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Thermal Properties of Conventional and Non-Conventional Materials in the Construction of Rural Housing

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— Abstract—

The determination of the thermal conductivity of four materials used in rural housing construction is presented, pine wood board, reinforced concrete slab, concrete block, and a non-conventional proposal of a sawdust panel, in addition to calculating the thermal resistance of systems using the values obtained. The thermal conductivity was obtained according to the ASTM C177-91 (2019) standard, by the steady-state test method using a guarded hot plate equipment (EPCG). The thermal conductivity data were used to compare the differences in thermal resistance and their compliance with the Mexican standard NMX-C-460-ONNCCE-2009 (2009), a standard that indicates the method of calculating thermal insulation through thermal resistance called value "R" (Thermal resistance). The results indicate that the use of the conventional slab and the zinc sheet is very far from compliance with the minimum "R" of the standard, while options such as thermal insulators with local materials such as wood and sawdust panels allow us to get closer. to compliance with the standard. This has an impact on the thermal conditions inside that will contribute to improving the thermal comfort conditions of people, benefiting their health and minimizing the cold conditions that the inhabitants of the rural community of Monte Sinaí II usually perceive in a temperate climate. Fénix, in the municipality of Cintalapa, in the state of Chiapas.

In these temperate climate conditions, focusing on the rural community Monte Sinaí II el Fénix, in the municipality of Cintalapa, in the state of Chiapas. Another factor considered relevant is the cultural factor that people seek to transition from local materials to industrialized materials, an aspect that can be observed in the community, which is why this work seeks to disseminate the virtues and opportunities from the thermal factor presented by using the materials premises of a community.

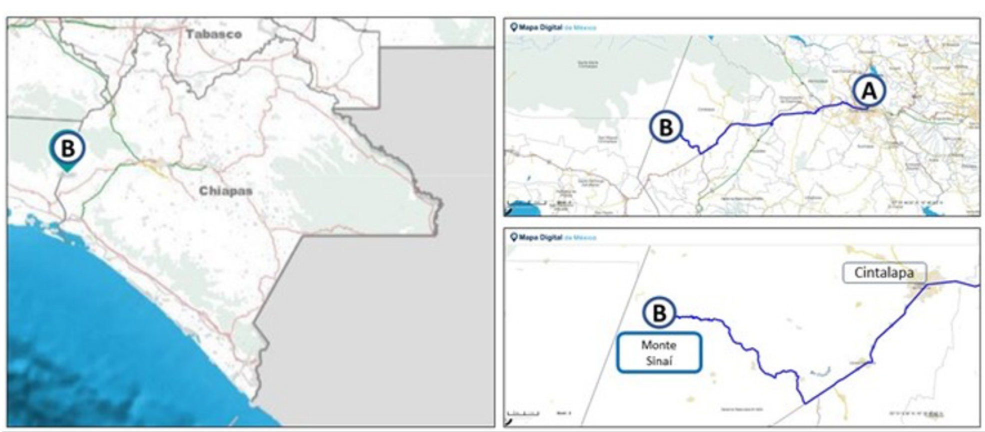
Keywords:

Thermal conductivity, thermal resistance, pine wood and sawdust panel.

In Mexico there are non-mandatory standards that allow evaluating compliance with thermal insulation of materials for construction, such as the official Mexican standard NOM-020-ENER-2011 (2011) and the Mexican standard NMX-C-460-ONNCCE-2009 (2009), although they have focused on evaluating and reducing the use of equipment to cool the space, such as air conditioning, commonly used to decrease air temperatures inside homes, thermal insulation can also be analyzed to reduce heat losses from an interior space.

In the case of homes, one of the components that has the greatest thermal loss or gain, which could contribute to thermal discomfort due to cold or heat, is the roof, since in a warm climate it receives direct and indirect solar radiation during sunny hours, while in a temperate climate, heat is lost during the nights. In this sense, it is considered an important factor to give technical values to the thermal virtues that the use of local materials can present, and in this case, the community has the sustainable forest management of pine wood, so it was chosen to determine the thermal properties of a sample of pine wood board and a panel of sawdust was prepared, a product of the sawmill managed by the Monte Sinai community.

