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Energy savings through solar reflectance and thermal insulation on roofs of residential and non-residential buildings in Mexico.

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Abstract

Thermal building simulations were carried out for the climate conditions of 20 cities in Mexico. We analyze the effects on thermal loads of variations in both solar reflectance and thermal insulation of a roof's exterior surface. The results are quantitative estimates of the reductions in annual (cooling + heating) loads reachable through adequate solar reflectance and thermal insulation of buildings in each city. Additionally, the adequate range of solar reflectance values is defined for each climate zone.

Keywords: *Solar Reflectance, Thermal Insulation, Cool Roofs, Energy Savings, Buildings.*

1. Introduction

According to the 2014 National Energy Balance, 17.97% of the total energy consumption in Mexico (including LP gas, firewood, electricity, natural gas, and thermal solar energy) occurs in buildings—residential, commercial, and public. Of the total energy consumption, 14.71% goes to residential buildings and 3.26% goes towards commercial and public buildings combined. It is estimated that, of the total energy used in residential buildings, 18.7% is used for heating and air conditioning (Fernández, 2011), but this percentage varies with the local climate conditions. In extremely hot climates, up to 50% of the electricity consumed can be dedicated to air conditioning.

The number of households with air conditioning in Mexico has increased since 1996, with an average annual growth rate of 7.5%, while the total number of households in the country has increased 2.7% over the same period (Oropeza and Østergaard, 2014). Rosas-Flores *et al.* (2011) published data on the increase in the fraction of Mexican households with air conditioning, which reached 24% in 2006. Due to the distribution of building types around the country, the greatest consumption of electricity comes from residential buildings, followed by schools and then restaurants/hotels (CMM, 2010).

This indicates that an important and growing part of the total energy consumption in Mexico is dedicated to air conditioning. The energy consumption needed for cooling a building depends to a large extent on the materials used in the building envelope, since some physical properties of these materials affect the heat flux that occurs between the building interior and the environment.

In Mexico, and generally in any location with tropical and arid regions, the roof is the part of a building’s envelope that presents the greatest heat fluxes. One of the most effective measures for reducing energy consumption is to select an adequate value of solar reflectance (SR) for the roof. In warm climates, a combination of high SR values and high infrared emissivity (IE) is most energy-efficient. High SR reduces the amount of heat absorbed (rather than reflected) by the roof, which contributes to the heat flow to the building interior. A high IE, meanwhile, allows for more building heat to be emitted from the building and into the atmosphere.

The annual savings associated with high SR in buildings have been estimated to reach 51 USD per 1000 ft^2 (about 0.55 USD per m^2) in residential buildings (Akbari *et al.*, 1999), and up to 1.14 USD per m^2 in commercial buildings (Levinson and Akbari, 2010); other studies have calculated the reductions in CO_2 emission (Akbari *et al.*, 2009), and the mitigating effects on urban heat islands in the USA (Rosenfeld *et al.*, 1995; Taha, 2008; Santamouris, 2014). Many other effects of cool roofs have been studied and reported for various other regions of the world; these effects include energy savings, improvements in thermal comfort, reduction of greenhouse gas emissions, and compliance with national and international standards (Boixo *et al.*, 2012; Bozonet *et al.*, 2011; Zinzi and Agnoli, 2012; Dias, *et al.*, 2014; Hamdana *et al.*, 2012, Hernández-Pérez *et al.* 2014). Some countries have even implemented cool roof regulations that specify minimum values of SR and IE—or indexes that include both properties—for the exposed surfaces of building roofs (Akbari and Levinson, 2008; Akbari and Matthews, 2012).

However, there are also downsides to cool roofs. In cities with temperate climate, where there are both heating and cooling needs, high values of SR and IE create a benefit during the summer but an added energy cost during the winter (Syneffa *et al.*, 2007). If applied to sloping roofs, furthermore, high-albedo coatings can be uncomfortably bright for people on the ground or in nearby buildings. Similarly, radiation reflected from a roof can impact neighboring high-rise buildings and affect their own energy balance.

Thermal insulation greatly increases the resistance of building envelopes to conductive heat transfer. However, the benefits of insulation in roofs depend greatly on the SR of the roof surface. Certain combinations of low thermal insulation but high SR can yield overall cooling costs similar to those of high thermal insulation and low SR (Simpson and McPherson, 1997).

