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PRACTICAL ISSUES FOR USING SOLAR-REFLECTIVE MATERIALS TO MITIGATE URBAN HEAT ISLANDS

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Abstract—Solar-reflective or high-albedo,* alternatives to traditionally absorptive urban surfaces such as rooftops and roadways can reduce cooling energy use and improve urban air quality at almost no cost. This paper presents information to support programs that mitigate urban heat islands with solar-reflective surfaces: estimates of the achievable increase in albedo for a variety of surfaces, issues related to the selection of materials and costs and benefits of using them. As an example, we present data for Sacramento, California. In Sacramento, we estimate that 20% of the 96 square mile area is dark roofing and 10% is dark pavement. Based on the change in albedo that is achievable for these surfaces, the overall albedo of Sacramento could be increased by 18%, a change that would produce significant energy savings and increase comfort within the city. Roofing market data indicate which roofing materials should be targeted for incentive programs. In 1995, asphalt shingle was used for over 65% of residential roofing area in the U.S. and 6% of commercial. Built-up roofing was used for about 5% of residential roofing and about 30% of commercial roofing. Single-ply membranes covered about 9% of the residential roofing area and over 30% of the commercial area. White, solar-reflective alternatives are presently available for these roofing materials but a low-*first*-cost, solar-reflective alternative to asphalt shingles is needed to capture the sloped-roof market. Since incoming solar radiation has a large non-visible component, solar-reflective materials can also be produced in a variety of colors. © 1997 Elsevier Science Ltd.

Key word index: Building materials, solar radiation, solar reflectance, heat island, cooling load, air-conditioning, energy efficiency, roofing.

INTRODUCTION

Urbanization alters the Earth's surface, causing city-scale climate modification. Heat transfer from absorptive surfaces within the city and the interception of outgoing long wave radiation by buildings contribute to create "urban heat islands." The removal of natural vegetation can also contribute to urban heat islands by reducing shading and evaporative cooling. In summer, air-conditioning is used to maintain indoor comfort, thereby increasing energy costs and pollution costs. Where air-conditioning is not used, there is discomfort and even death, as occurred in the Chicago heat wave of 1995. There is also evidence that high ambient air temperature over a heat island also alters urban air chemistry, and consequently increases smog formation (Taha, 1997).

Shade trees and solar-reflective surfaces may be used as inexpensive strategies for mitigating urban heat islands. This article focuses on solar-reflective materials, which maintain low surface temperatures in sunlight and thereby have direct and indirect effects on cooling energy use. Direct effects refer to the energy savings of an individual building achieved by increasing the exterior albedo and reducing heat transfer through the building envelope. Experiments in California and Florida have produced summer direct cooling energy savings of 10–70% (Akbari *et al.*, 1993; Parker *et al.*, 1993). In theory, increasing the overall albedo of a community results in lower ambient air temperature and a consequent indirect reduction in cooling demand. The effect of solar-reflective surfaces on energy use is expected to be greater in the summer than in the winter because of lower winter sun angles and more cloud cover in winter, so that increases in winter heating are expected to be negligible for most climates dominated by cooling loads (Taha *et al.*, 1988). Nevertheless, in areas with cold climates implementation should not proceed without careful investigation of the possible heating penalty from high-albedo roofs.

BACKGROUND

Summer urban heat islands with daytime average air temperatures 2.5°C (5°F) higher than surrounding rural areas are found throughout the world. In Los

*Albedo is the hemispherical reflection of radiation, integrated over the solar spectrum (0.3–2.5 mm). It includes specular and diffuse reflection.

Angeles, summer monthly average temperatures have been increasing at a rate of 0.5°C (1°F) per decade since 1940 (Rosenfeld *et al.*, 1995). Similar warming trends have been documented in other cities. Nationwide, this warming has caused an increase of 1.5–3.0% in peak cooling demand for each 0.5°C (1°F) increment. On a hot afternoon, about 10 gigawatts (GW) of the U.S. air-conditioning load results from the heat island effect. This additional power generation is worth about $1 million/h and costs electric-rate-payers $1 billion yr^{-1} (Akbari *et al.*, 1990). Although black pavement and roofing are contributing to these high costs, there are significant barriers to changing traditional practice, especially when the decision-maker is not aware of the ensuing costs to the community. Despite the barriers, creating cool communities has become a priority with new targets to reduce carbon emissions in response to global climate change, such as those outlined in the U.S. Climate Change Action Plan (Option #9).