Monte Sinai II (El Fénix) is an indigenous rural community located in the municipality of Cintalapa, located east of the state in the mother mountain range of Chiapas, bordering the state of Oaxaca, with geographical coordinates of 16.67 degrees North latitude and 94.01 degrees West longitude, with an altitude of 1300 m.a.s.l. El Fénix stands out because Chiapas is one of the states in the country where deforestation is growing and illegal logging predominates. This community transitioned 15 years ago to sustainable forest use and has approximately half a thousand inhabitants and 56 ejidatarios that share 1080 hectares. Today they have a certified community forestry company, granted by the Forest Stewardship Council (Guzmán & Díaz, 2019).



Note. Source: Ruiz et al, 2022.

Figure 1. Monte Sinai Location (A: Tuxtla Gutierrez; B: Monte Sinai II El Fénix)

MATERIALS AND METHODS

For the measurement of thermal conductivity, a Guarded Hot Plate Equipment (GHP) was used. This team is in the Faculty of Architecture developed within the framework of the National Laboratory of Housing and Sustainable Communities of UNACH. The equipment consists of a hot plate connected to a variable voltage transformer and a cold plate connected to a recirculating thermostatic bath. The flatness of the sample was verified, its thickness was measured at three points per side, and it was placed between the cold plate and the hot plate. A transfer of thermal energy (heat) is generated in the hot plate towards the cold plate through the sample. The thermal conductivity at the time of achieving the steady state in the system is calculated by ASTM C177-91 (2019). The temperatures of the plates were measured with "t" type thermocouples, collecting the data with an acquirer connected to the measurement interface programmed in LabView, the records are programmed every 10 seconds to determine when the stable state of the system is achieved. The thermocouples were calibrated using a thermostatic bath by ASTM E 220-07A. The thickness of the samples was carried out with a vernier calibrator, the measurement area with a flexometer, and the power supplied with digital multimeters.

The apparent thermal conductivity of the material was determined from the steady state equation for the hot plate equipment:

$$\lambda = \frac{q\,L}{\Delta T\,A}$$

Note. Source: Lira Cortés, 2010.

Figure 2. Equation 1. Equation to calculate the thermal conductivity of the material

Where:

- q is the heat flow through the sample in W.
- λ is the apparent thermal conductivity of the sample in W/m K.
- ΔT is the temperature difference applied to the sample in °C or K.
- L is the thickness of the sample in m.
- A is the effective cross-sectional area in m^2.

When a material sample is a laminar composite and contains porosities, empty cells, or mixtures of materials, heat can be transferred by convection and radiation. In addition to conduction, in these cases, the parameter λ, of the previous equation is called effective or apparent thermal conductivity.

Thermal resistance is defined as the inverse of the thermal conductivity multiplied by the thickness of the sample.

$$R = \frac{L}{\lambda}$$

Note. Source: NMX-C-460-ONNCCE-2009 (2009).

Figure 3. Equation 2. The equation for calculating thermal resistance

The measurement area of the system is 0.199 m x 0.197 m being an area of 0.128 m2. The guard area comprises 0.10 m on each side, for this reason, samples with a minimum dimension of 0.20 m x 0.20 m are requested.

For thermal resistance, we followed the standard NMX-C-460 ONNCCE-2009 (2009). The total thermal resistance of an element of the envelope; the "R" value is the sum of the surface resistances, internal and external, and the thermal resistances of the various layers of the various materials that make up the element of the envelope, this sum is also known as "R" value. The equation for the calculation "R" is as follows:

Equation 1: Simplified calculation of the thermal resistance of a homogeneous material.

$$K = \frac{1}{R_T} = \frac{1}{\frac{1}{hi} + \frac{1}{he} + \frac{L_1}{\lambda_1} + \frac{L_2}{\lambda_2} + \frac{L_3}{\lambda_3} + \frac{L_n}{\lambda_n}}$$

Note. Source: NMX-C-460-ONNCCE-2009 (2009).