Gentle *et al.* (2011) studied the combined effect of three factors—SR, IE, and conductive heat transfer resistivity (R)—on the heat gains and losses through the roof, using simulation in EnergyPlus. These authors used a simple building model with no windows, high R in walls and roof, and the arid climate conditions of Sydney, Australia. One of their main conclusions was that the highest benefits of reflective roofs (high SR) appear when R is small. In fact, high SR and low R result in lower energy use overall than high R alone, due to the contribution of low R to desirable nocturnal heat dissipation. A cost-benefit analysis of thermal insulation in walls and roofs of 6 Mexican cities with different energy needs showed that thermal insulation is not effective in reflective roofs for the tropical city of Acapulco (Lucero-Álvarez-García *et al.*, 2016).

Mexico has implemented some standards related to the thermal energy efficiency of buildings, including NOM-008-ENER-2001 and NOM-020-ENER-2011, which limit heat gains through the envelope of non-residential and residential buildings, respectively. The recommended measures for reducing heat transfer during the summer include insulation of walls and roof, as well as the shading of windows. Studies have measured the energy savings from both these passive methods, and those studies were used to develop the standards mentioned above (Halverson *et al.*, 1994; Álvarez-García *et al.*, 2014), but both these cases considered only the energy costs from cooling. A new non-mandatory standard for evaluating the solar reflective performance of roof coatings (PROY-NMX-U-125-SCFI-2015) is currently also under development (Mendez-Florián *et al.*, 2016).

For the purpose of building thermal analysis, Mexico has been divided into four climate zones based on the Degree-Day method (NMX-C460-ONNCCE-2009). Climate zones 1 and 2 have high cooling needs, with refrigeration degree-days (RDD) above 5,000 and above 3,000, respectively. Climate zone 3 has high energy requirements for both refrigeration (2,500 to 3,500 RDD) and heating (<3,000 heating degree days, HDD), which climate zone 4 has higher heating (>2,000 HDD) than refrigeration needs (Table 1).

Tab. 1: Criteria for defining climate zones in Mexico

Climate Zone	Refrigeration Degree-Day (RDD10)	Heating Degree Day (HDD18)	Type of Region
1	> 5,000		Low elevation, tropical and arid-warm
2	3,500 - 5,000		Sub-tropical and arid-dry
3*	2,500 - 3,500	< 3,000	Mexican Plateau, semi-arid and temperate
4*	< 2,500	> 2,000	Semi-arid and temperate, cold winters

*Climate Zones 3 and 4 are subdivided into three categories (A, B and C), according to the average annual precipitation.

A detailed dynamic simulation study evaluated the impact of cool roofs on 7 Mexican cities (Alvarez *et al.*, 2014). The analysis consisted of varying the roof SR of non-residential and residential buildings meeting Standard NOM-008-ENER-2001 and NOM-020-ENER-2011, to determine the effect of SR on the cooling loads of these buildings. The greatest savings were observed for hot and dry climates, with no significant savings in temperate climates. Due to its extensive urban area, in Mexico City there were significant savings for non-residential buildings.

Another previous work evaluated the effect of roof SR, IE, and R on the annual energy load of buildings, including cooling as well as heating (Lucero-Álvarez *et al.*, 2014). This work included a parametric analysis in which the optical properties were changed between 0.1 and 0.9, at 0.1 intervals, for low income single-family houses with two levels of insulation and one case of no insulation. The authors used climate data from 20 Mexican cities, and found that the greatest energy savings occur in cities from climate zones 1 and 2. Both zones require high levels of SR, and insulation (R) has a significant effect only if the SR values are inadequate.

In this work, we analyze the combined effect of SR and R on two building models. Both models (one residential and one non-residential building) are comparable to those used to develop the Mexican regulations. This study considers both cooling and heating, in order to determine the specific values of solar reflectance most appropriate for various cities and when it is most useful to use thermal insulation.

2. Methodology

TRNSYS simulations were used to estimate energy needs, considering both SR and R. 20 cities in Mexico were selected to represent the 4 climate zones defined by Mexican regulations for energy efficiency in buildings. These 20 cities are listed in Table 2 and are ordered according to their climate zones as they appear on the Mexican Standard NMX-C460-ONNCCE-2009.

Tab. 2: Representative cities in the thermal zones

Zone 1	Zone 2	Zone 3A	Zones 3B and 3C	Zone 4
1. Acapulco	5. Cuernavaca	9. Mexico City	13. Chihuahua (3B)	17. Tlaxcala (4A)
2. Campeche	6. Guadalajara	10. Morelia	14. Coahuila (3B)	18. Toluca (4A)
3. Culiacán	7. Hermosillo	11. Puebla	15. San Luis Potosí (3B)	19. Pachuca (4B)
4. Veracruz	8. Monterrey	12. Queretaro	16. Orizaba (3C)	20. Zacatecas (4C)

Figure 1 presents a map of the climate zones in Mexico and the cities studied in this work.