Creating cool communities requires lowering the average surface temperature of the city so that there is less surface-to-air heat transfer. Vegetation, which maintains a cool surface temperature because of evaporation, is one component of a cool community. For building and pavement surfaces in the sun, surface characteristics such as albedo, emissivity, and roughness, are relevant. For a surface under the sun and insulated underneath, the equilibrium surface temperature, T_s is obtained from

$$(1 - a)I = \varepsilon\sigma(T_s^4 - T_{sky}^4) + h_c(T_s - T_a)$$

- a solar-reflectivity or albedo of the surface
- I total solar radiation incident on the surface, W/m^2
- ε emissivity of the surface
- σ Stefan–Boltzmann constant, 5.6685×10^{-8} $W\,m^{-2}\,K^{-4}$
- T_s equilibrium surface temperature, K
- T_{sky} the effective radiant sky temperature
- h_c convection coefficient, $W\,m^{-2}\,K^{-1}$
- T_a air temperature, K (ASHRAE, 1989).

Most urban surfaces that are not metallic exhibit high emissivity. The most practical parameter in equation (1) to alter on a large scale is albedo. At the same time, it is necessary to avoid low-emissivity materials, such as bare metals and aluminum coatings. Adding vegetation is also an effective means of lowering urban surface temperature.

AIR QUALITY

The heat island phenomenon has a number of effects on urban air quality, making it difficult to quantify the results of a large-scale mitigation effort. Air-conditioning used to compensate for summer heat islands results in emissions of air pollutants, including carbon dioxide, a "greenhouse" gas, and nitrogen oxides, ozone precursors. Compounding the problem of air pollution is the high air temperature of the heat island. High air temperature is connected to increased emissions of reactive organic hydrocarbons, also ozone precursors, from automobiles and vegetation. High air temperature will also accelerate the formation of smog. For an overview of the effects of heat islands on urban ozone formation, refer to Cardelino and Chameides (1990). Rosenfeld *et al.* (1995) estimate that the probability of smog increases by 2–4% per °C. Below 21°C (70°F) there are almost never smog "episodes" in Los Angeles. Above 23°C (73°F), smog episodes are evident and exceed 50% probability by 32°C (90°F). Eliminating the 3°C (7°F) heat island will lower the average air temperature to 22°C (71°F), and may greatly reduce smog incidents. The impacts of large-scale albedo changes on ozone air quality in the Los Angeles area have been modeled by Taha (1997).

POTENTIAL FOR INCREASING URBAN ALBEDO

An investigation of the surface area in Sacramento, California, shows that the potential for altering urban albedo is significant. We used data describing the land-use of Sacramento (Orvis, 1992) and aerial photographs to estimate the proportion of each land-use category occupied by vegetation, and light and dark roofs and pavement. Table 1 shows the composition of Sacramento, by area, which we found to be 28% rooftop, 16% streets and 14% other impervious surfaces, such as parking lots, driveways, and sidewalks. The results are comparable to those of a similar but earlier study (Myrup and Morgan, 1972). Based on the values in Table 1, and the albedos typical of urban surfaces, we have estimated the potential for modifying the urban albedo to be 18% in Sacramento (Table 2).

EXISTING SOLAR-REFLECTIVE MATERIALS

There are a number of high solar-reflectance materials presently available. Roofs and walls may be recoated with white surface coatings. Built-up roofs may be surfaced with a white roof coating or white gravel. Single-ply roofing membranes are available in white. Residential roofs can be shingled with white metal shingles or white tiles (concrete or clay). Walls may be recoated with white surface coatings or resided with light-colored siding. High-albedo pavement includes concrete and conventional asphalt with white aggregate.

Roofs

A roof may be a continuous membrane or a series of individual, overlapping units. Continuous membranes are typically used on flat or gently sloping roofs, while overlapping units are installed on a slope so they can shed water. Continuous roofing includes

Table 1. Estimates of the surface composition of Sacramento, CA

Surface type	Residential landuse (58% by area) (%)	Commercial/ industrial (32% by area) (%)	Area-wide average[a] (%)
Roof	33	27	28
Dark color roof	29	10	20
Light color roof	4	17	8
Roadway	16	19	16
Impervious other[b]	7	30	14
Dark color	1	29	10
Light color	6	1	4
Green[c]	44	24	43

[a]Includes schools, parks, open space and freeways, as well as residential and commercial/industrial areas.
[b]Includes parking lots, driveways, sidewalks, etc.
[c]Includes tree canopy.

