Development of Straw Insulation Board: Fabrication, Testing, Performance Modeling

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ABSTRACT

An insulation board has been developed that is made from straw and has an excellent environmental profile. The boards were made at low density, 80-160 kg/m^3 (5-10 lb/ft^3) and have good thermal properties for an air-based insulation, meaning a conductivity of 0.036-0.048 W/m·K (thermal resistance of R4 to R3 per inch [Btu·in./h·ft^2·°F]$^{-1}$). The initial effort focused on boards suitable for northern Pakistan, where we have studied the needs and construction of schools and houses.

A survey of possible fabrication methods included binding straw particles with such adhesives as PVA and sodium silicate, applied with such methods as spraying, foaming, and dipping. Small samples were formed at a range of densities to test structural and thermal properties. Experimental work showed it was difficult to compete commercially with existing insulation boards in North America or Pakistan.

In the final phase of the project, boards were made with a thermosetting resin. Milled straw and resin were mixed in a blender and the boards formed in a hot press. The boards, made at a range of densities and resin contents, were tested thermally and structurally. 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 pressure required to compress the 160 kg/m^3 (10 lb/ft^3) boards to 10% of their original thickness is approximately 102 kPa (15 lb/in.^{2}), and the modulus of rupture in bending is in the range of 340 kPa (50 lb/in.^{2}). Removing the fine particles from the straw improved board strength markedly.

The best boards had an estimated materials cost of 3.8¢ per unit of thermal resistance and surface area (m^2·K/W)·m^2), (2¢ per R-ft^2), substantially less than the retail cost of the expanded polystyrene available in Pakistan or of any rigid board insulation sold in North America.

INTRODUCTION

Purpose of Work

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 improve living conditions; in hot climates, thermal comfort could be greatly improved by the use of insulation under the roofs of the houses. This paper 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 made of uninsulated stone or concrete block. (A fuller description of this work can be found in Charlson [1997], Harvey [1997], and Charson et al. [1998].) We would like to make the board from locally available waste or near-waste materials, 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.

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This rigid insulation will not have the thermal performance of foams filled with low-conductivity gas, but it must insulate well enough to justify the effort and material going into it. We should be able to approach the thermal value of foams that are not 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.

We have chosen straw for the primary material, as it has a long history of use in buildings, including structural and insulating boards, and is available at little cost in Pakistan. Another obvious option is wood, which might mean sawdust and shavings from sawmills and could include the bark. There are many other agricultural or forest products worth considering in other countries, such as rice and peanut hulls, bamboo, coconut hulls, flax shaves, cornstalks, sugar cane bagasse, convey, jute, sisal, hemp, pine needles, etc.

The first phase of the project was to research the making and use of fiber insulation boards and straw boards in particular, as well as a more general study of pulping methods, adhesives, and insulation heat transfer. We then identified three general approaches for fabricating boards, which might be described as (1) little or no processing, holding the straw stalks together in panel form by some containment; (2) maximal processing, which could mean pulping the straw to form a strong homogeneous board; and (3) some combination of slight processing, such as shredding or soaking or heating, and adhesive binding. We focused on one promising adhesive, methane di-isocyanate (MDI), and this paper describes the making of boards at the MDI manufacturer's research facility and subsequent testing and analysis in our laboratory. The paper closes with conclusions and directions for further development.

Insulations Used Today

Table 1 gives approximate 1996 North American retail prices for common insulation materials. In Pakistan, prices for expanded polystyrene are in the range of 8.6-14.3 ¢/(m^2·k/W)·m^2 (4.5-7.5¢/R·ft^2) (Sullivan 1995). Cost per insulating unit is the cost of one square meter (square foot) of material thick enough to have a thermal resistance of 1 (m^2·K)/W [1 h·ft^2·°F/Btu].

Insulation Boards Made in the Past

Table 2 lists a number of insulating materials used earlier in this century and phased out as plastic foams became available (Harvey 1997). Comparing Table 1 with Table 2, it can be seen that the plastic foams have very low densities relative to natural material boards. Boards made from natural materials at such a low density would fall apart (barring a major technological advance). However, for our project, there are no especially stringent requirements for high R per inch values or for structural performance: the most important criteria are cost and availability. Higher density organic boards with modest thermal and structural properties, such as those listed in Table 2, may be a reasonable solution for places such as Pakistan.

