STUDY ON ROOF SYSTEM REFLECTIVITY AND NEAR-SURFACE AIR TEMPERATURES IN CHICAGO, ILLINOIS

By

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ABSTRACT

In June 2001, the City of Chicago revised its energy code. As a result, all low-slope roof systems constructed were prescribed to have a minimum thermal resistance along with an initial solar reflectivity of 0.65. After three years, the roof reflectivity was to achieve a minimum of 0.50 (washed or unwashed).

A Roofing Industry Alliance was formed and a study team was established to evaluate the on-site reflectivity values of low slope roof systems in Chicago. Further work helped develop solar reflectivity criteria for using light colored roof aggregate. This effort led the City of Chicago to change the solar reflectivity level in its energy code to a minimum (aged) value of 0.25 until 2009, pending a study of the impact of different roof systems' solar reflectivities on urban air temperatures.

This paper outlines the practical findings of Voogt and Krayenhoff regarding near-surface air temperatures in Chicago, as part of the Roofing Industry Alliance effort. It describes the modeling of roof systems and walls in Chicago's Downtown Loop area and in a dense, urban, residential area. The findings indicate that if all roof systems were changed from black (solar reflectivity of 0.06) to white (solar reflectivity of 0.65 or greater), a decrease in average annual daily air temperatures of less than 1° C would occur in the residential area.

In the Downtown Loop area, advection (horizontal air movement) significantly reduces the effects of summertime daily average and maximum air temperatures.

This paper also addresses theoretical temperature changes resulting from changing roof systems' reflectivity in both Downtown Loop and dense, urban residential areas.

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BACKGROUND

The City of Chicago made broad changes to its energy code in June 2001. The revised code contained sweeping changes for which the local building industry was unprepared. The changes included minimum requirements for thermal insulation of the building envelope, including roof systems, walls, exposed foundations and fenestration products (windows, doors and skylights). Roof insulation was to meet ASHRAE Standard 90.1-1989 values for the region.

Along with the new ordinance, the use of certified energy inspectors is also now required. Licensed architects and engineers are invited to become certified energy inspectors by attending mandated training seminars sponsored by the City of Chicago. The energy inspectors have to certify plans for new buildings, reroofing projects or any modifications to a building envelope. The design conditions mandated by the City of Chicago are found in Title 18 of the Municipal Code of Chicago (18-13.301 to 18-13.306).

Exterior design conditions cited for use by the new energy code include the following:

Winter, Design Dry Bulb (ºF)	-10º F
Summer, Design Dry Bulb (ºF)	92º F
Summer, Design Wet Bulb (ºF)	74º F
Heating Degree Days (HDD)	6151
Cooling Degree Days (CDD)	1015

Thus, Chicago's building inventory must withstand temperature variations of more than 100º F, (56º C). Furthermore, the number of heating degree days (HDD65) exceeds cooling degree days (CDD65) by a factor of +6. By comparison, other major U.S. urban environments have heating/cooling ratios that are different than Chicago's, as shown below.

U.S. City	**HDD 65**	**CDD65**	**HDD/CDD ratio**
Phoenix, AZ	1382	3647	-0.38
Honolulu, HI	0	4150	No heating required
Columbus, OH	5493	789	+6.96
Houston, TX	1346	2891	-0.47
Boston, MA	5775	695	+8.31
Tampa, FL	575	3047	-0.19
Chicago, IL	6151	1015	+6.06

The above data were derived from Appendix C, ASHRAE Standard 90.1-1989, "Energy Efficient Design of New Buildings Except New Low-Rise Residential Buildings," pages 130-134. The base temperature used for determining the number degree days of heating and cooling is 65º F (18º C).

The Chicago Energy Code also introduced minimum requirements for roof systems' solar reflectivity. The surfaces of low-sloped roof systems (2:12 or less) were to have a minimal solar reflectance of 0.65. At three years of age, these roof systems were to have a minimum of 0.50 solar reflectance value.

Medium-sloped roof systems (2:12 through 5:12) were to have minimum 0.15 solar reflectance regardless of age.

A minimum emissivity of 0.90 was also mandated for roof systems.

These requirements were intended to minimize the urban heat island (UHI) effect for the City of Chicago.

Exceptions to the energy code's roof system solar reflectivity requirements are permitted by providing roof systems or portions of roof systems that use solar panels, green roof systems and/or photovoltaic systems.