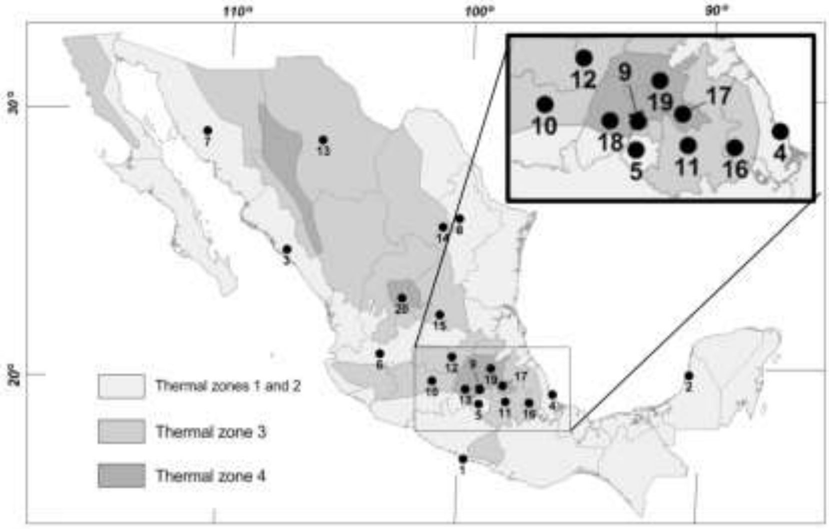

Fig. 1: Location of cities considered in this analysis. The borders of the thermal zones are illustrative and based on the standard NMX-C-460-ONNCCE-2009. Numbers correspond to the list of cities in Table 2.

The roof coatings most commonly used in Mexico include asphalt-based waterproofing (SR of about 0.1) and acrylic paint that vary from red (SR ~ 0.3) to white (SR ~0.8). The values of SR in our simulation were varied between 0.1 and 0.9, in increments of 0.1. In addition to the base cases (zero insulation), we considered two common thicknesses of building insulation, 1 and 2 inches of extruded polystyrene, which we approximated as 25 and 50 mm. The prices of different coatings vary over a small range, compared to the typical cost of thermal insulation.

The main parameter evaluated in this study was the annual thermal load, which corresponds to the sum of the thermal loads of cooling and heating. We considered a set point temperature of 25ºC for cooling calculations, in agreement with previous studies, and a set point temperature of 20ºC for heating.

2.1. Climate data

In order to perform thermal simulations of buildings, it is necessary to have climate data representative of the city where the building is located. These data include ambient temperature, relative humidity, wind speed, and solar radiation, all available at relatively short time intervals (1 hour). In this work, that climate data was generated in TRNSYS from mean monthly measurements of the same variables. The mean monthly values of solar radiation were obtained from the Solar Radiation Data Service (SoDA, 2012), while the mean values for temperature, relative humidity, and wind speed were obtained from the Mexican National Meteorological System (SMN, 2010).

2.2. Building characteristics

The relevant parameters for residential and non-residential buildings were obtained from a report prepared for WinBuild Inc (Álvarez-García *et al.* 2014). These buildings models correspond to those used to develop the Mexican Standards NOM-008-ENER-2001 and NOM-020-ENER-2011 (Halverson *et al.* 1994; Álvarez-García *et al.* 2014), which makes it possible to compare these results with those from previous works. Both kinds of buildings are built with brick walls and single-pane windows, and have roofs made of a 10 cm concrete slab with plaster finish on the inside and waterproofing on the outside.

Residential building

The residential building is a typical Mexican 2-story house, with a total construction area of 100 m², a roof area of 54 m², and a north-facing façade. The geometry of the house was an important determinant of the shading of walls and windows. The walls were simulated with an SR of 0.1. The building is inhabited by 4 people, who are present in the building from 0:00 to 8:00 hours and 15:00 to 24:00 hours every weekday, and 24 hours on Saturday and Sunday. The heat gains from the inhabitants were calculated in TRNSYS according to the parameters established in Standard 7730, and added to heat gains from electrical appliances and lighting. The infiltration for the building is 2 air change per hour (ACH), not considering the ventilation.

The windows were modeled as single-pane glass with the thermo-physical properties given by the TRNSYS library (thermal transmittance or U-value of 5.68 W/m²•K and solar transmittance of 85.5%). The windows cover a surface of 5.20 m² in the walls that face north, 5.60 m² that face south, 0.8 m² that face east, and 2.0 m² that face west.

Non-residential building

The non-residential building model has three stories, each with 625 m² of surface area and a square floor plan (25 m on the side). The walls each contain 40% window space, and have an albedo (SR) of 0.25. This work's simulation considered internal heat gains from electrical equipment, lighting, and people that were present Monday through Friday, between 8:00 AM and 10:00 PM. The ventilation requirements during work hours correspond to ASHRAE Standard 62, which states an air exchange value of 0.043 m³/min•m² (Halverson *et al.* 1994). The properties of the building materials and their distribution throughout the building envelope (of both building models) are shown in Table 3.

