Cooler Paving Materials for Heat-Island Mitigation

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ABSTRACT

Many cities suffer summer daytime temperatures greater than their suburban or rural surroundings. One of the causes of this "heat island" phenomenon is the absorption of sunlight by dark pavements. In warm climates, the urban heating damages the environment by adding to air-conditioning demand and creating smog. If urban roads, driveways and walkways were paved with light colored, and consequently cooler, materials these penalties would be diminished. However, lighter materials may cost more than the usual asphalt materials. In this report, the dollar value of potential air conditioning and smog savings from lighter pavements is estimated, and compared to the extra cost of such roads. The extra cost is minimized if the lighter-colored coating is applied as a thin layer when normal maintenance is performed. We find that, in Los Angeles, increasing the albedo from 0.1 to 0.35, could produce an air-conditioning saving of $0.012/m^2-yr. and smog savings of about $0.06/m^2-yr. The present value of these savings, for the 5 year lifetime of the resurfacing, is about 5 times the annual saving, or about $0.36/m^2. (The particular climate and smog problem clearly influence this result.) Thus one could purchase a "cooler" material whose extra cost is this amount, with no net expense. If roads are cooler they may also last longer and thus save money.

Introduction

It has been observed that the temperatures in urban areas are generally higher than in their suburbs (Taha 1997b). In warm climates this has the deleterious environmental effects of increased smog and higher use of energy for air conditioning. This "heat island" effect is believed to be caused by sunlight falling on the materials and structures in the cities, rather than the expended energy of human activity. Among the likely contributors to the excess heating are asphalt pavements. To make a pavement, a binder is mixed with an aggregate to form a composite known generically as "concrete". The most common concrete uses asphalt, a bituminous and black material, as the binder. The aggregate is rocks. This composite is properly called asphalt concrete, or AC. (AC is the abbreviation[1] used in the pavement industry, not to be confused here with air conditioning.) The aggregate provides strength and the asphalt binds the aggregate together against the forces of traffic and weather. Because of the dark asphalt binder, AC absorbs about 90% of the sunlight that falls on it and is among the hottest surfaces in a city. And it is widespread; in the urbanized parts of cities, pavements cover about 15% of the land area (Cal-Stats 1990). In this paper we discuss methods to reduce the contribution of pavements to the heat island effect.

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[1]The other common concrete uses Portland cement as the binder and the aggregate is rocks; this is (Portland) cement concrete, often abbreviated as "PC" or "PCC". In this paper we must distinguish the kind of binder, so we avoid the common usage that refers to asphalt concrete as "asphalt" and Portland cement concrete as "concrete". "Asphalt" will be used in its strict meaning of the black binding material and "concrete" will mean a generic composite.

Urban pavements are made predominantly of asphalt concrete. We shall ignore the common alternative, cement concrete, in this report. There is an ongoing debate whether cement concrete should be preferred because of its longer lifetime, but we will not consider that here. The questions we address are whether there are ways to reduce the heating of cities caused by asphalt concrete and whether this can be economical and practical.

We consider two issues: 1) the savings in energy and smog that might result from using lighter-colored asphalt concrete pavements. This requires a detailed analysis of the effect of pavement reflectivity in a particular climate. We shall summarize our results for Los Angeles, the one city that we have thus far scrutinized. 2) the monetary savings that might occur if cooler pavements are either cheaper to build or have lower lifetime costs. We find that the criteria for this benefit involve the high and low temperatures to which the pavement may be subjected. Thus the discussion shall be more general. There are other potential benefits of lighter colored pavements but we shall mention them only in passing in the Conclusion.

Methods and Results

A few basic facts should be mentioned first. A typical AC mix has about 7 % of asphalt by weight, or about 17% by volume; the remainder is rock aggregate, except for a few percent of voids. The cost of ordinary asphalt (1998 prices) is about $125 per ton, and the price of aggregate is about $20 per ton, exclusive of transportation costs. Thus, in one ton of mixed AC the cost of materials only is about $28/ton, of which about $9 is in the binder and $19 is in the aggregate. For a pavement about 10 cm thick (4 inches), with a density of 2.1, the cost of the binder alone is about $2 per m^2.

The measure of the reflectivity of solar energy from a surface is the "albedo". By definition, albedo varies from 1, for perfect reflectors, to 0 for perfectly absorbing surfaces. Experimentally, the albedo of a fresh AC pavement is about 0.05 (Pomerantz et al. 97) because the relatively small amount of black asphalt coats the lighter colored aggregate. As it is worn down and the aggregate is revealed, we observed an albedo increase to about 0.15.

Energy and Smog Savings Caused by Increased Pavement Albedo

An estimate of the benefits to society can be deduced by first finding the temperature decrease that would result if a city were resurfaced with more reflective materials. Lower temperature has two effects: 1) reduced demand for electricity for air conditioning and 2) decreased production of smog (ozone). We sketch now the cost savings of both reduced demand for electricity and the externalities of lower ozone concentrations. The details are presented elsewhere (Rosenfeld et al. 1998) .

Electric Power Savings in Los Angeles.

