Wooden Concrete–High Thermal Efficiency Using Waste Wood

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Wood concrete mixture of wood shavings, lime, and cement is widely used in European building construction. In spite of many advantages, this material is almost unknown in the U.S. Eventual application of wooden concrete in building block production is discussed in this paper. Based on finite difference computer modeling, the thermal performance of several masonry wall systems and their components have been analyzed. The total wall system thermal performance for a typical single-story ranch house also has been determined. At present, typical experimental wall measurements and calculations do not include the effects of building envelope subsystems such as corners, window and door openings, and structural joints with roofs, floors, ceilings, and other walls. In masonry wall systems, these details may represent significant thermal bridges because of the highly conductive structural concrete. Many of the typical thermal bridges may be reduced by application of wood concrete elements.

Introduction

In Europe, only 25% of the freshly cut forest wood is actually utilized (Mielczarek 1989). There are many areas of industry where the wood utilization reaches only 15%. In the U. S., forestry, wood, building, paper industries, and transport companies (waste pallets) produce large sources of waste wood, which could be used as a raw material for concrete elements.

Wood-concrete has been well-known and highly appreciated in Europe since World War II. It has been used to produce lightweight concrete block and wall forms or as forms for bond beams, headers, etc. This material has been almost unknown in the U.S. In this paper, thermal performance of wooden-concrete wall technologies is discussed. A novel method of wall system thermal evaluation is used in this analysis.

The present techniques for quantifying the thermal performance of wall systems have many obvious shortcomings. Building envelope subsystems, such as window and door frames, along with the additional structural support that these subsystems require, are usually ignored. The impact of construction details such as wall corners and floor and ceiling interfaces with the wall system are overlooked. These simplifications can lead to errors in determining the energy efficiency of the building envelope. In addition, today's techniques de-emphasize creative energy-efficient design of the wall system details. Since envelope system designers cannot claim performance benefits due to innovative detailing, the building community is less likely to concern itself with energy efficient detailing concepts.

Typically, the thermal calculations for building wall systems are based on the measured or calculated thermal performance of the clear wall area. In this paper, the phrase "clear wall area" is defined as the part of the wall system that is free of thermal anomalies due to building envelope subsystems or thermally unaffected by intersections with other surfaces of the building envelope. The most widely used analytical techniques for estimating thermal performance of the masonry wall systems are described in Chapter 22 of the *ASHRAE Handbook of Fundamentals* (ASHRAE 1993). The isothermal planes method allows the user to calculate the R-value of clear wall assuming that an isothermal surface exists whenever there is a change in the wall unit geometry. The error associated with this simplification is dependent on the wall system being analyzed.

Measurements of wall systems are typically carried out by an apparatus such as the one described in ASTM C 236, Standard Test Method for "Steady-State Thermal Transmission Properties of Building Assemblies by Means of a Guarded Hot Box" (ASTM 1992). A relatively large (approximately 8 x 8 ft or larger) cross-section of the clear wall area of the wall system is used to determine its thermal performance. Thermal anomalies such as concrete webs, or core insulation inserts are typically included in the tested configuration. The precision and bias of this test method are reported to be approximately 8% (ASTM 1992).

For concrete and masonry walls, building envelope intersections and opening perimeters represent significantly different thermal efficiency. The thermal properties measured or calculated for the clear wall area may not adequately represent the total wall system thermal performance. In the past, that fact has been frequently ignored, and, as a result, wall details have not been thermally examined and improved. It is important to investigate areas of possible heat losses in buildings and minimize thermal shorts, possibly by eliminating highly conductive materials. Building elements made of wooden concrete may be very useful in reducing influence of thermal bridges in buildings, because of the lower thermal conductivity.

Analytical experiments using a finite difference computer model have been performed on popular masonry wall systems, and their subsystems. Using a standard building wall elevation, these results have been combined to compute the amount of clear wall area and to determine the overall wall system thermal performance for a typical single-story ranch house. These data were compared against results of simulation for the same wall systems containing wooden concrete components. Based on this comparison, it was possible to evaluate some of the wooden concrete building technologies thermal benefits.