Tab. 3: Construction materials and their thermal-physical properties.

Building section	Material	Thickness l [m]	Thermal conductivity λ [kJ/h·m·K]	Specific heat Cp [kJ/kg·K]	Density ρ [kg/m³]
Ground floor	Tile	0.01	4.0896	0.795	2600
	Concrete	0.1	6.264	0.84	2300
Upper floors	Tile	0.01	4.0896	0.795	2600
	Concrete	0.1	6.264	0.84	2300
	Plaster	0.015	1.3392	1	800
Wall	Plaster	0.015	1.3392	1	800
	Brick	0.14	2.916	0.8	1600
	Mortar	0.015	2.592	0.837	1890
Roof	Plaster	0.015	1.3392	1	800
	Concrete	0.1	6.264	0.84	2300
	Waterproofing	0.02	0.612	0.8	1127

3. Results

3.1. Comparison with previous studies

Figure 2 compares the cooling loads from this study with those obtained by Álvarez-García *et al.* (2014). The annual loads agree for some cities, such as residential buildings in Monterrey and Hermosillo. Other city results disagree, such as non-residential buildings in Guadalajara. The greatest reduction in cooling load attributable to SR (the difference between the highest and lowest cooling loads for a given building and location) varied the most between these two studies for residential buildings in Hermosillo.

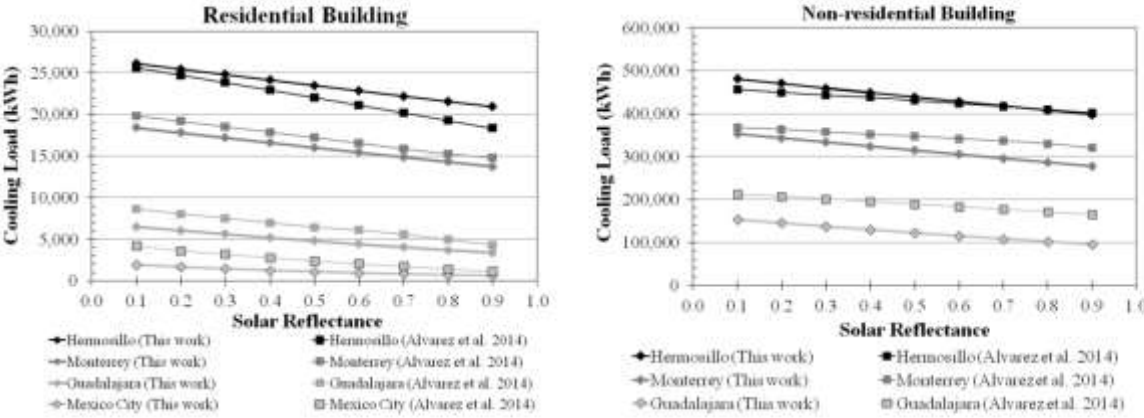

Fig. 2: Comparisons between this work and Alvarez-Garcia *et al.* (2014).

3.2. Effect of SR on a roof with no thermal insulation.

Figures 3 to 7 show the effect that different values of SR can have on the annual cooling load of the two types of modeled buildings. Climate zones 1 and 2 correspond to the hottest climates (and to Figures 3 and 4, respectively), where cooling needs dominate over heating needs. These zones show an inverse linear relationship between thermal load and SR; moreover, the annual loads were consistently higher per m^2 for the non-residential building. This thermal load varies between 230 and 370 kWh/m^2 in the non-residential building, and between 150 and 230 kWh/m^2 in the residential building. Despite this difference in magnitudes between the two buildings, the effect of SR (given by the slope of the lines) was very similar. These are the climate zones with the greatest energy savings achievable through changes in SR.