In addition to these materials, straw has a long track record as a building material. Compressed, whole-stalk strawboards made by the Stramit process have been used in buildings in Europe and North America since the 1930s. Straw has also been used in bale form, with wood framing at doors and windows, to provide structure and insulation in house walls. Such straw bale houses were first built in the western United

TABLE 1
Density, Thermal Resistance, and Cost of Current Insulation

Insulating Material	Density kg/m^3 (lb/ft^3)	Conductivity W/m·K (R per inch)	Cost \$/(m^2·K/W)·m^2 (¢/R-ft^2)
Wood Fiber Insulation Board	272 (17)	0.051 (2.8)	
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)
Proposed Straw Board	160 (10)	.041 (3.5)	

TABLE 2
Insulating Materials Used in the 1920s to 1960s

Material Description	Density kg/m^3 (lb/ft^3)	Conductivity W/m·K (R per inch)
Soft Flexible Sheets		
Chemically Treated Wood Fibers	35 (2.2)	0.039 (3.7)
Felted Cattle's Hair	176-208 (11-13)	0.038 (3.8)
Combination of Hair and Jute (75/25 Or 50/50)	96 (6)	Unknown
Flax Fibers with Paper Facers	80 (5)	0.040 (3.6)
Eel Grass with Kraft Paper Facers	54-74 (3.4-4.6)	0.047 (3.1)
Asbestos with Jute or Hair	128-160 (8-10)	0.040 (3.6)
Semi-flexible Sheets		
Flax Fiber	208 (13)	0.045 (3.2)
Flax and Rye Fiber	218 (13.6)	0.047 (3.1)
Corkboard, Still Used for Bulletin Boards and Flooring	112-256 (7-16)	0.038-0.045 (3.8-3.2)
Rock Wool Block with Binder	232 (14.5)	0.048 (3)
"Lith" Board with Rock Wool, Flax, and Straw Pulp	229 (14.3)	0.058 (2.5)
Stiff Fibrous Sheets		
Sugar Cane Fiber (Bagasse)	208-240 (13-15)	0.050 (2.9)
Hardboard from Waste Wood (Sawdust, Etc.)	High	High (low)
Pulped Wood Insulation Board, Made Today	256-272 (16-17)	0.050 (2.9)
Pulped Board from Cornstalks and Other Materials	Unknown	0.048-0.055 (3-2.6)
Cornstalk Pith Board	Unknown	0.034-0.044 (4.2-3.3)
Loose Fill		
Vermiculite, Micalike Hydrated Laminar Mineral, Expanded by Heating, Contains Al-Fe-Mg Silicates	64-128 (4-8)	0.063-0.069 (2.3-2.1)
Perlite, Naturally Occurring Siliceous Volcanic Glass, Expanded by Rapid Heating, Mostly Aluminum Silicate	32-176 (2-11)	0.058-0.036 (4-2.5)

States circa 1900, and the practice has been revived in the pasti 20 years. Experience with these products shows that straw resists rot as long as it stays dry and that at densities greater than 128 kg/m^3 (8 pcf) it does not sustain fire.

FIBROUS INSULATION HEAT TRANSFER

To make the insulation—to decide what material to use, how dense, how fine the pores, how to orient the fibers, what surface properties the fibers should have, etc.—we need to model the various components of heat transfer. Generally, the different heat transfer mechanisms can be thought of as operating in parallel, so that

$$k_{app} = k_s + k_g + k_r + k_{conv} \tag{1}$$

where

k_{app} = apparent thermal conductivity of the insulation,

k_s = contribution of conduction through the solid portion to k_{app},

k_g = contribution of conduction through the gas in the pores,

k_{conv} = contribution of convection,

k_r = contribution of radiation.