Solar reflectivity (sometimes called roof albedo) is the fraction of solar flux that is reflected. Thus, a dark or black roof surface will reflect little sunlight, perhaps 5 percent to 8 percent of the incoming sunlight for newly installed roof systems. White roof membranes can reflect large amounts of sunlight when new; some can achieve greater than 75 percent reflectivity. Solar reflectivity is most often stated as a percent value or between a range of 0.00 and 1.00. Practically speaking, the solar reflectivity for new roof systems in the U.S. ranges from 0.05 to 0.80.

Solar reflectivity is a measure of visible light from the sun, which constitutes less than 50 percent of the total solar energy received. Infrared (IR) energy constitutes more than 50 percent of the incoming energy; ultraviolet (UV) energy radiated by the sun accounts for less than 5 percent of the total. Solar reflectivity does not address the IR and UV components of solar insolation (flux).

RESPONSE OF ROOFING INDUSTRY ALLIANCE TO CODE CHANGES

The City of Chicago's changes to its energy code are far ranging, mandating new inspection and permitting processes along with severe civil penalties for noncompliance. Furthermore, few roofing manufacturers had products in 2001 that were verified to meet the minimum initial and aged solar reflectivity and emissivity values cited in the code.

An informal working group of roofing professionals was formed and includes manufacturers, contractors and design professionals, as well as members of the United Union of Roofers, Waterproofers and Allied Workers Local No. 11, Chicago Roofing Contractors Association (CRCA), National Roofing Contractors Association (NRCA), Asphalt Roofing Manufacturers Association (ARMA) and Roof Coating Manufacturers Association (RCMA).

This group, referred to as the Roofing Industry Alliance, held meetings with the City of Chicago Building Department and elected officials to ask for time to study the overall effect of the energy code changes. A two-phase program was laid out.

Phase I: Determine the range of roof system solar reflectivities existing in the Chicago roofing inventory, which roof materials hold their solar reflectivities and the effects new energy code have on the roofing labor force, as well as develop an interim proposal for solar reflectivity values.

Phase II: Study the effect roof systems have on the near-surface air temperatures in downtown Loop Area of Chicago and a dense residential environment. Report back with a final recommendation for solar reflectivity that is achievable for the Chicago area.

Results of Phase I Study

The Roofing Industry Alliance decided to survey existing roof systems in the Chicago area to determine their aged solar reflectance values. The types of roof systems surveyed included aggregate-surfaced built-up membranes, granule surfaced and smooth modified bitumen membranes, coated roof systems, and EPDM and CSPE single-ply roof systems. The age, description and solar reflectance values found are provided below.

Table 1: Solar Reflectance (SR) of Existing Chicago Roofs*

Age (years)	Description	SR (percentage)
15	Aggregate-surfaced BUR	25.3
22+	Aggregate-surfaced BUR w/ Heavy Ponding	16.3
22+	Aggregate-surfaced BUR w/ Blisters	15.5
10+	Aggregate-surfaced BUR	27.8
15+	Aggregate-surfaced BUR	17.1
10-15	Aggregate-surfaced BUR	19.7
10-15	Aggregate-surfaced BUR	19.3
3 Months	Smooth-surfaced APP – Fibrated AL 2:12 slope	57.7
13	Slate-surfaced APP	14.4
13	Slate-surfaced APP w/ 50 percent granule loss	8.7
13	Slate-surfaced APP w/ 90 percent granule loss	5.5
3	AL coated APP w/4:12 slope	25.9
1	45-mil Reinforced EPDM	10.3
1	45-mil Reinforced EPDM at dust in ponded areas	29.5
10	Ballasted EPDM	26.9
10	Beige concrete pavers	44.5
1 Week	White-coated CSPE	72.6
1	White granule-surfaced modified bitumen	30.5
4	Smooth-surfaced SBS – Fibrated AL coating	54.7
4	Smooth-surfaced SBS – Fibrated thin AL coating	39.7
6	Smooth-surfaced APP – Non-fibrated AL coating	45.6
8	Smooth-surfaced APP – Tan granules 3:12 slope	25.1
8	Smooth-surfaced APP – Tan granules at laps	16.2

* Measured by the D & S method, known as ASTM C1549, "Standard Test Method for Determination of Solar Reflectance Near Ambient Temperature Using a Portable Solar Reflectometer".

