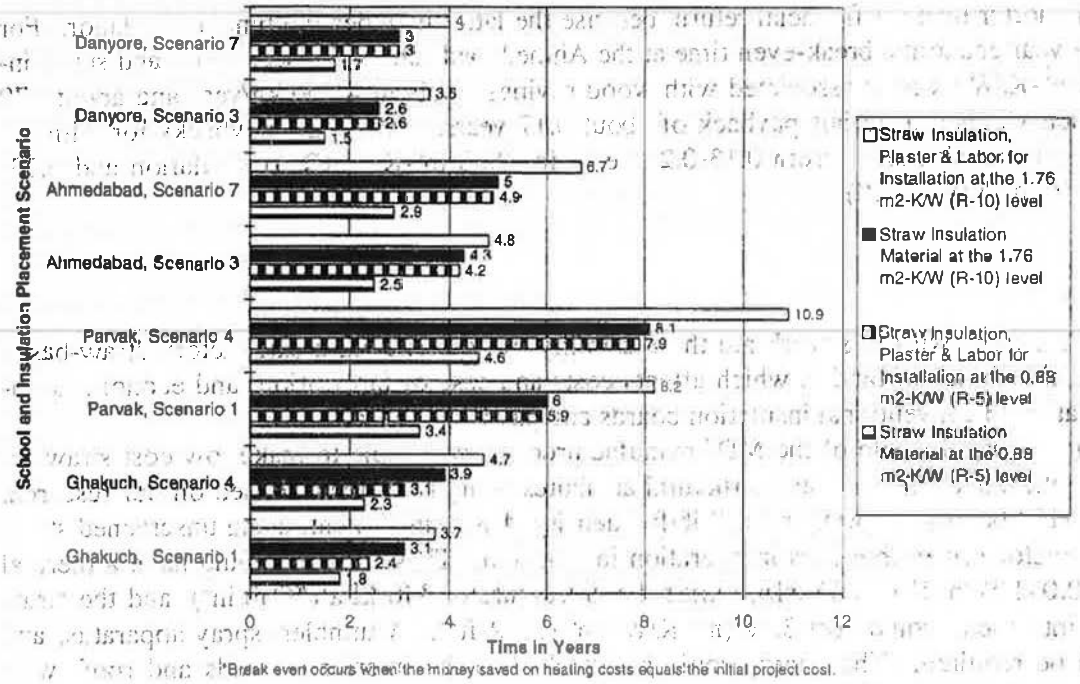

Figure 7. Payback periods for two preferred straw placement strategies at each school.