Figure 4. Equation 3. Simplified calculation of the thermal resistance of a homogeneous material

The following values make up the said equation:

- K is the coefficient of thermal transmission, in W/m² K.
- L is the layer thickness of the material in the component, in m.
- λ is the thermal conductivity of the material obtained from tabulated values, manufacturer's reports, or laboratory tests, in W/(m K).
- *hi* is the interior surface conductance, in W/m²K, its value (of the standard NOM-008-ENER-2001) is 8.1 for vertical surfaces, 9.4 for horizontal surfaces with upward heat flow (from floor to indoor air or from indoor air to ceiling), 6.6 for horizontal surfaces with downward heat flow (from ceiling to indoor air or from indoor air to floor).
- *he* is the external surface conductance, in W/m²K, its value is equal to 13 (of the NOM-008-ENER-2001 standard).
- *N* is the number of layers that make up the portion of the envelope.

- *RT* is the total thermal resistance of a portion of the building envelope, surface to surface, m² K/W.

RESULTS

In the different samples, the surfaces were not treated because they met the characteristics of the contact of the surfaces with the hot plate and cold plate. The results obtained from the determination of thermal conductivity using EPCG are presented below.

Reinforced concrete slab

The sample of reinforced concrete slab evaluated has an average thickness of 0.1018 m. The sample complies with the minimum area for the test, measuring 0.30m x 0.30 m. The measurement period was on October 6, 2022, from 9:00 a.m. to 7:00 p.m.

Figure 5. Reinforced concrete slab sample

Table 1
Reinforced Concrete Slab Test Results

Variable	Average Value
Apparent thermal conductivity (W/m K)	**2.036**
Thermal resistance (m^2 K/W)	0.05
Thickness (m)	0.1018
EPCG Average Working Temperature (°C)	31.05
Temperature on hot plate (°C)	40.35
Temperature on cold plate (°C)	21.54
Plate temperature difference (°C)	18.81
Effective measurement area (m^2)	0.128
Power supplied (W/ m^2)	381.83
Start of test (hr:mm) – end of test (hr:mm)	9:00 h to 19:00 h 10 hours of measurement approx.

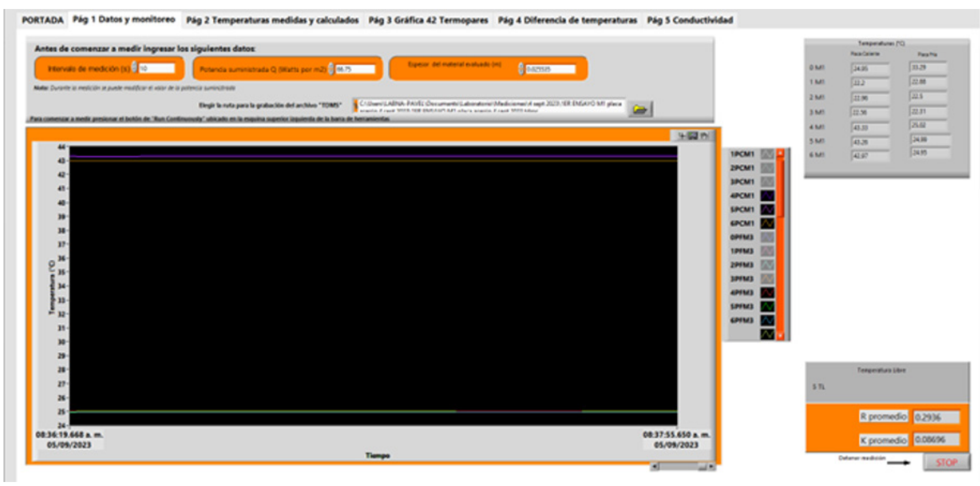


Figure 6. LabView Measurement Interface in Reinforced Concrete Slab Test Stabilization

Solid concrete block

The concrete block sample has an average thickness of 0.15096 m. The sample complies with the minimum area for the test, measuring 0.30m x 0.30 m. The measurement period was on November 2, 2022, from 9:00 a.m. to 7:00 p.m.