The solar reflectance data cited above includes aggregate-surfaced roof systems beyond 22 years of age and modified bitumen roof systems up to 13 years of age. These roof system types are predominant in the Chicago area, along with coated membranes systems and single-ply membrane systems. It was noted that the roof aggregate can, with proper roof drainage, self-clean and maintain initial solar reflectance value. Granule-surfaced roof membrane systems appear to be the next best in ability to self-clean. Backenstow 1987 specifically noted regarding single-ply membrane roof systems that black EPDM lightens up and white EPDM darkens with exposure and age. This is primarily attributed to airborne dirt settling on roof surfaces. The EPDM roof systems in this study showed that where airborne dust accumulated into ponded areas, the roof surface in those areas had a reflectivity of 29.5 percent, while the EPDM itself had a 10.3 percent reflectivity. New EPDM (black) typically has a solar reflectivity from 6 percent to 8 percent.

After observing the solar reflectivity values of the aged, aggregate-surfaced roof systems, the Roofing Industry Alliance decided to sample quarries in the Chicago area for light-colored roofing aggregate. Using an independent laboratory along with Oak Ridge National Laboratories (ORNL) for measurement, a surprising range of moderate reflectivity roofing aggregate was found to exist. A total of 11 different roofing aggregates samples were tested. Pea gravel aggregate ranged from 22.2 percent to 34.7 percent solar reflectivity (washed). Aggregate ballast had a solar reflectivity of 39.2 percent and limestone chips had a solar reflectivity of 37.6 percent (washed). The overall average solar reflectivity for washed roof aggregates from nine different sources was 33.1 percent.

ORNL was then asked to review the results of the roofing aggregate reflectivity study and calculate the energy savings between a roof system surface with a minimum reflectivity of 25% versus 50% (the latter being the value for aged reflectivity required by EPA's Energy Star roof products program for three-year old materials). Using these values ORNL calculated a potential energy savings of $40 per year for a 10,000 square foot (930 sq. meters) roof area. This study (Dupuis 2002) concluded that the minimal energy savings should be weighed against the direct cost of mandating light colored roof systems and the economic impact of eliminating more traditional built-up roof systems.

For smooth-surfaced, white single-ply membrane roof systems, solar reflectivity are known to degrade with exposure time, not holding their initial values. A report (Roodvoets 2004) regarding the long-term reflectivity of single-ply membrane roof systems was sponsored by SPRI and performed by ORNL. Roof systems with various initial reflectivities were exposed for three years in East Tennessee in the SPRI study. Reportedly, white single-ply roof systems experienced a loss of initial reflectivity of 25 percent to 50 percent, with most of the loss occurring within two years. Analysis indicated the parameters influencing the decrease in reflectivity include relative humidity, average daily temperature change, time, and the number of rain days. These parameters are believed to assist the formation of a thin film-like biological growth on roof surfaces, depending upon airborne dirt deposits and membrane plasticizers. As a remedy to such biological growth, Roodvoets 2004 suggest periodic power washing of the roof systems at a cost of one cent per square foot.

A summary of the finds from the Roofing Industry Alliance's Phase I study follows:

- Moderate reflectivity of 0.25 can be achieved with current locally available roof aggregates and some of the granule-surfaced products available.

- Significant movement away from smooth, black roof coverings will take place in the marketplace.
- Coatings can also be used to bring existing roof systems up to moderate or high levels of solar reflectivity.
- Highly reflective single-ply roof membrane systems will continue to be used, although the aged reflectivity and demonstrated longevity of some recently developed systems is not quantified.
- New products, coatings or process methods may bring about higher solar reflectivity values for some of the existing roof systems.
- Chicago's union labor force would not be disrupted as they construct all types of roof systems.

The Phase I data supporting an interim roof reflectivity value of 0.25 were submitted to the City of Chicago's Building Department by Rene Dupuis on November 24, 2002. After reviewing the findings, the Building Department set forth a minimum initial and aged roof reflectivity value of 0.25 that would change to 0.65 effective January 1, 2009. This decision was based on a practical, as well as realistic assessment of what was learned in Phase I. The Roofing Industry Alliance agreed to undertake Phase II regarding the effects of roof system reflectivity on the air temperature surrounding these buildings and Chicago's urban heat island. The City of Chicago's Building Department has agreed to review the findings of the Phase II study and may issue a different minimum solar reflectivity value for roof systems other than the current 0.25 value or the 0.65 value to be in-place in January 2009.