Waste Wood Utilization for Wooden Concrete Building Materials Production

Application of waste wood as a raw material for building materials production was started in Switzerland in the 1940s. Actually, Swiss branch, "DURISOL," is well-known on several continents as a wooden concrete prefabrication technology. In 1980, in former Soviet Union, wooden concrete production exceed 150 million of m^3 of wooden concrete products. Also, in other Central European countries like Austria, Germany, and Poland, wooden concrete is a very popular material for small residential building. Wooden concrete can be effectively used as a raw material to produce:

- wall forms,
- wall units replacing highly conductive concrete elements in areas of existing thermal bridges, and
- insulating plates and forms for bond beams, headers, etc.

Wooden concrete building elements possess several useful advantages such as

- low thermal conductivity (one-tenth of concrete 120 lb/ft^3 or, 1920 kg/m^3),
- almost perfect acoustic performance,
- can be cut with a handsaw,
- surface treatment can be done by simple hand tools,
- nailing is simple and drywall can be easily fixed,
- due to high porosity, plaster finish fits very well with wooden concrete wall, and
- wooden concrete is virtually nonflammable and bioresistible.

In North America, wooden concrete is sometimes used in production of noise-absorbing highway barriers due to its high sound absorbance. Wooden concrete materials are almost unknown by U.S. residential building market. At present, residential building foundation walls are constructed very often of two-core and cut-web blocks which are used as wall forms. They are reinforced and filled-in place with structural concrete. Reinforcement and core concrete create structure of such walls, so wall units no longer have to be made of strong structural concrete. This creates opportunity of wider application of lightweight concretes (including wooden-concrete) in residential buildings. Multicore wall units are very popular in Europe. They are traditionally made of lightweight concretes or burnt as ceramic blocks.

Wooden Concrete

Production of wooden concrete elements does not require any unique equipment or technology. Most U.S. producers of concrete blocks could start production at once without significant equipment investments.

The basic wooden concrete components are: wood shavings, mineralizators, cement, and lime. Only coniferous tree shavings can be used in wood-concrete production. Deciduous tree wood contains too many sugars, i.e., glucose, sucrose, fructose, and tannin, which break down cement hydratation. As a result, they stop concrete setting process. These compounds are called "cement poisons." Possible deciduous tree wood contents should be less than 10% of total wood shaving input. The wood shaving moisture has to be less than 20%. In Europe, decayed wood shavings are not used as a wooden concrete ingredient. Portland cement is used as the binder.

A mineralization process helps protect wood decorporation and also provides better setting with cement paste. The most commonly used mineralizators are as follows:

- 3-5% water solution of calcium chloride CAC1$_2$, and
- 3-6% water solution of aluminum sulfate A1$_2$(S0$_4$)$_3$.

Slaked lime is used for calcium chloride treatment, and burnt lime is used for aluminum sulfate treatment.

In the U. S., a modern mineralization process was developed using kaolin to hold "cement poisons" in wood pores (Walter 1991). Thanks to this technology, it was possible to increase the deciduous wood content of wooden-concrete mixtures. Another advantage of this process is that decayed wood can be used (personal communication with Mr. Hansruedi Walter Insul Hols-Beton Systems Inc., Windsor, S.C.).

Different values of compressive strength for wooden-concrete are published due to the variety of production receipts and different test procedures in several countries. In Poland, concrete compressive strength is measured in 16-cm circular samples. According to J. Dabrowski (Dabrowski 1961), wooden concrete compressive strength is as follows:

- light wooden-concrete 37.5 lb/ft^3(600 kg/m^3) -1.0-1.4 MPa,
- normal wooden-concrete 37.5-43.8 lb/ft^3(600-700 kg/m^3) -1.6-2.4 MPa, and
- heavy wooden-concrete 43.8-50.0 lb/ft^3(700-800 kg/m^3) -1.9-2.7 MPa.

Compressive strength of "Durisol" wooden concrete was measured by means of cubic samples (10 x 10 x 10 cm). Its value varied between 1.2-3.5 MPa (Mielczarek 1989). For that produced in former Soviet Union, "Arbolit" wooden concrete, the value of compressive strength is referred to as 3.0-3.5 MPa (Filimonow, Nanazasvili 1981) (Nanazasvili 1983).

According to the increase of the binder hardness, the wooden-concrete strength continues to increase longer than 28-day, a common strength reporting period. For lightweight wooden-concrete, 28-day compressive strength is 70% higher than for 14-day samples. The results for 90-day samples are 100% higher than for 14-day samples (Dabrowski 1961). Bonding strength for wooden-concretes is 30-40% lower than compressive strength.