Figure 7. Concrete Block Sample

Table 2
Concrete Block Test Results

Variable	Average Value
Apparent thermal conductivity (W/m K)	**1.815**
Thermal resistance (m^2 K/W)	0.08318
Thickness (m)	0.15096
EPCG Average Working Temperature (°C)	28.01
Temperature on hot plate (°C)	33.07
Temperature on cold plate (°C)	22.95
Plate temperature difference (°C)	10.12
Effective measurement area (m^2)	0.128
Power supplied (W/ m^2)	121.514
Start of test (hr:mm) – end of test (hr:mm)	9:00 h to 19:00 h 10 hours of measurement approx.

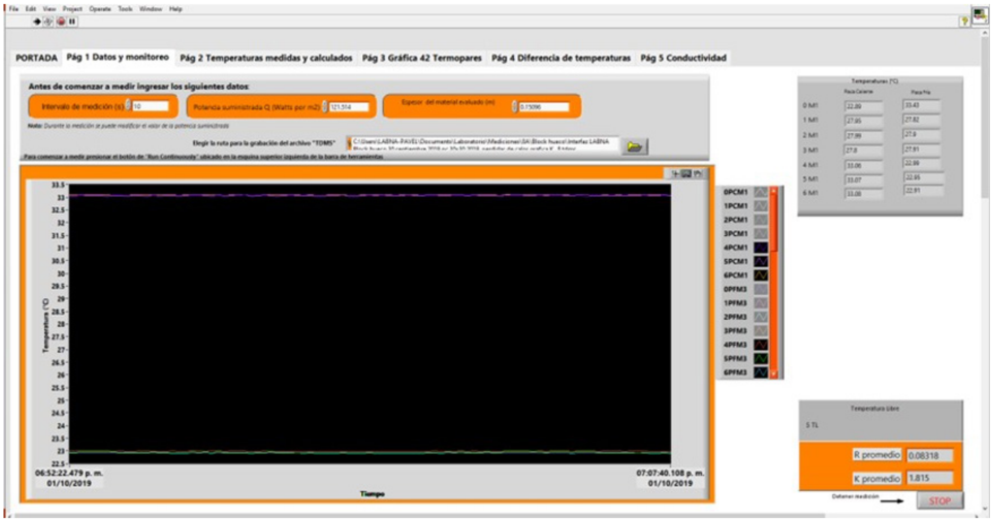


Figure 8. Measurement interface in LabView in concrete block test stabilization

Pinewood

The test of the pinewood board, with an average thickness of 0.0229 m. The samples comply with the minimum requested area of the test, measuring 0.30m x 0.20 m. This board is from the sustainably managed pine wood of Mount Sinai.

Figure 9. Pine Wood Board Test

Figure 10. Enabling Wood Panel on Hot Plate Equipment (EPCG)

Table 3
Pine Wood Board Test Results

Variable	Average Value
Apparent thermal conductivity (W/m K)	**0.1191**
Thermal resistance (m² K/W)	0.1923
Thickness (m)	0.0229
EPCG Average Working Temperature (°C)	31.6
Temperature on hot plate (°C)	37.93
Temperature on cold plate (°C)	25.28
Plate temperature difference (°C)	12.64
Effective measurement area (m²)	0.128
Power supplied (W/ m²)	69.12
Start of test (hr:mm) – end of test (hr:mm)	11:30 h (28 Jan) - 14:20 h (29 Jan). 14 hours with 50 minutes of measurement approx.