<u>Results of Phase II Study</u>

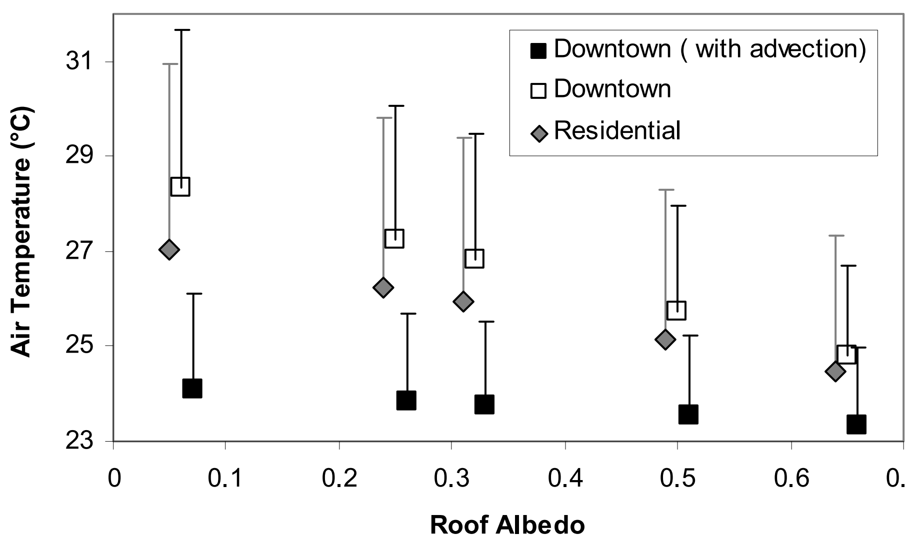
The Roofing Industry Alliance retained the services of Dr. James Voogt and E. Scott Krayenhoff, BSc. (Hons.) of the University of Western Ontario to run model simulations urban air temperatures in the Chicago area as they are effected by changes to solar reflectivity of roof systems' surfaces. The study by Voogt and Krayenhoff considered two land use areas of Chicago: the highly built-up downtown environment and an urban residential area (Norridge, Illinois). The downtown environment chosen was along LaSalle Street where the buildings and street canyons represent the Chicago Downtown Loop area. The residential area modeled closely spaced homes with some vegetation. The urban surface and urban canopy layer air volume modeled by Voogt and Krayenhoff used the Town Energy Balance (TEB) of Masson (2000). According to the researchers, the overlying atmospheric boundary layer and troposphere were modeled using the Oregon State University (OSU) one-dimensional planetary boundary layer.

Model simulations were run for three-day periods of clear sky conditions in summer, winter and spring. Simulations assumed no advection (horizontal import or export from the column), which provides a worst-case hypothetical scenario. Researchers also were asked to include a simulation for a normally anticipated summertime wind or lake breeze for comparison.

The urban (LaSalle Street) and residential (Norridge) areas were physically modeled for building height, height/width ratios, wall area/roof area and building plan area fraction. Four-layer roof system models were used, including a BUR roof membrane with a two layer insulation system. The roof membrane accounts for two layers; the top surface and the roof membrane itself. The walls also used a four-layer system; weighted averages were used to reflect different wall system constructions, including windows. The average product of thickness and heat capacity were used to represent the variety of building constructions present. The streets were similarly modeled, assuming an asphalt overlay was used to cover an original concrete pavement.

The results of the Voogt and Krayenhoff study are shown in Figure 1, where we see the effects of different roof sysem reflectivity (albedo) values on the near-surface air temperatures for the Downtown Loop area (LaSalle Street) and the urban, residential area (Norridge). The air temperatures values are at 45 meters off the ground in the downtown street canyon and at 15 meters off the ground in the residential area. The daily averages are represented by symbols in Figure 1 and the daily maximums by the vertical bars. Symbols are offset by up to 0.01 albedo units to avoid over plotting. Day 2 results are shown of the three-day run. These results are for clear days with no wind or horizontal movement of air (advection) in the residential case. The urban model was run without wind and with a lake breeze effect. Wind was found to have a substantial effect and help negate the effect heat absorption may have on the urban heat island.