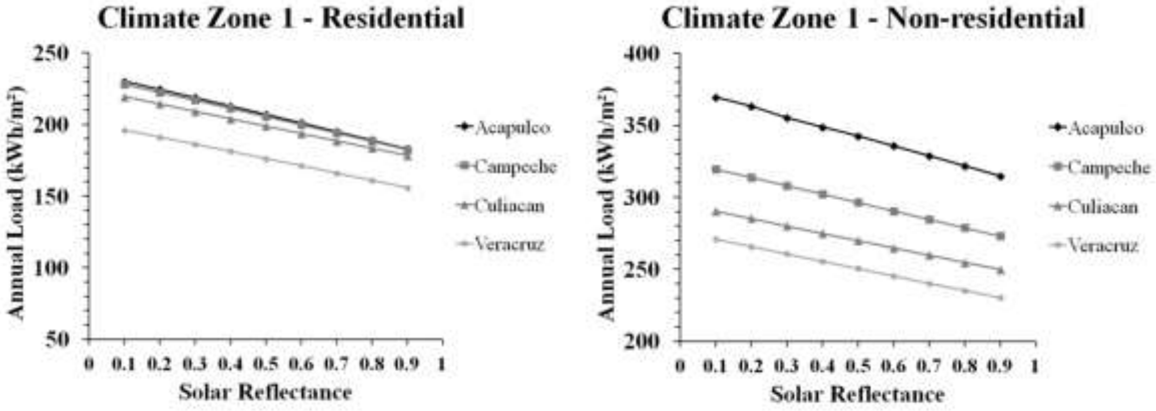

Fig. 3: Annual thermal load as a function of solar reflectance for cities in climate zone 1

For climate zone 2, there is an important difference in magnitude between the annual load in the cities of Hermosillo and Monterrey, compared to those of Cuernavaca and Guadalajara. The annual loads for Hermosillo and Monterrey are comparable to the results of climate zone 1 cities, despite being in a different zone.

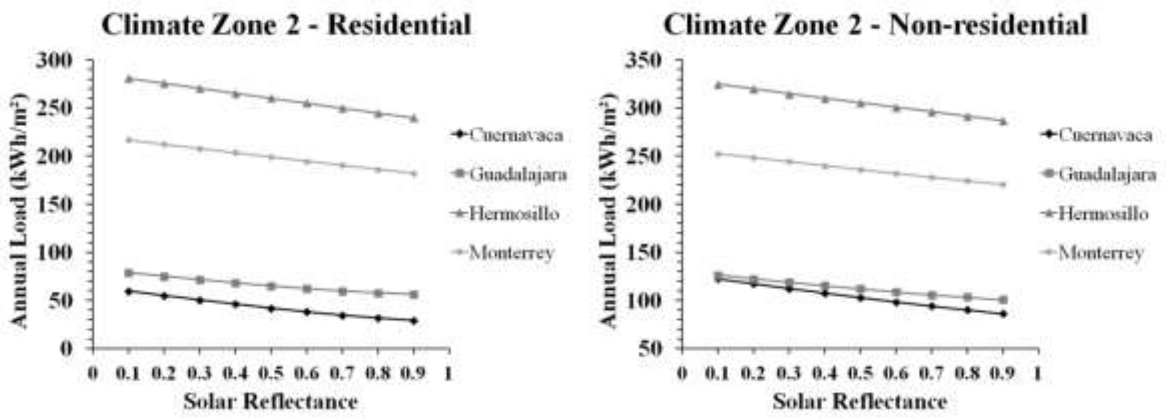

Fig. 4: Annual thermal load as a function of solar reflectance for cities in climate zone 2

Figures 5 and 6 show the results for climate zone 3. This zone has lower cooling needs than climate zones 1 and 2, but higher need of heating. Some of the cities in climate zone 3 present a linear relationship between annual energy load and SR, as had been observed in climate zones 1 and 2. The optimal reflectance for these cities is 0.9, similar to that of climate zones 1 and 2. However, in zone 3 there potential for energy savings is lower than in the hotter zones. The graphs for cities like Mexico and Puebla contain local maxima, marking optimal SR values different than 0.9, and also have smaller differences between the minimum and maximum values of the annual load (Figure 5).

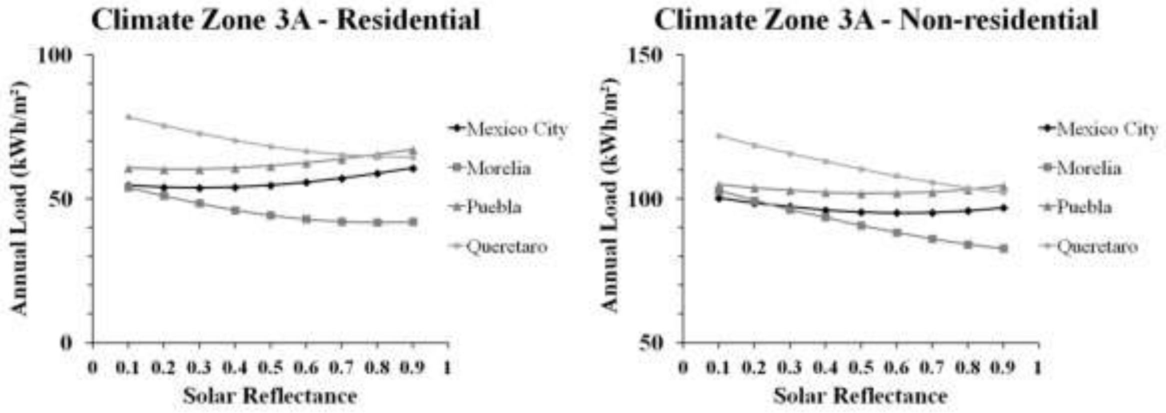

Fig. 5: Annual thermal load as a function of solar reflectance for cities in climate zone 3A