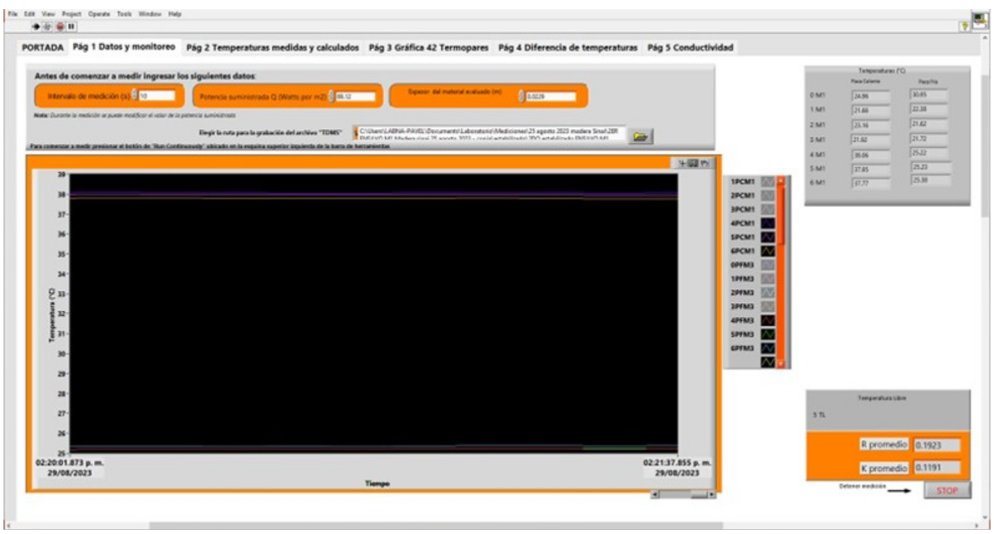


Figure 11. LabView Measurement Interface in Pinewood Board Test Stabilization

Sawdust panel

The sawdust panel sample has an average thickness of 0.1018 m. The sample complies with the minimum area for the test, measuring 0.30m x 0.30 m. This panel was manufactured. The measurement period was from October 27, 2022, at 1:30 pm, to October 28 at 8:37 am.

Figure 12. Sawdust Panel Sample

The sawdust panel was made with easily accessible materials, and it was initially experimented with its elaboration in a wooden mold, compressing it manually, and bonded with a mixture of water and white glue, the ratio used of the mixture was 1:8, a portion of white glue and 8 portions of water. The drying time was about one week. The elaboration can be seen in the following figure, in addition to the fact that students were involved in this activity.

Figure 13. Preparation of sawdust panel, a product of Mount Sinai sawmill

Table 4
Pine Wood Board Test Results

Variable	Average Value
Apparent thermal conductivity (W/m K)	**0.08696**
Thermal resistance (m² K/W)	0.2936
Thickness (m)	0.025535
EPCG Average Working Temperature (°C)	34.09
Temperature on hot plate (°C)	43.19
Temperature on cold plate (°C)	24.99
Plate temperature difference (°C)	18.2
Effective measurement area (m²)	0.128
Power supplied (W/ m²)	66.75
Start of test (hr:mm) – end of test (hr:mm)	13:30 h to 8:37 h 17 hours with 7 minutes of measurement approx.