The conductivity terms are functions of the material conductivities and the geometry and void fraction of thep-orous medium. The void fraction δ is the volume portion of the material occupied by gas.

$$\delta \approx \frac{\rho_{solid} + \rho_{insul}}{\rho_{solid}} = 1 - \frac{\rho_{insul}}{\rho_{solid}} \tag{2}$$

Here ρ_{insul} is the bulk density of the insulation, and ρ_{solid} is the density of the solid materials in their nonporous state. The void fraction of the straw insulation boards is difficult to estimate because the density of the porous straw base material is unknown. However, straw is a lignocellulosic material similar to wood, with 15% to 20% lignin where wood has 20% to 25%. Assuming that the base straw density is between that of the bulk density of softwood (480 kg/m^3 [30 lb/ft^3]) and the density of wood cell walls (1440 kg/m^3 [90 lb/ft^3]), we can estimate that the void fraction is in the range of 50% to 93% (it is also a function of the bulk density of the insulation). For comparison, in fiberglass batts, δ is usually 99%; in polyurethane foam, 97%; and in cellulose insulation, 94%.

Convective heat transfer should not be present in an insulating material. One of the purposes of the cellular structure is to trap the gas in small pockets in which convection cannot take place. Natural convection is governed by the Rayleigh number (Ra), and although there is some fluid motion when Ra is greater than zero, there is no significant convective transfer until Ra equals 1000 (Mills 1995). The standard Rayleigh number is defined as follows, where the characteristic dimension and the temperature difference apply to one pore of the material.

$$Ra = \frac{g\beta\Delta T_{pore}L_{pore}^3}{\nu^2}Pr \tag{3}$$

where:

g = gravitational constant, 9.8 m/s^2;

β = volumetric coefficient of thermal expansion, K^{-1};

ΔT_{pore} = temperature difference across the pore, °C;

L_{pore} = average dimension of the pore, m;

ν = kinematic viscosity, m^2/s;

Pr = Prandtl number for the gas in the pore.

For a 25 mm (1 in.) thick insulation board with a temperature difference of 28°C across it (50°F), Ra will not reach 1000 until pore size is 10 mm (0.4 in.). At average pore sizes of 3 mm and 6 mm (0.13 in. and 0.25 in.), Ra is 10 and 140, respectively. All the strawboards we made had average pore sizes less than 0.25 in., by inspection, so that even though there is considerable nonuniformity, there should be no appreciable convection in these boards.

For conductive heat transfer, a model established for polyurethane foams treats the gas and solid as parallel paths. The model provides a conduction term for isotropic struts as follows:

$$k_{cond} = k_{air}\cdot\delta + \frac{1}{3}k_{straw}(1-\delta) \tag{4}$$

where the factor of 1/3 arises from the fact that in a regular array of cubical cells one-third of the struts are oriented parallel to the direction of heat flow, while the remaining struts are perpendicular and so do not contribute to conduction through the medium. In the case of fiberglass, where δ is very high and the conductivity of the glass is 30 times greater than that of the air, the solid term in the above equation can be neglected. In the case of strawboards, the solid conduction term cannot be neglected, as the solid makes up a comparatively large share of the volume.

The remaining important term is radiation. In fiberglass, radiation is only important at densities below 32 kg/m^3 (2 lb/ft^3). If the particles in insulation are opaque and black to infrared radiation, then k_r can be found from a linearized form of the equation for radiative transfer between black bodies:

$$k_r = 4\sigma T_m^3 d \tag{5}$$

where

T_m = mean absolute temperature, K;

d = distance between black surfaces, here average pore size, m;

σ = Stefan-Boltzmann constant.

Rough organic materials generally have an emissivity of 0.9 or greater, and the straw pieces are sufficiently thick that they may be assumed opaque. Estimating the parameter d as 1 mm to 2 mm, radiation could account for 14% to 28% of the total heat transfer in the straw boards.

A simple model for heat transfer in the boards comes from Equation 4 above, with the addition of the radiation conductivity.

$$k_{app} = k_{air}\cdot\delta + \frac{1}{3}k_{straw}(1-\delta) + 4\sigma T_m^3 d \tag{6}$$

MEASUREMENTS

We measured the thermal conductivity of all the insulation boards under investigation in an apparatus consisting of a nichrome screen heated by an electric current, sandwiched by insulation boards 38 cm × 64 cm (15 in. × 25 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 (.25 in.) thick 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 is described more fully in Harvey (1997).