Table 2. Potential for modifying the albedo of Sacramento, California using Table 1, Column 4

Surface type		Area (% of city)	Typical albedo (%)	Δ Albedo achievable (%)	Total Δ albedo (%)
Roadways	dark color	16	5–40	30	5
Roofs	dark color	20	5–10	50	10
	light color	8	50–80	0	0
Impervious other[a]	dark color	10	5–15	30	3
	light color	4	35–40	0	0
Total		58	NA	NA	18

[a]Includes parking lots, driveways, sidewalks, etc.
Note: Based on the values in Table 1, and the solar-reflectances typical of urban surfaces shown here in Table 2, we have estimated the potential for modifying the solar-reflectance of Sacramento to be 18%.

(1) built-up membranes – alternating layers of bitumen and felt that are usually covered with a surfacing such as gravel, mineral granules or roof coating; (2) liquid-applied membranes – roll-on or spray-on flexible coatings; (3) single-ply membranes – sheets of modified bitumen or of polymeric materials. Overlapping units include shakes, shingles, tiles and panels that are mechanically attached to the substrate (1991 Sweet's Catalog File, 1990).

Walls

Estimates of the potential for altering the urban albedo of Sacramento shown in Table 1 are based on a two-dimensional analysis and do not consider vertical surfaces like walls. Walls absorb radiation at low sun angles, and thus are also targets for albedo modification. West and south-facing walls in particular may contribute significantly to cooling loads. Walls are typically repainted every ten years or so, and at the time they are repainted a white paint may be selected in place of a darker color for no additional cost. The same is true for exterior siding.

Pavements

In the United States, hot mix asphalt pavement, also called bituminous or asphaltic concrete, is commonly used to pave city streets. It consists of a mixture of liquid asphalt cement and aggregates that have been processed to meet certain specifications. Also known as "blacktop," hot mix asphalt is visibly absorptive at initial installation, with an albedo of approximately 5–10%. As it wears, the aggregate in the pavement becomes exposed and oxidation causes the binder to fade, together resulting in an albedo increase to approximately 15–20%.

Conventional pavements tend to be absorptive, but there are nevertheless possibilities for creating solar-reflective pavement. One technique for light-colored pavement is to use white or light colored aggregate in an asphalt binder. Light-colored aggregates that are suitable for asphalt pavement mixtures include high silica gravel, quartz, white stone, white marble, and some types of granite.

Two types of concrete overlays are also used in the U.S.: a thin bonded overlay of about 3–5 in., and an unbonded full-depth concrete inlay, usually 8–13 in. thick. The bonded overlay is usually added to a distressed but otherwise sound pavement surface or to a pavement that needs additional structural capacity for future traffic needs – the process is commonly referred to as 'white topping.' The unbonded inlay is essentially a complete new pavement laid over an old

Table 3. Low and high solar-reflectance options for typical roofing materials

Low solar-reflectance option			High solar-reflectance option		
Description	Albedo (%)	Average cost[a] ($ ft^2)	Description	Albedo (%)	Additional cost[b] (% of avg. cost in column 2)
Sloped roofs					
Composite asphalt shingle; fiber-glass asphalt shingle; organic asphalt shingle	5–15	0.95–1.92	White asphalt shingle with "premium" white granules	35	< 1%
Clay tile	25–35	7.22–9.55	White painted clay or concrete tile	70–80	35%
Concrete tile	10–30	3.17–4.80	White concrete tile	70–80	< 20%
Fiber-cement shingle	10–30	2.84	White fiber-cement tile	60–80	0
Unpainted metal (steel, aluminum) shingle	70[c]	3.49–6.00	White painted metal shingle	55–80	0
Flat or low-slope roofs					
Built-up roof with dark gravel;	5–10		Built-up roof with white gravel;	40	0
Built-up or coal tar roof with smooth asphalt surface;	5–10	1.25–2.13	Built-up roof with gravel and cementitious coating;	60	< 20%
Built-up roof with aluminum coating	30–55[c]		Smooth surface built-up roof with white roof coating	70–80	< 30%
Black single-ply membrane (EPDM, CPE, CPSE)	5–10	1.06–2.01	White single-ply membrane (EPDM, CPE, CPSE);	70–80	20%
			White coating on a black single-ply membrane	70–80	< 30%
Modified bitumen roof with mineral-surface cap sheet	10–20	1.44–1.84	White cementitious coating over a mineral surface cap sheet	65	< 20%
Unpainted metal roof	70[c]	1.72–3.74	White painted metal roof	55–80	0