Thermal insulating ability, like for other lightweight concretes, is good. The value of thermal conductivity depends on density of concrete and its moisture content. The lowest thermal conductivity referred for "Durisol" wooden-concrete is 0.42 Btu in./h-ft^2-F (0.06 W/mK). Wooden-concrete thermal resistivities, measured in Bialystok Politehnik, Poland (Wyszynski, Sadowski 1985), are depicted in Figure 1. Wooden concrete thermal resistivity varies from 1.5 h-ft^2-F/Btu-in. for concrete density of about 30 lb/ft^3(500 kg/m^3) to 0.32 h-ft^2-F/Btu-in. for concrete density of about 62 lb/ft^3(1000-kg/m^3).

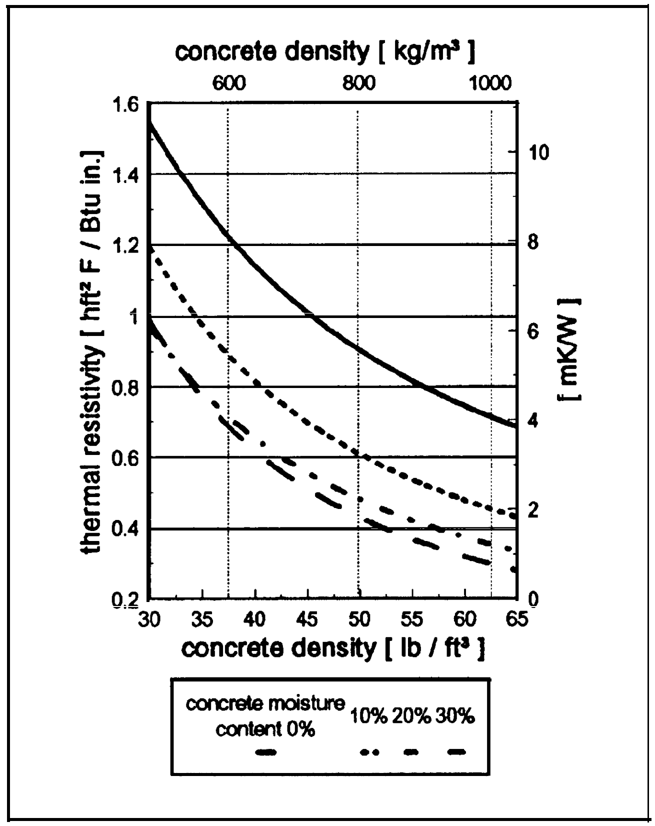

Figure 1. Wooden Concrete Thermal Resistivity vs Concrete Moisture Content Ratio

Thermal Analysis

Five masonry wall systems containing 12-in. (30-cm.) wall units were considered during computer modeling:

- 2-core hollow block,
- cut-web block,
- multicore block, and
- two solid blocks with interlocking insulation inserts,

For each wall system, models of the clear wall area, comer, roof/wall intersection, floor/wall intersection, window header, window sill, window edge, door header, and door edge were analyzed. Geometries of these details were obtained from standard architectural drawings (Hoke 1988) or system manufacturers' design guides (National Concrete Masonry Association 1975). A significant amount of clear wall area was included when modeling the subsystem:

- corner - 32-in. (80 cm),
- wall/ceiling intersection - 28-in. (71 cm),
- wall/floor intersection - 16-in. (40 cm),
- door and window sides - 18-in. (45 cm), and
- door and window headers - 8-in. (20 cm).

The interaction between the subsystem and the clear wall area was included in the computations, and the area thermally affected by the subsystem could be derived. The temperatures and wind speeds used in all of the modeling runs were 70°F (21°C) and 0 MPH for the interior space and -20°F (6.6°C) and 15 MPH for the exterior environment.

A finite difference heat conduction code, Heating 7.2, developed by Oak Ridge National Laboratory (ORNL), was used for thermally analyzing clear wall areas, wall subsystems, and exterior wall intersections with other building elements. Heating 7.2 can solve steady-state and/or transient heat conduction problems in one-, two-, or three-dimensional Cartesian, cylindrical, or spherical coordinates (Childs 1993). Two-dimensional modeling was used for most of the clear wall areas. For wall subsystems and for areas where the exterior wall intersects with other building elements, three-dimensional modeling was necessary. The resultant temperature maps were used to calculate average heat fluxes and then wall system R-values.