With estimates of the relevant parameters, Equation 6 seems to model the material well: the measured apparent thermal conductivity of one of the test boards (one made at 160 kg/m^3 [10 lb/ft^3] density and with 4% MDI resin content) was 0.042 W/m·K (0.29 Btu·in./h·ft^2·°F) between the estimated values shown in Table 3. Actual values of δ, ρ_{straw}, k_{straw}, and k_r are not known, however.

The most important considerations for the early stages of strawboard work are that pore size must be less than 10 mm (0.4 in.) and that solid conduction should be minimized as much as possible by increasing the void fraction, which means reducing overall density.

TABLE 3
Estimated Thermal Conductivity of Straw Insulation

Estimated Parameters	ρ_{straw} = 480 kg/m^3 (30 lb/ft^3) δ = 0.67 k_{straw} = 0.144 W/m·K (1 Btu·in./h·ft^2·°F) d =1mm (0.039 in.)	ρ_{straw} = 1440 kg/m^3 (90 lb/ft^3) δ = 0.9 k_{straw} = 0.288 W/m·K (2 Btu·in./h·ft^2·°F) d = 2 mm (0.078 in.)
k_{app} W/m·K (Btu·in./h·ft^2·°F)	0.036 (0.25)	0.045 (0.31)

ADHESIVES AND STRAW

As a considerable part of our effort was devoted to making boards from straw held together by some kind of glue, we needed to identify those adhesives suitable for our purpose and understand their limitations and mode of action. We considered natural and synthetic adhesives for compatibility with straw, adhesive strength, ease of use, cost, availability, viscosity, surface properties, toxicity, and resistance to heat and moisture. We selected four candidates representative of different classes of adhesive. Polyvinyl acetate (PVA) is a medium-cost, medium-performance thermoplastic adhesive with great availability and ease of use. Sodium silicate is a low-cost, low-tack inorganic adhesive. Wheat paste is a natural, low-cost, starch adhesive with good binding properties but poor resistance to moisture and biological agents. Methane diisocyanate (MDI) is a higher cost, high-performance thermosetting resin used for wood board products.

We tested loose straw, not formed into boards, to establish the thermal value of the material. 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/m^3 (6 lb/ft^3), so we measured them at that density. The measured thermal conductivities and densities, along with the mean temperature and temperature difference across the test sample, are shown in Table 4.

This suggests that the fines improve insulating qualities somewhat when present with the larger pieces, as we expect. The radiation component of heat transfer is reduced by increased "barriers," while solid conduction is not appreciably affected. We cannot ascertain how the fines alone perform in comparison with the larger pieces until we have tests at exactly the same density.

The profile of fiber lengths in the screened and unscreened furnishes are as follows. The output from the hammer mill is composed of approximately 33% fines, 58% medium fibers, and 8% large fibers by weight, according to the criteria shown in Table 5, and is referred to hereafter as unscreened furnish. After passing through a 4 mm mesh screen, the furnish output is composed of approximately 12% fines, 79% medium fibers, and 9% large fibers.

MDI STRAW BOARDS

Initial efforts were made with three readily available, nonhazardous, 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, such that the estimated cost per insulating unit was too high, at 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.

Fabrication

We made forty-two 50-by-70 cm (20 in. by 28 in.) hammer-milled wheat-straw boards at the research plant of a manufacturer of MDI adhesive. For most of the tests we used the complete straw furnish, 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.

TABLE 4
Thermal Resistance of Loose Straw

Straw	Density kg/m^3 (lb/ft^3)	Conductivity W/m·K (Btu·in./Rft^2·°F)$^{-1}$	Mean Temp. K (°F)	Temp. Diff. °C (°F)
Unscreened	87 (5.4)	0.038 (3.83)	302 (84.6)	11.1 (19.9)
Screened	87 (5.4)	0.041 (3.52)	304 (87.1)	10.7 (19.3)
Fines	95 (5.9)	0.041(3.48)	303 (85.1)	10.3 (18.5)

TABLE 5
Furnish Fiber Size Characteristics

Qualitative Name	Average Length mm (in.)	Average Width mm (in.)
Fines	5 (0.20)	1 (0.04)
Medium	10 (0.39)	2 (0.08)
Large	19 (0.75)	3 (0.12)

The furnish was placed in a rotating blender and sprayed for 10 to 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.