[a]Average installed cost, including materials and labor. Sources: for all roofs except concrete tile: R.S. Means, *Assemblies Cost Data 1996*, R.S. Means Company, Kingston, MA, 1995. For concrete roof we used a supplier's estimate of material cost and R.S. Means estimate of installing a clay tile roof.

[b]Additional costs are rough estimates of the additional installed cost, based on calls to manufacturers.

[c]Unpainted metal and aluminum coatings exhibit low emissivity, resulting in higher surface temperatures in sunlight than their albedo would suggest.

Note: The first column shows typical low solar-reflectance roofing materials. For each material we give the albedo range (for non-white varieties), the installed cost, alternative high solar-reflectance options for the same type of roof, the albedo of the alterntive roof, and the additional cost for choosing the high solar-reflectance option.

one after grinding, and is not included in our analysis (Renier, 1987).

SELECTION CRITERIA FOR HIGH-ALBEDO MATERIALS

Full solar spectrum albedo

Light-colored surfaces,† such as white paint and concrete, are the most obvious and readily available choices for increasing urban albedo. But since roughly half of the solar radiation reaching the earth's surface is near-infrared radiation, significant improvements in conventional colors are also possible (Berdahl and Bretz, 1997).

Albedo before and after weathering

Not just the initial solar-reflectance but the solar-reflectance over the lifetime of the surface bears consideration. Dark roofing materials tend to increase in albedo over time, because of dirt collection and asphalt oxidation. In contrast, solar-reflective roofs decrease in albedo as dirt collects on the surface. A twenty-five sample survey of existing white-coated roofs found a first-year decrease in solar-reflecivity of about 15%, followed by a 2% annual decline in solar-reflectivity in subsequent years. The decline in solar-reflectance over time may vary depending on the material. In this survey, a cementitious coating on gravel surface was found to be a particularly attractive solar-reflective roofing option because of low cost and only a minor decrease in albedo over time (Bretz and Akbari, 1997).

†Although the color of a surface is only indicative of its visible reflectance, light-colored surfaces tend to also be reflective in the near-infrared. Before using a material for heat island mitigation, albedo should be measured. We use the terms "white" and "light-colored" in this paper to mean high-albedo.

Emissivity

In addition to albedo, the emissivity of a surface affects surface temperature, as shown in equation (1). A low-emissivity material maintains a higher surface temperature in the sun than a high emissivity material with the same solar-reflectance. Low-emissivity materials include many aluminum coatings and unpainted metal shingles or panels.

COSTS

Roofs

High-albedo alternatives to conventional roofing materials are usually available, often at little or no additional cost. For example, a built-up roof is typically surfaced with a protective layer of mineral granules, gravel or coating. In this case, choosing a solar-reflective surfacing at the time of installation should not add to the cost of the roof and will provide the building resident with benefits from energy savings and increased comfort. High-albedo roofing options that require an initial investment may be more attractive in terms of life-cycle cost than conventional low-albedo alternatives. Usually, the lower life-cycle cost is because of longer roof life and/or energy savings. Table 3 lists additional costs for increasing the solar-reflectance of various roofing materials.

Pavements

The cost of pavement aggregate is dependent upon local availability, since shipping aggregate is expensive. If white aggregate is not locally available, we assume the cost of aggregate for the top layer of the pavement may increase by about 50%, increasing the initial cost of resurfacing by about 12%, and the initial cost of repaving by about 2%. Assuming that the light-colored aggregate is locally available, the practice should not add to the cost of the pavement. To create a solar-reflective surface, the aggregate must be exposed. Aggregate becomes exposed as pavement wears or it can be rolled into the top layer of the pavement, as with hot-rolled pavement, or chip seals.