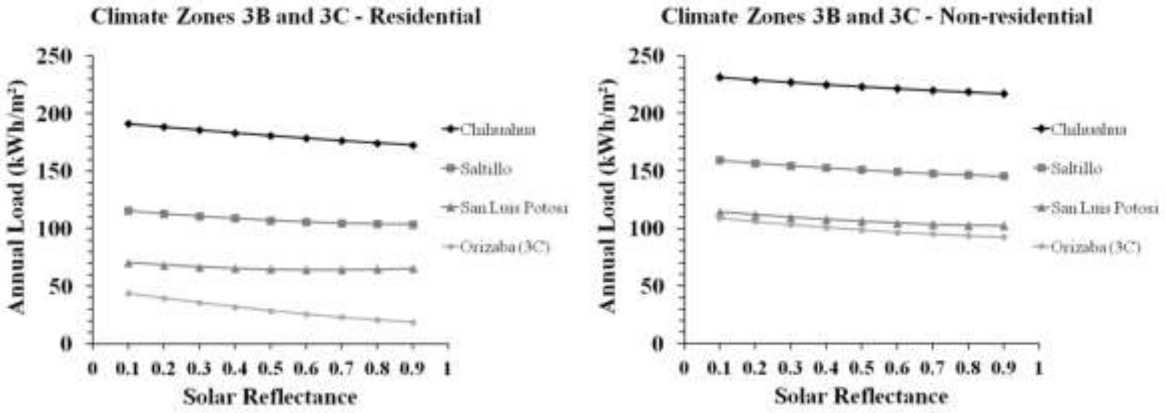

Fig. 6: Annual thermal load as a function of solar reflectance for cities in climate zones 3B and 3C

Climate zone 4 has drastically higher heating needs and lower cooling needs compared to the other zones. This results in relatively horizontal curves; SR has little effect on the annual load. In Toluca, heating needs actually dominate cooling needs and the normal relationship between SR and thermal load is inverted. Thus, the optimal value of SR for this city is very low (Figure 7).

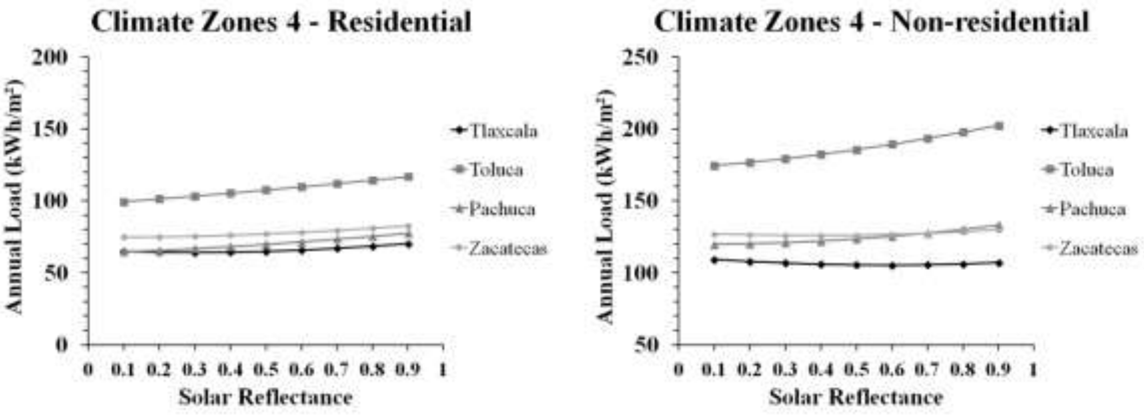

Fig. 7: Annual thermal load as a function of solar reflectance for cities in climate zone 4

3.3. Combined effect of thermal insulation and solar reflectance

The effect of insulation depends to a great extent on the use of an adequate value of SR in the roof. Figure 8 shows the annual energy load for three levels of insulation in the residential building, using climate data for Acapulco and Chihuahua. In Acapulco, insulation can have a very important effect only for low values of SR. If, on the other hand, roofs have a proper value of SR such as 0.9, then the added savings from insulation are negligible. In some cities with a significant cost of heating, such as Chihuahua, insulation has a significant effect even for optimal values of SR (Figure 8).