MDI Test Results

We fabricated boards with densities of 64 to 240 kg/m^3 (4-15 lb/ft^3) and with resin content of 1% to 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 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. The resin does not create significant additional paths for heat conduction. Therefore, it is possible to increase resin content to strengthen the boards, within cost constraints. Increased resin does not increase compressive strength, but it does appear to modestly increase the modulus of rupture, a measure of bending strength.

The use of screened vs. unscreened straw particles had no consistent effect on thermal resistance over a range of densities. We speculate that the fines reduce radiative transfer but increase solid conduction, so that the net effect is small, certainly much smaller than the effect of density. 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. The impact of screening the straw on thermal resistance is relatively small and variable over the range of board densities, increasing thermal resistance for both the lightest and heaviest boards and decreasing resistance for boards of moderate densities of 128 and 160 kg/m^3 (8 and 10 lb/ft^3).

Density has a strong effect on thermal conductivity, as shown in Figure 1. As density rises, conduction through the solid straw pieces becomes greater as conduction through the entrapped air decreases. The conductivity of the solid straw base material is assumed to be close to that of wood (0.10 to 0.024 W/m·K [R0.6 to R1.4 per inch]), which is much greater than the conductivity of still air, 0.027 W/m·K (R5.4 per inch). Therefore, we expect the lower densities to insulate better, up to the point at which pore size becomes so great that convection occurs. At densities lower than those tested, radiative heat transfer may also become important.

For a given material, we wish to maximize the R value. Since polystyrene at 0.036 W/m·K (R4 per inch) is available, we would like to at least approach that value. At densities above 160 kg/m^3 (10 lb/ft^3), thermal qualities drop off. One important question, then, is whether or not the 128-160 kg/m^3 (8-10 lb/ft^3) density boards, which have a more desirable 0.041 W/m·K (R3.5 per inch) conductivity, 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 the 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}) 10% compression pressure, have greater strength in compression than such widely used boards as expanded polystyrene at 32 kPa (4.6 lb/in.^{2}) and rigid fiberglass at 11 kPa (1.6 lb/in.^{2}).

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) strawboards have an MoR equivalent to extruded polystyrene, which has remarkable structural properties and is used in forming concrete foundations and under footings. On the other hand, the foamed plastic boards are clearly superior to the strawboards 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 may

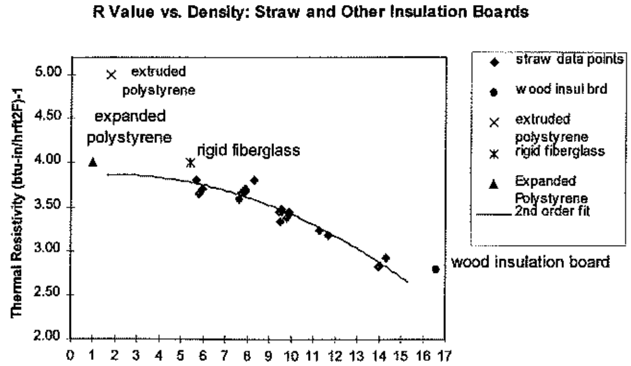

Figure 1 *R value vs. density.*

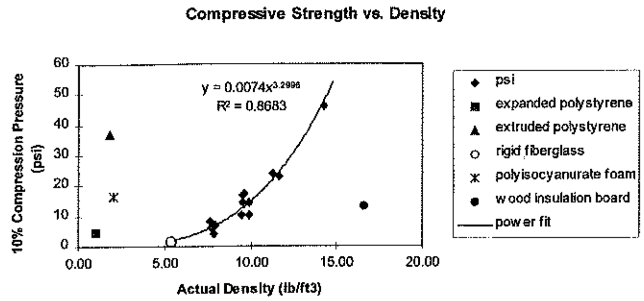

Figure 2 *Compressive strength vs. density.*

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 can still cost less than the polystyrene currently available for 1.1¢/(m^2·K/W)·m^2 (6¢/R·ft^2). Figure 4 then defines a probable operating range for board manufacture, shown as the shaded region in the center bottom of the plot. Boards with density of 160 kg/m^3 (10 lb/ft^3) and 2% or 4% resin meet the cost criteria, have moderate thermal performance, and are strong enough or could be made so with minor improvement.