Table 4 lists costs and solar reflectances of several pavements. The costs are for repaving an existing city street in the Sacramento area, and do not include the cost of preparing the area for paving.

Concrete pavements have higher initial costs than equivalent asphalt pavements, but typically last longer and have lower maintenance costs. They are especially suited for parking lots and driveways, where access to underground utilities is not necessary. White cement concrete offers a higher solar-reflectance than does standard concrete. Although white cement concrete is more expensive than the standard variety, in some cities the indirect cooling energy savings may justify the expense.

It appears that most light-colored surfaces are equivalent in cost to conventional dark surfaces and may last longer because they are less susceptible to the damaging effects of solar radiation and thermal shock. Although we have found no quantitative data to support this hypothesis, it is common knowledge among roofing professionals that white asphalt shingles last longer than dark asphalt shingles. Since "white" asphalt shingles are in fact quite absorptive (75% absorptive) when compared to white paint (25% absorptive), it would seem that small improvements in albedo can significantly affect service life.

PROGRAMS TO PROMOTE THE USE OF HIGH SOLAR-REFLECTANCE MATERIALS

Tables 5 and 6 show estimates of the percentages of various new roofs by area for the United States. Given these percentages, marketing programs should be aimed at asphalt shingle, single-ply roofing and built-up roofs, since these accounted for over 80% by area of new roof cover in 1995. For residential roofing, asphalt shingle and single-ply systems cover the largest area of new roofing, and for the commercial sector built-up roofing and single-ply membranes are most extensive.

Programs that would support solar-reflective urban improvement include: labeling of paints and roofing materials according to their temperature in full

Table 4. Cost and albedo estimates for various pavements from Martien *et al.* (1989) with updated lifetimes

Pavement type	Service life (yr)	Cost 94\$/m^2	Albedo (new) (%)	Albedo (weathered) (%)
Asphalt (18 cm)	15	18	5–10	15–20
Whitetopping (13 cm)	25	18	35–40	25–30
Asphalt with light aggregate (18 cm)	15	18	5–10	35–40
Whitetopping with white cement[a]	25	21	70–80	40–60

[a]Gray (1990).

Note: The costs are for repaving an existing city street in the Sacramento area, and do not include the cost of preparing the area for paving. We compare pavement thicknesses with similar load-bearing capacity (a thinner layer of concrete is needed to match an asphalt pavement).

Table 5. Market share of commercial roofing systems[a] in the U.S., 1995 (Source: NRCA, 1996)

	Reroofing		New Construction		Total
Roofing type	B \$	% of area	B \$	% of area	B \$
Built-up roofing (BUR)	2.82	26.8	0.85	23.5	3.67
EPDM (single-ply)	2.26	24.6	0.96	31.1	3.22
Modified bitumen—APP	1.14	11.7	0.22	7.0	1.36
Modified bitumen—SBS	1.16	11.5	0.32	9.9	1.48
Metal-structural	0.08	0.7	0.04	1.0	0.12
Metal-architectural	0.32	3.4	0.16	5.0	0.48
PVC (single-ply)	0.40	4.0	0.15	4.8	0.55
CSPE/Hypalon (single-ply)	0.23	2.2	0.09	2.6	0.32
Other single-plies	0.20	1.9	0.07	2.0	0.27
Sprayed Polyurethane	0.26	2.6	0.09	2.4	0.35
Liquid-applied	0.21	2.2	0.05	0.9	0.26
Tile	0.09	0.8	0.05	1.2	0.14
Asphalt shingles	0.61	6.5	0.23	7.5	0.84
Other	0.10	1.1	0.04	1.1	0.14
Total	9.88	100	3.32	100	13.12

[a]Roof coatings are not included in system types. Coatings are used as surfacing on many of the roof systems listed.
Note: Statisics for the commercial roofing market from a survey of the Natonal Roofing Contractors Association. Sales in billions of 1995 dollars are for the value of contracts, and include labor, materials and profit. Percentages show the area of roofing covered by each material.