Figure 1: Summertime Daily Average and Maximum Air Temperature for Roof System Reflectivity Simulations Conducted in the Urban (With and Without Advection) and Residential Areas



The model does not account for all the heat energy from HVAC units operating, vehicle emissions, engine heat from street traffic or other forms of heat released to the atmosphere from human activities. This would include all forms of combustion using fossil fuel. All this unaccounted energy is referred to as "anthropogenic heat." Estimates of urban anthropogenic heat and its effect on the heat island have been made by Sailor 2003. Heat energy of this type appears to contribute 0.4º C to the daytime heat island (air surrounding the street environment) and 0.8º C at night.

Pavements affect the air temperature because they absorb solar energy, but this is factored in by the model. However, Pomerantz 2000 stated for a large city increasing the albedo of the pavement from 0.1 to 0.35 may decrease in summertime air temperatures by 0.6º C. Pomerantz 2000 also states "the effects of albedo changes will be washed out where the wind is high."

Chicago has clear conditions 23 percent of the time (up to 0.3 cloud cover) with 29 percent partly cloudy and 48 percent cloudy. A summer day with no wind, clear air and no cloud cover is the worst case scenario. This event rarely occurs, as heating of the urban and suburban areas typically bring about surface winds. Therefore, the results in Figure 1 represent a theoretical worst case, assuming no wind (advection), not a commonly occurring situation in the Chicago area. With advection, the difference between a roof system with a solar reflectance of 0.06 and 0.65 is less than 1º C on air temperature. This is in a range with the heat energy caused by human activity in HVAC units operating, vehicles, etc. Because many of the models used to date to study urban heat islands did not account for wind or anthropogenic heat, these results are not surprising.

Discussion

The urban area air temperatures seen in Figure 1 vary significantly between no wind (still air) and the presence of normally occurring winds, such as a lake breeze. Wind currents are known to be present at the street level in large U.S. cities as the large buildings block the flow of a breeze, turning the streets into wind tunnels. Air is also moving across roofs' surfaces at rates that vary significantly during different periods of the day. Early mornings on roofs are known to be the calm during summer days. As the typical day progresses, winds typically pick up as the sun's heat is absorbed by different surfaces at different rates, depending on the surrounding buildings, soil, land form and a number of other variables.

Anthropogenic heat (Sailor 2003) is another factor that is real and present, but it is not accounted for in the Voogt and Krayenhoff study. Another factor not included is changes in pavement reflectivity known to be washed out by wind. The same effect will occur on roof systems' surfaces.

The ability of roofing aggregates to hold their initial, installed values of solar reflectance was previously unaccounted for and offers a solution without great burden on the roofing industry for those roof systems using aggregate surfacing. Improved granule formulations are forthcoming. When applied to roof surfaces with positive slope, granule-surfaced roof systems will self-clean with rainwater, but not as well as aggregate materials that truly have vertical definition. Roof coatings are capable of providing moderate to high solar reflectance values while protecting the membrane from ultraviolet exposure.

Smooth-surfaced roof membranes, such as white single-ply membranes, are known to provide a relatively high reflective roof surface. Smooth-surfaced materials have the most difficult time of self-cleaning unless they have carefully designed drainage to remove the airborne dirt totally with water flow. Some current, white, single-ply membrane roof system inventory develops a biological growth within a thin dirt film, degrading its solar reflectance. Because of this and the inability to have vertical dimension to self clean in a rainfall, it is best to keep the initial reflectance as high as possible because it diminishes and hopefully levels off.

The notion of washing a roof surface for a dollar per square (9.3 sq. meters) as stated in Roodvoets 2004 is unachievable when you take into account the true cost of labor and overhead, including providing water to a roof (with pressure), washing equipment and safety procedures to be practiced at the roof perimeter, not to mention the inherently slippery nature of single-ply membranes. A survey of actual costs for roof cleaning was conducted by the Roofing Industry Alliance from the upper Midwest to Texas and revealed the lowest cost to be $4.50 per square (9.3 sq. meters) for a single-story, big box retail store with water readily supplied. Roof cleaning costs quickly escalate to $11 to $15 per square (9.3 sq. meters) for buildings with multiple roof levels, in small-towns or in shopping mall environments. Washing a roof surface on downtown high rise buildings in Chicago will cost $25 to $35 per square (9.3 sq. meters), depending on a number of factors. Washing a roof is clearly not an expense a typical owner wants to incur. The roofing industry has attempted, largely unsuccessfully, to convince building owners to inspect their roof systems at least once or twice a year for preventative maintenance purposes. For the roofing industry to insist that building owners now wash their roof systems is beyond realistic; most building owners want less to do with roof maintenance and its costs, not more.