The author verified the accuracy of Heating 7.2's ability to predict wall system R-values by comparing Heating 7.2 simulation results with published test results for 18 masonry walls (Kosny, Desjarlais 1994). Ten empty 2-core, 12-in. concrete masonry units (CMUs), reported by Valore (Valore 1988), Van Geem (Van Geem 1986), and James (James 1990), were modeled. These data were selected for modeling because complete geometric descriptions and thermal properties of the components used to fabricate the wall system were available. The average difference between the simulated and tested R-values for these ten wall systems was 4%. This exercise was repeated for eight filled, 2-core, 12-in. CMUs; in this case, the average difference was less than 6%.

Considering that the accuracy of the guarded hot box method is reported to be approximately 8%, the ability of Heating 7.2 to reproduce the experimental data is within the accuracy of the test method. The thermal resistance (R-value) of each wall detail was computed by dividing the average surface-to-surface temperature difference by the average heat flux.

The influence of subsystems on the overall wall thermal performance is different for every house because of the variety of architectural designs. To normalize the calculations, a standard building elevation was used to combine the R-values of the various details and to compute the overall wall system thermal resistance (Kosny, Desjarlais 1994). The standard elevation selected for this purpose is a single-story ranch style house that has been the subject of previous energy efficiency modeling studies (Huang et al. 1987). A schematic of the house is shown in Figure 2.

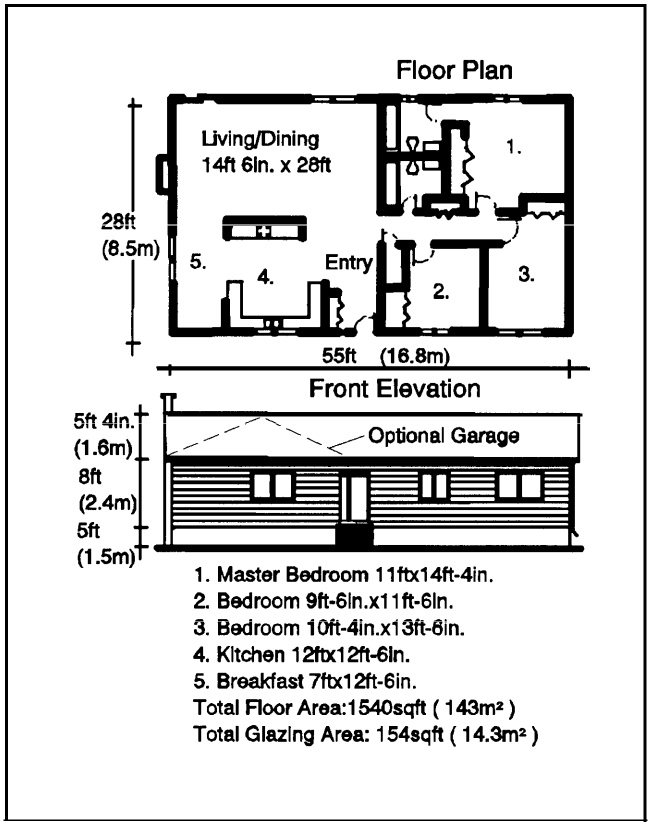

Figure 2. Floor Plan and Elevation of 1-Story Ranch House

The overall thermal resistance of the wall systems was computed by combining in an area weighted method the thermal resistance of the subsystems, wall intersections, and clear wall area. The amount of clear wall area was calculated by subtracting the area of each subsystem from the total exterior wall area.

Wall System Thermal Performance

Five popular shapes of wall units were considered for the clear wall thermal modeling. Overall wall thermal analysis was prepared based on a case of the 2-core masonry technology. Thermal resistance for each block was estimated for five different values of concrete thermal resistivity {0.19 (1.32), 0.28 (1.94), 0.40 (2.77), 0.59 (4.09), and 0.86 (5.96) h-ft^{2}F/Btu-in. (mK/W)}, These values correspond with the following densities of concrete:

- 120 lb/ft^3(1920 kg/m^3),
- 100 lb/ft^3(1600 kg/m^3),
- 80 lb/ft^3(1280 kg/m^3),
- 60 lb/ft^3(980 kg/m^3), and
- 40 lb/ft^3(640 kg/m^3).