Table 6. Market share of residential roofing systems[a] in the U.S., 1995 (NRCA, 1996)

	Reroofing		New Construction		Total
Roofing type	B \$	% of area	B \$	% of area	B \$
Built-up Roofing (BUR)	0.22	5.2	0.05	4.4	3.67
Single-plies	0.35	8.8	0.06	8.6	3.22
Modified bitumen	0.25	5.9	0.04	5.2	1.48
Metal	0.12	2.8	0.04	2.6	1.36
Clay tile	0.06	1.0	0.04	2.4	0.12
Concrete tile	0.09	1.0	0.06	3.9	0.48
Fiberglass asphalt shingle	2.20	54.3	0.40	50.3	0.50
Organic asphalt shingle	0.55	13.7	0.11	12.8	0.32
Cement-based shingles	0.04	0.5	0.04	0.8	0.27
Wood shingles/shakes	0.11	2.4	0.04	4.0	0.35
Slate	0.08	2.0	0.04	3.5	0.26
Composite/synthetic	0.04	0.5	0.02	0.3	0.14
Other	0.08	1.3	0.02	1.3	0.84
Total	4.19	100	0.96	100	13.12

[a]Roof coatings are not included in system types. Coatings are used as surfacing on many of the roof systems listed.
Note: Statistics for the residential roofing market from a survey of the National Roofing Contractors Association. Sales in billions of 1995 dollars are for the value of contracts, and include labor, materials and profit. Percentages show the area of roofing covered by each material.

sun; marketing programs and informational materials to aid consumers in the selection of solar-reflective materials; low-cost loans for solar-reflective surfacing; utility cost-sharing of solar-reflective pavement; and including solar-reflective surfacing as an option for air pollution offsets by air quality management agencies.

CONCLUSIONS

High solar-reflectance materials can be used on urban surfaces to cost-effectively reduce cooling energy use and improve air quality. The albedo of Sacramento, California, could be increased by 18% overall. Surfaces with high potential for albedo modification include dark roofs (20% of the area) and dark pavement (10% of the area). Built-up roofs, single-ply membrane roofs, and asphalt shingle roofs are a large share of the area of new roofing in the U.S. Built-up roofs can be surfaced with a solar-reflective coating for little or no cost increase and white single-ply roofing membranes can be specified instead of black. But in the case of asphalt shingles, white asphalt shingles are actually about 75% absorptive, and solar-reflective alternatives to asphalt shingles, such as white metal shingles, have a higher initial cost. Despite the initial first cost, the alternatives may be cost-effective, and could be promoted through informational materials and financial incentives, such as low-cost loans. A labeling program for roofing materials and paints would be an ideal first step for promoting solar-reflective materials. High-albedo pavements include concrete overlays and asphalt with light-colored aggregates. Government programs that encourage life-cycle costing of pavements may result in the use of materials that have a higher solar-reflectance.

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REFERENCES

Akbari, H., Rosenfeld, A. and Taha, H. (1990) Summer heat islands, urban trees, and white surfaces. *Proceedings of American Society of Heating, Refrigeration, and Air-Conditioning Engineers*, Atlanta, Georgia; also Lawrence Berkeley National Laboratory Report LBNL-28308.

Akbari, H., Bretz, S., Fishman, B., Hanford, J., Taha, H., Kurn, D. and Bos, W. (1993) Monitoring peak power and cooling energy savings of shade trees and white surfaces in the Sacramento Municipal Utility District (SMUD) service area: data analysis, simulation and results. LBNL No. 34411, Lawrence Berkeley National Laboratory, Berkeley, CA.

ASHRAE Handbook Fundamentals, American Society of Heating, Refrigeration, and Air-Conditioning Engineers, Atlanta, Georgia.

Berdahl, P. and Bretz, S. (1997) Preliminary survey of the solar reflectance of cool roofing materials. *Energy and Buildings*, in press.

Bretz, S. and Akbari, H. (1997) Long-term performance of high-albedo roof coatings. *Energy and Buildings*, in press.

Cardelino, C. A. and Chameides, W. L. (1990) Natural hydrocarbons, urbanization, and urban ozone. *Journal of Geophysical Research* **95**, D9, 13,971–13,979.

Gray, E. (1992) Special products representative, Lehigh White Cement Company, 1980 Atlanta Avenue, Riverside, California. Personal Communication (June).

Kiley, M. D. and Reynolds, C. J. eds. (1994) 1995 *National Construction Estimator*, 43rd edn. Craftsman Book Company, Carlsbad, CA.

Martien, P., Akbari, H. and Rosenfeld, A. (1989) Light-colored surfaces to reduce summertime urban temperatures: benefits, costs, and implementation issues. Presented at the 9th Miami International Congress on Energy and Environment, Miami Beach, FL.