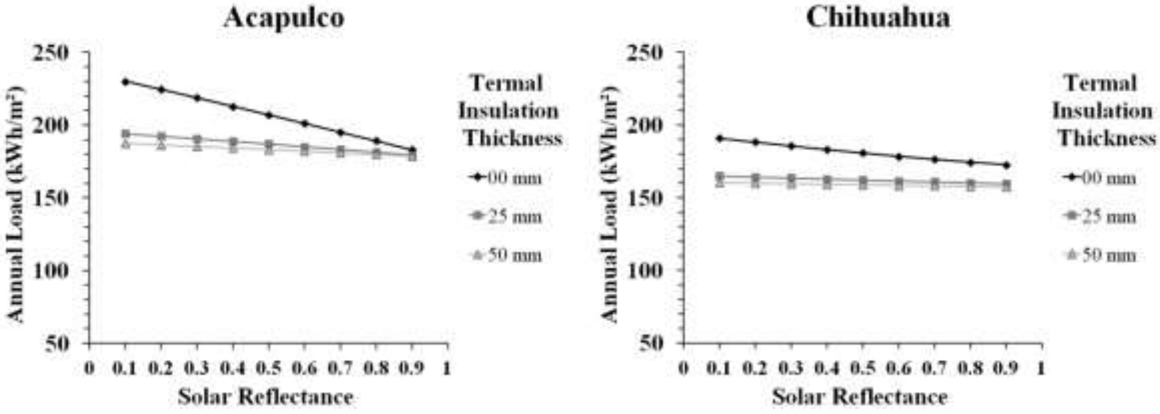

Fig. 8: Annual thermal load as a function of both solar reflectance and thermal insulation of roofs in Acapulco and Chihuahua

Although some improved coatings have SR values as high as 0.9, it is important to consider that this value tends to diminish over time. That is why we consider 0.8 to be the highest realistic value of SR. The value of SR has a strong effect on the benefits of insulation on the cost of energy needed to maintain the inside of buildings within comfortable ranges. Figure 9 shows the annual energy savings from 25 mm of insulation for 3 values of SR that correspond to coatings commonly used in Mexico (0.1 for black asphalt, 0.3 for red acrylic, and 0.8 for white acrylic). This figure shows how the savings from insulation vary greatly between different values of SR, especially in cities from climate zones 1 and 2. In a few cities such as Mexico City, Puebla, and Tlaxcala, the savings from insulation are almost the same for all three values of SR.

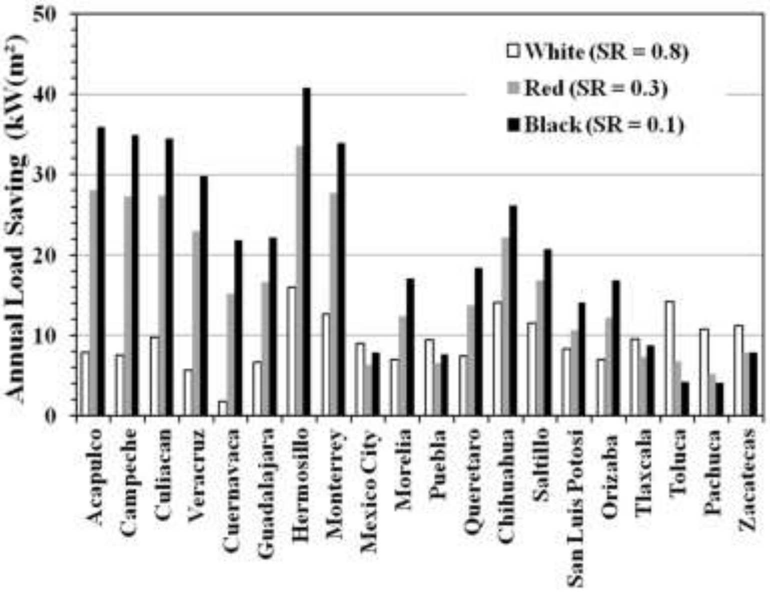

Fig. 9: The annual load savings from 25 mm of thermal insulation for three common values of solar reflectance of roof coatings used in Mexico

Insulation is a very costly investment, compared to the difference in cost between coatings with very different SR values. Figures 10 and 11 show the difference in energy costs between buildings with the best and worst coatings (black bars). The additional savings from insulation are shown in gray bars; these additional savings are calculated considering an optimal choice of coating.

In both building models it is apparent that for climate zones 1 and 2 the selection of a high SR value is a key factor in reducing the annual thermal load. Only in some cities from climate zone 2 (semi-arid climate, such as Monterrey and Hermosillo) can insulation be an important measure for increasing energy savings; this occurs at an SR value of 0.8.