According to data presented in Figure 1, wooden-concrete thermal resistivity varies from 0.32 to l.55h-ft^{2}F/Btu-in., when that commonly used in the U. S., concrete of density 120 lb/ft^3(1920 kg/m^3), thermal resistivity can be assumed as equal to 0.1-0.2 h-ft^{2}F/Btu-in. (ASHRAE 1993).

Figure 3 depicts dependence between concrete thermal conductivity y and clear wall thermal resistance. It is seen that for wooden concrete, (35-40 lb/ft^3) resistivity of 0.86 h-ft^{2}F/Btu-in. unit R-value can be 2-4 times higher than for 120 lb/ft^{3}concrete (resistivity 0.19 h-ft^{2}F/Btu-in.). It is interesting that insulated 2-core units reach almost the same R-values as those uninsulated multicore units. The highest R-values, about R-20, can be attained by insulated multicore units and by solid units with self-locking insulation inserts made of lightweight wooden concrete. For insulated cut-web unit made of wooden concrete, R-values can exceed 10 h-ft^{2}F/Btu.

Figure 3 shows that, for the most popular shapes of wall units, eventual possibilities and limits of increased wall thermal resistance as a result of lightweight concrete application. It is seen how important the shape of wall units is.

Thermal insulation inserts are always very expensive components of wall units. Therefore, it is important to use insulation material effectively. Defined by Kosny and Christian (Kosny, Christian 1993), thermal efficiency of usage of insulation material in masonry units, "TE," can serve in evaluation of existing concrete masonry systems. A way of estimating "TE" is described in Figure 4. Thermal effect of consumed insulation can be estimated by comparing R-values of insulated (R_i) and uninsulated (R_U) units. Equivalent R-value of insulation insert, (R_e), can be calculated for the layer of insulation of the same dimensions, such as block side surface and containing the same volume that is used to insulate block. Thermal efficiency of used insulation, "TE," can be computed by the following formula:

$$TE = \left[\frac{R_i - R_u}{R_e}\right] * 100\% \qquad (1)$$

Dependence of "TE" from concrete thermal conductivities, is presented in Figure 4, for assumed thermal resistivity of insulation material is equal 4.0 h-ft^{2}F/Btu-in. For that traditionally produced in the U. S., 2-core units made of 120 lb/ft^3(1920 kg/m^3) concrete, the thermal efficiency of insulation is about 30%. This means that the same insulation effect could be gained by using only 30% of the insulation insert volume in a uniform homogeneous layer.