Payback Periods on Initial Investment in Polystyrene Insulation

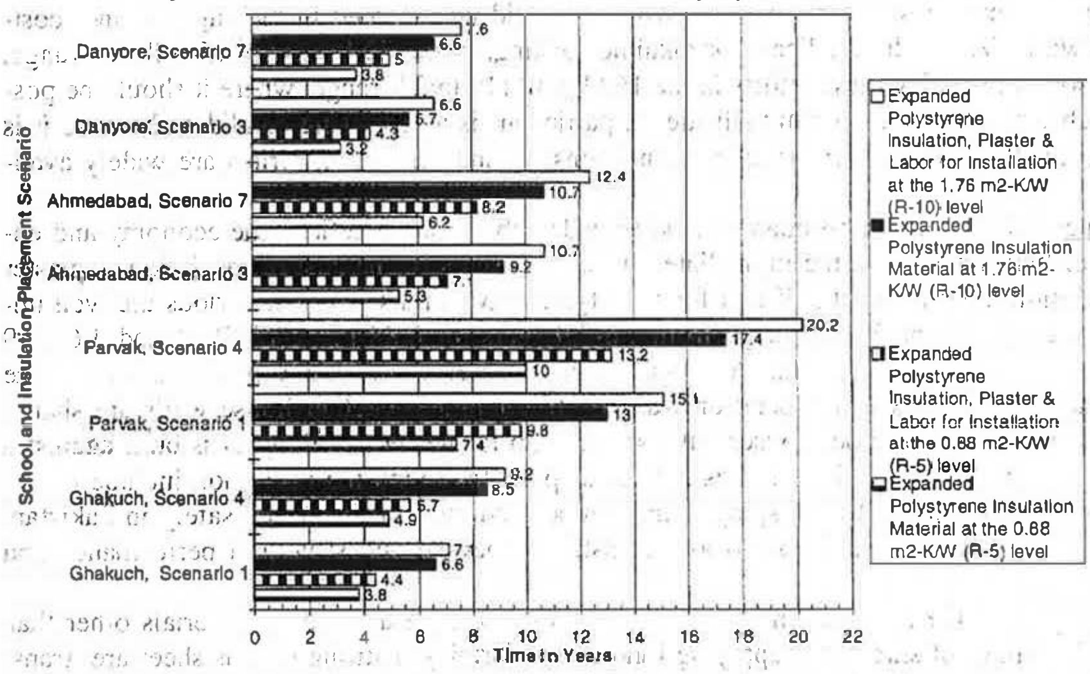

Figure 8. Payback periods for two preferred polystyrene insulation placement strategies at each school.

wood) are much shorter than for financial return, because the latter includes the binder and labor. For example, the 2.9 year economic break-even time at the Ahmedabad school for scenario 7 and straw insulation at 0.88 m^2-K/W (R 5) is associated with wood savings of about 4,000 kg/year and about 770 kg of straw, which yields a materials payback of about 0.17 years. Materials paybacks for Ahmedabad, Ghakuch and Parvak ranged from 0.13-0.27 years for 0.88 m^2-K/W (R 5) insulation and 0.23-0.47 years for 1.76 m^2-K/W (R 10).

Discussion

Our key concerns with this work are the feasibility of constructing a satisfactory straw-based insulation board; the choice of binder, which affects costs and ease of fabrication; and economics, including costs relative to conventional insulation boards and payback periods.

Feasibility. With the help of the MDI manufacturer, we were able to make low cost straw insulation boards with modest thermal and structural attributes using MDI resin. Based on our research, we would make MDI boards at 160 kg/m^3 (10 lb/ft^3) density, 4% resin content, using unscreened straw from the small, tractor-driven threshers in operation in Pakistan. These boards would have a thermal conductivity of 0.041 W/m K (R3.5/inch), a modulus of rupture of 340 kPa (50 lb/in^2), and the straw and resin going into them would cost 3.8¢/(m^2 K/W)-m^2 (2¢/R-ft^2). A tumbler, spray apparatus, and hot press would be required. The boards could be attached to the interior of walls and roofs with screws or nails, and plastered. Although this product should perform well, and is ready for small-scale field testing, it is likely that with further work even better boards will be created.

Binder. As noted earlier in this paper, we initially experimented with pulping the straw and using binders other than MDI. After our experience with the MDI boards, it became apparent that we were working at too low densities in this early work. We did not succeed in making a sound, cost-effective board with PVA, sodium silicate, or alkaline soaking, in the 80-96 kg/m^3 (5-6 lb/ft^3) range, but it would be worth repeating these efforts in the 160 kg/m^3 (10 lb/ft^3) range, where it should be possible to use much less adhesive. Sodium silicate, in particular, is a promising candidate because it is noncombustible, unattractive to microorganisms, inexpensive, and the raw materials are widely available.

Economics. Straw insulation-boards could provide substantial benefit to the economy and environment of Northern Pakistan in the immediate future. For schools, the cost of insulation, a plaster finish and installation labor is about half that for polystyrene. Materials payback periods are well under one year and economic paybacks, range from 2.6-7.9 years for 0.88 m^2-K/W (R 5) and 3.6-10.9 years for 1.76 m^2-K/W (R 10) insulation. A similar thermal and economic analysis has yet to be done for houses. Results for houses will depend on wall construction and whether house walls are shared with neighbors (as is typical of older houses but less common for newer dwelling, or is built against a hillside (as is also common with older houses). Next steps to take with the insulation include development of a low-cost tumbler and MDI sprayer that can be used inexpensively and safely in Pakistani villages, and field tests of the insulation to assess installed thermal and structural performance and long-term durability.

In the long term, the methods engendered in this work can be applied to materials other than straw. The fundamentals of shredding, applying binder, and forming a strong porous sheet are transferable to other materials, so that inexpensive, environmentally benign insulation can be made in parts of the world where such low-value materials are available. This could be significant in efforts to provide shelter, slow global warming, and alleviate pollution.

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