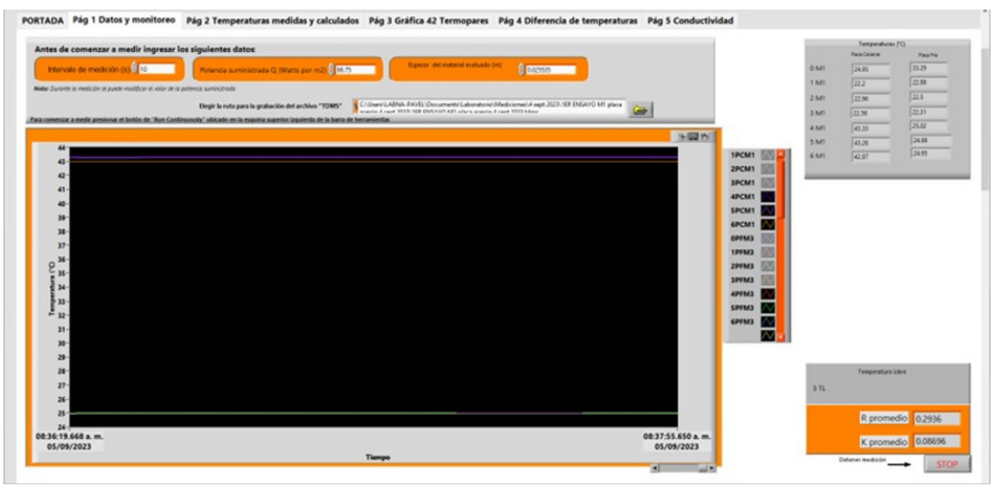


Figure 14. Measurement interface in LabView in sawdust panel test stabilization

OBTAINING THE THERMAL RESISTANCE VALUE

In the case of the calculation of thermal resistance, the values obtained from the determination of thermal conductivity were used. Only the case of the sheet was not determined because it is a standardized material and that of the Catalogue of Constructive Elements of the CTE (2010) was used, another reference to compare determined values of thermal conductivity was that presented by Eduardo González (2003). Below are calculations and systems composed of layers according to the calculation of NMX-C-460-ONNCCE-2009. Zinc foil roofing is added as a comparison as it is commonly used in rural communities. For thermal conductivity value of the zinc foil, the CTE (2010) was used.

Table 5

Calculated thermal resistance for a zinc foil

Material (**)	Thickness (m) b	Conductivity thermal (W/mK) h o K (***)	Thermal insulation (m²C/K) Formula [b/(h o k)]
rsi		6.6	0.152
Zinc foil	0.003	110	0.00003
rse		13	0.077
		R (m²°K/W)	0.228

Tabla 6

Calculated thermal resistance of a reinforced concrete slab

Material (**)	Thickness (m) b	Conductivity thermal (W/mK) h o K (***)	Thermal insulation (m²C/K) Formula [b/(h o k)]
rsi		6.6	0.152
Reinforced concrete slab	0.10	2.036	0.04912
rse		13	0.077
		R (m²°K/W)	0.278

Table 7

Calculated thermal resistance of an apparent concrete block wall

Material (**)	Thickness (m) b	Conductivity thermal (W/mK) h o K (***)	Thermal insulation (m²C/K) Formula [b/(h o k)]
rsi		8.1	0.123
Concrete block	0.15	1.815	0.08264
rse		13	0.077
		R (m²°K/W)	0.283

Table 8

Calculated Heat Resistance of Zinc Sheet Roofing with Wood

Material (**)	Thickness (m) b	Conductivity thermal (W/mK) h o K (***)	Thermal insulation (m²C/K) Formula [b/(h o k)]
rsi		6.6	0.152
Pinewood	0.0229	0.1191	0.19228
Zinc foil	0.003	110	0.00003
rse		13	0.077
		R (m²°K/W)	0.421

Table 9

Calculated thermal resistance of zinc sheet roofing with sawdust panel

Material (**)	Thickness (m) b	Conductivity thermal (W/mK) h o K (***)	Thermal insulation (m^2C/K) Formula [b/(h o k)]
rsi		6.6	0.152
Sawdust panel	0.01018	0.08696	0.11707
Zinc foil	0.003	110	0.00003
rse		13	0.077
		R (m^2°K/W)	0.346

Table 10

Calculated heat resistance of a wall system with wood and air inside

Material (**)	Thickness (m) b	Conductivity thermal (W/mK) h o K (***)	Thermal insulation (m^2C/K) Formula [b/(h o k)]
rsi		6.6	0.152
Pinewood	0.0229	0.1191	0.19228
Air	0.1	0.026	3.84615
Pinewood	0.0229	0.1191	0.19228
rse		13	0.077
		R (m^2°K/W)	4.459

A summary of the calculated thermal resistance values of the different systems is presented below for discussion.