If better thermal performance were desired, we could push the envelope of that operating range by going to 128 kg/m^3 (8 lb/ft^3) boards with either screened furnish or higher resin content. For example, an 128 kg/m^3 (8 lb/ft^3), 2% resin, screened board would cost 3.6¢/(m^2·K/W)·m^2 (1.9¢/R·ft^2) if the fines are discarded and 2.5¢/(m^2·K/W)·m^2 (1.3¢/R·in.) if the fines have value, both figures being within our cost target. These boards are almost strong enough to use, with an MoR of 120 kPa (18 lb/in.^{2}), and have a good thermal value of 0.040 W/m·K (R3.6 per inch). On the other hand, 128 kg/m^3 (8 pcf) boards with higher resin content (8%-11%) would cost too much and still have unacceptable strength. The data suggest that we can get more structural improvement per dollar spent by screening the straw than by increasing resin load.

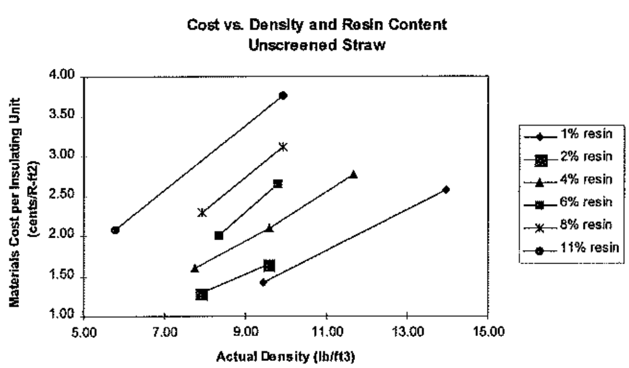

Figure 3 *Cost vs. density for straw boards.*

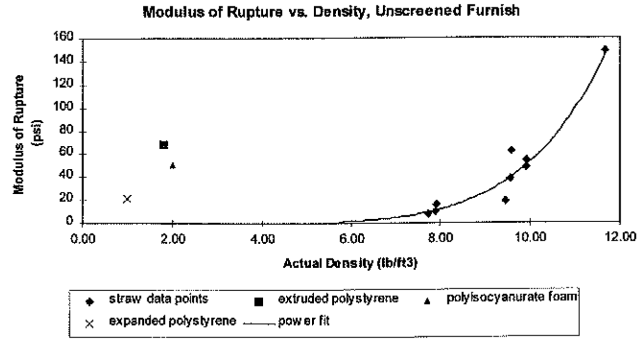

Figure 4 *Modulus of rupture vs. density.*

CONCLUSIONS

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 as received from the thresher. These boards would have a thermal conductivity of 0.041 W/m·K (R3.5 per inch), a modulus of rupture of 60 psi, 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.

After our experience with the MDI boards, it is apparent that in our earlier work with pulping and water-soluble glues we were trying to work at too low a density. 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 still a promising candidate because it is noncombustible, unattractive to microorganisms, and inexpensive and the raw materials are widely available. Although it does not have tremendous adhesive power in comparison to other glues, it would probably be sufficient at a higher density and with better technique.

In our case, we know from the microscope that the adhesive in our earlier efforts was not fully exploited. We could see that large amounts of adhesive were concentrated uselessly on the straw particles between the intersections of pieces, rather than at the joints where the adhesive would serve to bind piece to piece. More efficient glue use could be achieved by the same methods used at the MDI manufacturer's research facility, namely, (1) better mixing action, requiring at least a rudimentary tumbler or blender with spray capability, (2) faster drying, probably by heat, as solvents are too expensive, and (3) pressure during setting.

These boards could provide substantial benefit to the economy and environment of northern Pakistan in the immediate future. 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 will be transferable, so that inexpensive, environmentally benign insulation can be made in all parts of the world with whatever low-value materials are available. This could be significant in efforts to provide shelter, to slow global warming, and to alleviate pollution.

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