Climate zone 3 (where optimal SR values vary between 0.3 and 0.9) and climate zone 4 (0.1 to 0.5) present a lower effect of SR on thermal load than climate zones 1 and 2. This is due to the penalty associated with using extreme SR values during the wrong period, such as a high SR when trying to heat the building or a low SR when trying to cool it. For some cities from climate zones 3 and 4, which have relatively high heating needs, the use of insulation is more important than the choice of SR—especially for non-residential buildings.

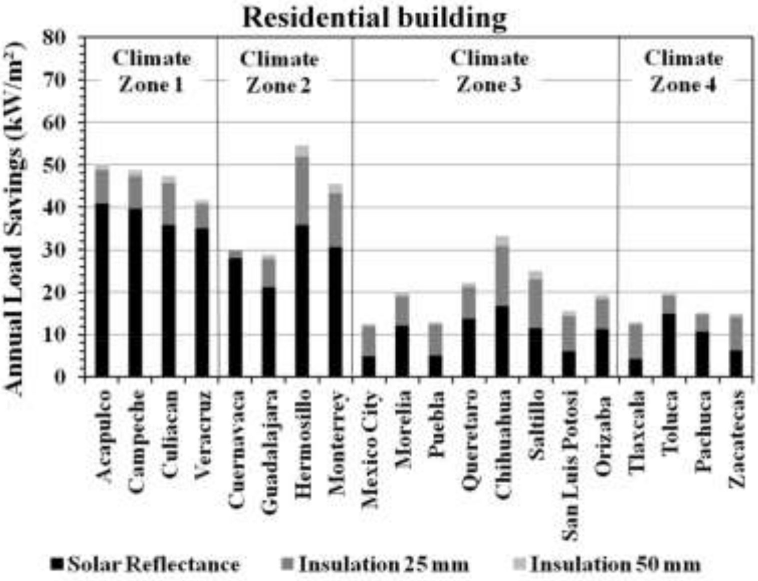

Fig. 10: Annual load savings achievable through solar reflectance optimization, followed by 25mm and 50mm of thermal insulation, in residential buildings

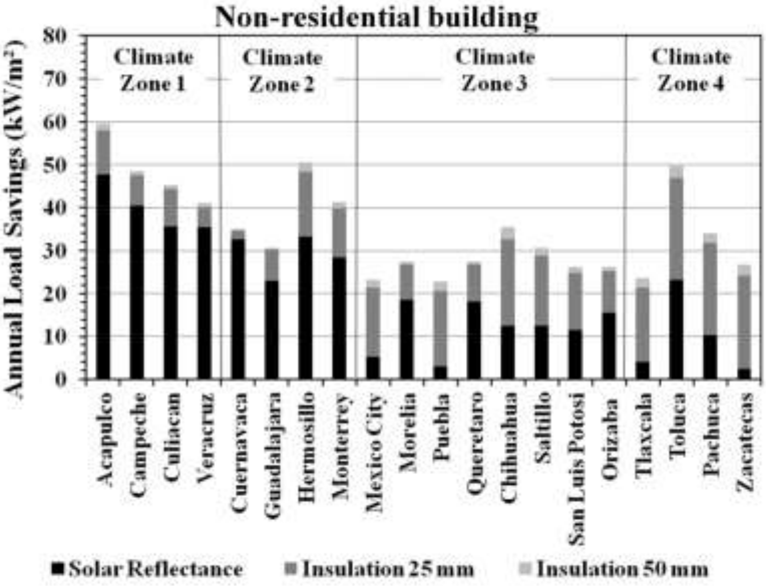

Fig. 11: Annual load savings achievable through solar reflectance optimization, followed by 25mm and 50mm of thermal insulation, in non-residential buildings

4. Conclusions

In warm climates with minimal heating needs, it is best to reduce energy consumption through adequately high values of solar reflectance. In Mexico, cool roof regulations that maximize the values of SR are justified in climate zones 1 and 2. The use of insulation can be suggested in cities with semi-arid climate that have heating needs during the winter, or required to replace the effect of a high SR in cases where buildings choose to have lower reflectances. This may be the case for buildings with heavily sloped rooftops, which can reflect a significant amount of radiation to neighboring buildings, but also for short buildings next to taller ones or for homeowners that simply want non-reflective roofs for aesthetic purposes.

The use of insulation is appropriate for climate zones 3 and 4, where heating is an important component of the thermal load. The effect of SR is very modest in some of these cities, which is why a deeper analysis is needed on whether it is useful to regulate a range of acceptable SR values. Insulation may be suggested—or even required for non-residential buildings—since it does create an important extra reduction in the energy load than can be obtained from proper choice of SR.

5. Acknowledgement

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