Table 11

The concentration of thermal resistances calculated from the thermal conductivity, obtained in the laboratory

<table>
<tr><th>Type of system</th><th>Constructive system</th><th>Calculated thermal resistance R (m^2K/W)</th><th>Reference thermal conductivity used</th></tr>
<tr><td rowspan="3">Conventional constructive systems</td><td>Zinc sheet roofing</td><td>0.0228</td><td>CTE (2010)</td></tr>
<tr><td>Reinforced concrete slab</td><td>0.0229</td><td rowspan="2">Lab test</td></tr>
<tr><td>Apparent concrete block wall</td><td>0.1</td></tr>
<tr><td rowspan="3">Non-conventional construction systems using local materials</td><td>Zinc sheet roofing with wood</td><td>0.421</td><td rowspan="2">Lab and CTE test (2020)</td></tr>
<tr><td>Zinc sheet roofing with sawdust</td><td>0.346</td></tr>
<tr><td>Wooden wall with internal air space</td><td>4.459</td><td>Lab test</td></tr>
</table>

CONCLUSION

Concerning the concentrate presented in Table 1, the thermal resistances of conventional systems, the highest R-value is 0.1 m^2K/W, being that of the apparent concrete block wall and the lowest value is 0.0228, being that of the zinc roof. Referring to the NMX-C-460-ONNCCE-2009, standard, where the reference to comply with it for roofs is a thermal resistance (R) of 1.4 m^2K/W and for walls a thermal resistance (R) of 1 m^2K/W, it is possible to identify that the value of the zinc foil roof does not approach 2% of the value that must be met for a roof. In the case of the apparent concrete block wall, it is 10% of the minimum value for walls.

For unconventional proposals, using local materials the R-value of the system, using a zinc roof but with a wooden board underneath, an R-value of 0.425 m^2K/W was obtained, representing 30% of the R-compliance value of 1.4 m^2K/W for roofs. For the sheet roof system with the sawdust panel, the R-value was 0.346 m^2K/W, representing 24.7% of the compliance value, and finally, the R-value of the wall system that has a layer of wood, the air inside and a layer of wood outside, obtained an R-value of 4.459 m^2K/W, exceeds compliance with the standard.

Based on comparing the thermal conductivity obtained in the wood fiber panel, the work of Troppová et al. (2015) is appreciated, where a work on the thermal conductivity of boards or panels from wood fiber is reported. The thermal conductivities were obtained with different conditions of working temperature of the system and humidity of the panel, in which a thermal conductivity from 0.048 W/mK to 0.088 W/mK was obtained; when comparing it with the value obtained in this work of the sawdust panel that resulted from 0.08696 W/mK (table 4), we see that the highest conductivity value coincides with conditions. In the work of Božiková et al. (2021), it was found that the thermal conductivity values of a panel made with pine wood residues from 0.08 W/mK to 1.0 W/mK, also results in values similar to that obtained in this work. Finally, in another research by Medved et al. (2021) determined a thermal conductivity of 0.084 W/mK, for a panel made with compressed wood fibers under pressure, carried out with a procedure similar to this work. These previous studies serve as a reference on the thermal conductivity of the wood fiber panel, determined in this work, is practically the same or similar to the values found in similar research. This value and reference are relevant because thermal resistance is calculated as a system and the different proposals are in Table 11. can be seen.

Therefore, it is evident that zinc foil roofing systems have an R-value well below the norm, and this allows us to infer that it is inefficient to resist heat flow, which causes the zinc foil to cool quickly during the night, losing heat to the interior space, so temperatures in a temperate climate could be cold inside. Otherwise, during the day it gains heat and quickly warms the inside. The option of using pine wood as an insulator would improve the thermal comfort conditions inside, with the virtue of being a local and replaceable material. The possibility of manufacturing panels with sawdust residues is also presented as an alternative use to insulate zinc roofing in this community.

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