The roofing industry is, however, making progress toward a better understanding of solar reflectivity and how roof systems can respond to this attribute. Cool, non-white colors are now available and more are in development, showing reflectivity values up to the 0.25 level for shingle applications. This would offer a good alternative to the values the current color palates shingles now have. We believe this and other developments will make a wide range of options available in the near future, while the industry re-engineers its existing systems to provide an increase in solar reflectivity. The industry also has some black membranes that weather exceptionally well; we need to re-engineer these products with proven coating systems that will provide for adequate solar reflectivity and allow their continued use.

The drive for higher roof system solar reflectivity cannot be carried on the back of one single roof system type or based solely upon one value for initial reflectance, as the variables of design, construction, environment and maintenance preclude that simple thought. When coupled with a better understanding of how each roof system and its top surfacing deals with dirt, pollution and water runoff, it is easy to see that many options are available for providing roof surfacings that will help mitigate the urban heat island effect. Models help us understand which variables in our urban features contribute to the excess heat energy. The Roofing Industry Alliance's study has shown that wind, even a light breeze, effectively diminishes the effect roof reflectivity has on the urban heat island. Clearly, there is room for a variety of roof systems to work in the aged solar reflectance range of 0.25 to 0.50. It just depends on how the problem is approached and the understanding of the inevitable effects of products' diminished reflectivity (which will occur with some systems) and the environment. Wind uplift resistance and the prediction of wind uplift forces is an everyday activity for designers, roofing contractors and manufacturers. As a practical matter, wind is an every day event on the roof. These same winds were seen to reduce significantly the air temperature rise associated with heat-absorbing materials and diminish the real impact roof systems have on the urban heat island.

Summary and Conclusions

Phase I has shown aggregate-surfaced roof systems provide a moderate solar reflectance value based on materials already available in Chicago. Light-colored granules also can achieve this level of reflectivity. Coatings and white single-ply membrane roof systems can also achieve higher reflectivity levels, albeit they will suffer fallback as they age.

The Roofing Industry Alliance's recommendation to the City of Chicago's Building Department was to use an interim solar reflectance value of 0.25. The City has agreed to implement this recommendation until 2009.

On the basis of a practical evaluation of the benefits of roof reflectivity on buildings' energy cost savings and the effect on the urban heat island, the authors conclude that increasing the solar reflectivity requirements in the Chicago Energy Code beyond the current level of 0.25 will provide little useful benefit in the urban area of Chicago. The cited ORNL research shows increasing the solar reflectivity of roof surfaces from a level of 0.25 to 0.50 on a hypothetical 10,000 sq. ft. (930 sq. meters) building in Chicago would result in an energy cost savings to the building owner of only about $40 annually, or less than $0.01 per square foot of roof area per year.

For the Downtown Loop area of Chicago, the work of Voogt and Krayenhoff shows an increase in reflectivity (0.25 to 0.65) may result in a reduction of summertime daily average temperature of less than 3º C. However, this temperature is reduced to less than a 0.5º C increase when advection, such as would be experienced with a summertime lake breeze, is considered.

For dense, urban residential areas, such as the model for Norridge developed by Voogt and Krayenhoff, some benefits of the use of reflective roof surfaces to minimize the urban heat island effect were seen. Given that the impetus for the City of Chicago to adopt its increased reflectivity requirements were originally intended to address the urban heat island effect in the city center (Downtown Loop area) and not the outlying residential area, this finding warrants further investigation.

In this study, the authors found different roof surface conditions respond differently to environmental conditions. For example, aggregate-surfaced roof systems will exhibit a solar reflectance at or near the original value. For the quarries in the greater Chicago area, aggregate was found to have an average solar reflectance of approximately 0.33. At the same time, single-ply membrane roof systems and smooth-surfaced roof systems with field-applied coatings are available with relatively high solar reflectance values. However, considering the effects of aging, dirt accumulation and discoloring of these system types, the effective solar reflectance of these coated roof systems should fall in the range of 0.25 to 0.50.

When coupled with wind and anthropogenic heat, moderately reflective roof surfacings, when looked at realistically, effectively upgrade the solar reflective canopy of the urban area. With this approach, the roofing industry can move toward a reflective roof surface solution to assist in mitigating the urban heat islands.

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