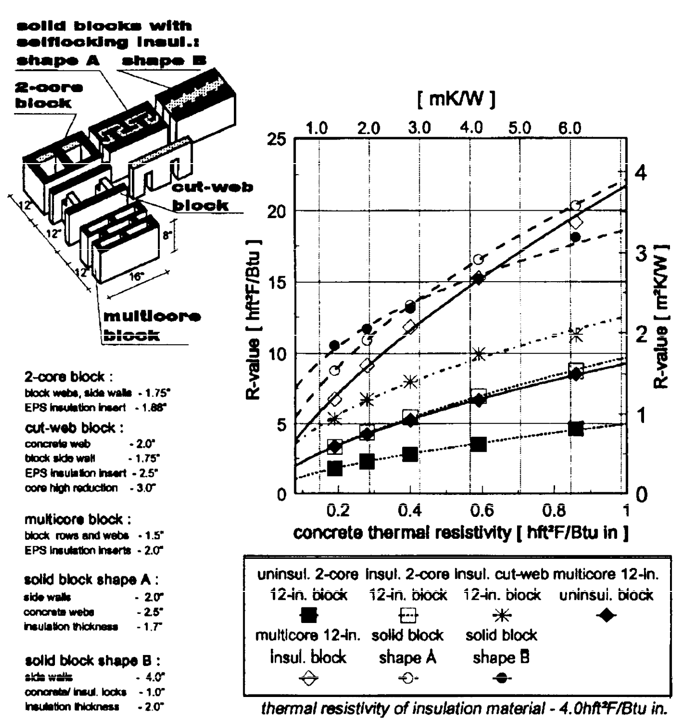

Figure 3. Thermal Performance of Popular Masonry Units

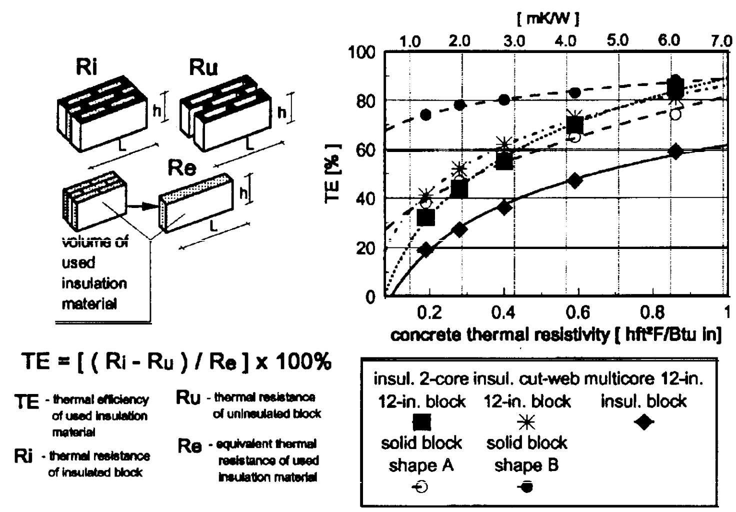

Figure 4. Thermal Efficiency of Insulation in Popular Masonry Units

Application of lightweight concretes in production of masonry units can help in increasing thermal efficiency of insulation. For blocks made of wooden concrete, it can reach 90%. Insulation located in multicore units is very ineffective. For concrete (120 lb/ft^3), it is below 20%. Maximum TE-value for such multicore units made of lightweight concrete will probably not exceed 65%. Also, it is seen that units made of 1920 kg/m^3(120 lb/ft^3) concrete create very inadequate "environment" for installing insulation material. The only exception is well known in Scandinavia - a solid unit with the interlocking insulation insert (Shape B). For this unit, thermal efficiency of insulation varies from 70 to 90% for range of concretes under consideration. In general, insulation inserts installed in units made of wooden-concrete are much more effective.

The total wall system thermal performance was determined for a typical single-story ranch house. For 2-core wall units, all wall components were modeled. Thermal resistances for the clear-wall and wall details were computed for the following cases of the material configurations:

- uninsulated 2-core units made of 120 lb/ft^3 (1920 kg/m^3),
- insulated 2-core units made of 120 lb/ft^3 (1920 kg/m^3), and
- insulated 2-core units made of wooden-concrete 40 lb/ft^3(640 kg/m^3).

Based on the computed wall detail R-values (ROW), the overall wall system R-values were computed by combining the thermal resistances of the wall details, subsystems, wall intersections, and clear-wall area in a parallel, area-weighted method:

$$R_{ow} = \left[\sum_{i=0}^{i=1} \left(w_i * \frac{1}{R_i} \right) \right]^{-1} \quad (2)$$

where R_i = R-value of wall detail (including clear wall),
i = number of wall detail, and
w_i = detail area weighting factor, where

$$w_i = \frac{area\ of\ detail}{overall\ wall\ area} \quad (3)$$

The simulation results for the clear wall and overall wall areas are summarized in Figure 5. Some of wall details are shown in Figure 6. With the exception of the uninsulated 2-core blocks, the clear-wall area thermal resistance is larger than for the overall wall area. For units made of wooden-concrete, the clear-wall R-value is 8.1% larger than overall wall R-value. These results suggest that improvements of details in this wall system are required. For the uninsulated 2-core block system, the R-value of the clear wall area is so low that poor detailing actually increases the R-value of the overall wall area. If comparing overall wall R-values of insulated units made of structural-concrete and wooden-concrete, it is seen that application of wooden concrete can increase overall wall R-value about 2.4 times.