Means Company (1990) *Means Building Construction Cost Data*. Construction Consulting and Publishing, Kingston, MA.

Myrup, L. O. and Morgan, D. L. (1972) Numerical model of the urban atmosphere. Dept. of Agricultural Engineering and Dept. of Water Science and Engineering, Contributions in Atmospheric Science No. 4, UC Davis.

National Roofing Contractors Association (NRCA) (1996) *1995–1996 Annual Market Survey*, NRCA, Rosemont, IL.

Orvis, K. (1992) Lawrence Berkeley National Laboratory, Personal Communication.

Parker, D. S., Cummings, J. B., Sherwin, J. S., Stedman, T. C. and McIlvaine, J. E. R. (1993) Measured A/C savings from reflective roof coatings applied to Florida residences. Florida Solar Energy Center FSEC-CR-596-93, (February). Florida Solar Energy Center, Cape Canaveral, FL.

Portland Cement Association (PCA) (1986) Asphalt vs. Concrete. *American City and County*, July, 31–38.

Renier, E. J. (1987) Concrete overlays challenge asphalt. *Civil Engineering* **57**, 54–57.

Rosenfeld, A., Akbari, H., Bretz, S., Fishman, B. L., Kurn, D. M., Sailor, D. and Taha, H. (1995) Mitigation of urban heat islands: materials, utility programs, updates. *Energy and Buildings* **22**, 255–265.

1991 *Sweet's Catalog File* (1990) *Vol. 3: Products for Engineering and Retrofit; Mechanical, Electrical, Civil and Related Products*, McGraw-Hill Information Systems Company, New York.

Taha, H. (1997) Modeling the impacts of large-scale albedo changes on ozone air quality in the south coast air Basin. Lawrence Berkeley Laboratory Report LBL 36890.

Taha, H., Akbari, H. and Rosenfeld, A. (1988) Residential cooling loads and the urban heat island: the effects of albedo. *Building and Environment* **23**, 271–283.

Taha, H., Sailor, D. and Akbari, H. (1992) High-albedo materials for reducing building cooling energy use. Lawrence Berkeley National Laboratory Report 31721.

APPENDIX A: GLOSSARY OF TERMS

ASTM: American Society for Testing and Materials. A voluntary organization concerned with development of a consensus standards, testing procedures and specifications.

Aggregate: a hard, inert mineral material such as gravel, sand, crushed rock, or slag used in the topping of pavement.

Asphalt: a dark brown to black cementitious material in which the predominating constituents are bitumens which occur in nature or are obtained from petroleum.

Asphalt shingle: a core material (either fiberglass mat or organic felt) that is coated with asphalt, and then covered with granules. Although both fiber glass and organic-based shingles are asphalt shingles the term "asphalt shingles" is often used to reference organic shingles only because they were developed before fiberglass shingles.

Built-up roof: a flat or low-sloped roof consisting of multiple layers of asphalt and ply sheets.

CSPE: Chlorosulfonated polyethylene, a type of single-ply roofing membrane that can be produced in white. Typical features are: moderate price, normally reinforced, seams are typically heat sealed, good fire resistance, good weatherability, good chemical resistance, and good compatibility for contact with asphalt, coal tar pitch and other materials.

Coating: a layer of a polymeric material or viscous asphalt applied to the base material into which granules or other surfacing may or may not be embedded.

Composite shingle: an asphalt shingle; basically, any shingle constructed of a base (fiber glass or organic), asphalt and granules.

EPDM: Ethylene–Propylene–diene terpolymer membrane, a type of single-ply roofing membrane that is an elastomer based on ethylene and propylene terpolymers with small amounts of a non-conjugated diene and which can be vulcanized. The membranes are about 1 mm thick but can resist large tensile strengths and are water resistant (ASTM D 471). They usually have a 2% linear dimensional change (ASTM D 1204) and are weather resistant according to ASTM G 26 or G 53.

PVC: a type of single-ply roofing membrane. A vinyl compound consisting of a vinyl resin, plasticizer, lubricant, stabilizer, fillers, pigments and sometimes polymeric modifiers.

Ply: the number of layers of roofing: i.e. one-ply, two ply.

Shake: usually a thick, hand-cut shingle.