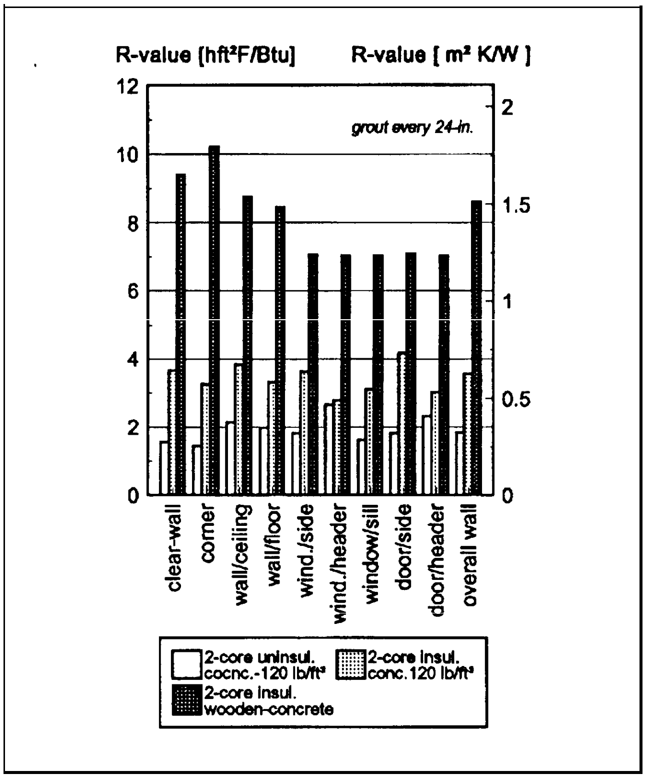

Figure 5. Wall Details R-values for 2-core Wall System

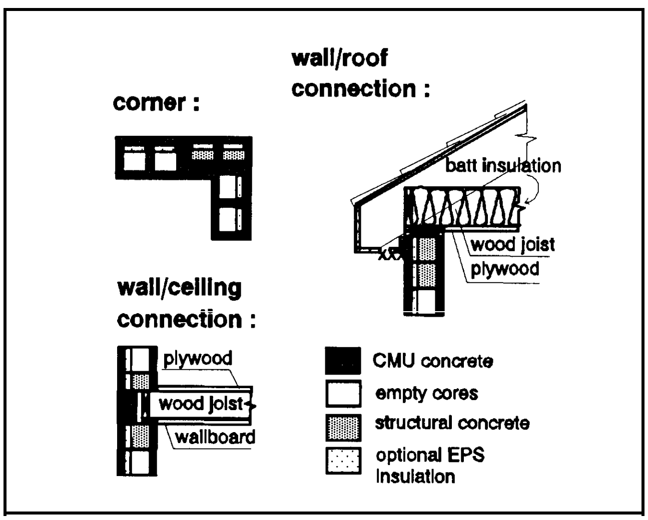

Figure 6. Wall Details for 2-Core Wall System

Conclusions

Using a finite difference computer code, five masonry wall systems, with their typical details, have been simulated. The modeling has been used to analyze the thermal effect of the application of wooden-concrete in building masonry. That is why, for popular shapes of wall masonry units, a comparative analysis was performed. Walls under consideration were simulated as those made of commonly used 120 lb/ft^3 (1920 kg/m^3) concrete and wooden concrete.

For the clear-wall scale, dependence between block R-value and concrete thermal conductivity was analyzed. Also, thermal efficiency of insulation material usage was estimated. These results have been examined and compared. The following conclusions have been developed:

1. Application of wooden-concrete in masonry units can bring a significant increase of wall R-value.

2. For made of light-weight concrete insulated multicore blocks and solid blocks with self-locking insulation, thermal resistance of R-20 can be exceeded.

3. In case of masonry units made of wooden concrete, considerable increase of efficiency of thermal insulation was observed. Thermal efficiency of insulation for masonry units made of 120 lb/ft^3 (1920 kg/m^3) concrete varies between 20-40 %. At the same time, thermal efficiency of insulation for units made of wooden-concrete can reach 60-90%.

For the overall wall scale, wall thermal performance was estimated for three configurations of 2-core units made of 120 lb/ft^3 (1920 kg/m^3) concrete and wooden concrete. The following conclusions were drawn:

1. Overall wall R-values of insulated 2-core units made of structural concrete is 2.4 times lower if compared with walls made of wooden-concrete.

2. The development of wall details can appreciably reduce the overall wall system heat losses. A more extensive review of wall details and elevations is required.

The above series of conclusions may be useful in the design and performance characterization of wall systems.

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