Previous simulations for Los Angeles indicate that a reasonable change in the city's albedo could cause a noticeable decrease in temperature. Taha predicted a 1.5 °C (2.7 °F) decrease in temperature of the downtown area. (The model assumes that all roofs (1250 km^2) have albedo increased by 0.35, from about 0.15 to 0.5, and all pavements (1250 km^2) have albedo increased from about 0.1 to 0.35. For practical reasons, we propose that the lighter-colored surfaces be installed as part of normal maintenance or replacement. In this way, any extra cost of the lighter materials is the only cost of obtaining the benefits of cooling. The lower temperatures in the city are calculated for the condition that all roads and roofs are improved.) From simulations of the temperature changes on one day in each season, the temperature changes for every day in a typical year were estimated for Burbank, typical of the hottest 1/3 of LA (Taha 1997). The energy consumptions of typical buildings were then simulated for the original weather and also for the modified weather. The differences are the annual energy changes due to the ambient temperature decrease. The result is a city-wide annual saving of about $71 M (million), due to combined albedo and vegetation changes. The kWh savings attributable to the pavement saves $15 M/yr, or $0.012/m^2-yr ($0.001 per ft^2-yr). Analysis of the hourly demand indicates that cooler pavements could save an estimated 100 MW of *peak* power in LA. Fewer power plants required to handle the growth of peak load need not then be built if cooler pavements are installed, which will save money, resources, and pollution.

Smog Savings in Los Angeles.

The production of ozone (O_3) requires precursors (nitrous oxides (NO_x) and volatile organic hydrocarbon gases), and, to drive the reactions, sunlight and heat. These reactions occur more rapidly as the temperature is increased. The influence of temperature is demonstrated by the dramatic dependence of smog incidents on the daily maximum temperature in Los Angeles (Rosenfeld et al. 1995). In 1985, there were no violations of the National Air Quality Standards of 120 parts per billion of ozone when the maximum temperature was below 72 °F. Above that temperature the number of days with violations increased steadily, until for peak temperatures of 95 °F the ozone concentrations can be almost double the allowable level. The simulations of the effects of higher albedo on smog formation indicate that an albedo change of 0.3 over the developed 25% of the city would yield a 12% decrease in the exceedance above the California standards (Taha 1997). It has been estimated (Hall et al. 1992) that people would be willing to pay about $10 billion per year to avoid the medical costs and lost work due to air pollution in LA. The bigger part of pollution is particulates, but the ozone contribution is about $3 billion/yr. Assuming a proportional relationship of the cost with the amount of smog exceedance, the cooler-surfaced city would save 12% of $3 billion/yr, or $360 M/yr. As above, we attribute about 21% of the saving to pavements. Thus the smog improvement from changing the albedo of all 1250 km^2 of pavements by 0.25 saves about $76M/yr. Per unit area, this is worth about $0.06/m^2-yr, ($0.0056/ft^2-yr).

Comparison of Cost vs Savings of Cooler Pavements.

The economic question is whether the savings generated by a cool pavement over its lifetime are greater than its extra cost. Properly, one should distinguish between initial cost and lifetime costs (including maintenance, repair time, and length of service of the road). Often the initial cost is decisive, so we will consider only that here. Consider first a new asphalt pavement; its lifetime is about 20 years. If it were made with a reflective aggregate it would generate a stream of savings ($0.07/m^2-year or $0.007/ft^2-year in LA) for this length of time. At a real interest rate of 3% per year, this has a present value about 15 times the current saving (Rosenfeld et al. 1998). Thus, the potential savings are worth $1.08/m^2 ($0.10/ft^2) at present. A survey of paving materials (Pomerantz et al. 1997) indicates that all *new* light-colored pavements cost more than $1.08/m^2 ($0.10/ft^2) more than black asphalt, and are thus too expensive.

However, to improve the reflectivity of a road it is sufficient that only the outer layer be reflective. The possibility that *resurfaced* layers may be competitively priced is estimated below. Even a new pavement needs periodic resurfacing, which offers the opportunity to use a light-colored material. Since good maintenance practice calls for resurfacing of a new road after about 10 years (Dunn 1996), and the lifetime of resurfacing is only about 5 years, within 10 years all the AC surfaces in a city can be made light colored. As part of this regular maintenance, any additional cost of the whiter material will be minimized. Note also that because the lifetime of the resurfacing is only about 5 years, the present value of the savings is 5 times greater than the annual savings[2]. Thus, for LA, the present value is about \$0.36 /m^2 (\$0.03/ft^2). Can a pavement be resurfaced with a light color at an added cost less than this saving?

From the survey of asphalt-based pavements (Pomerantz et al. 1997), we observe that, within ± 2 %, all of them are composed of about 93% aggregate and 7% binder, by weight (Asphalt-Institute 1989). We can thus express the cost of the *materials* of all asphalt-based layers as the sum of the costs of the aggregate and the binder. (We assume that there is no difference in cost between the laying of different kinds of pavements.) In what follows we give numbers in metric units. For *6 mm thick resurfacing,* 1 m^3 of paving has a volume of 0.006 m^3 = 6 liters (L), of which 17.5% by volume is binder (the density of aggregate is about 2.5 times greater than asphalt). Thus, in this volume there is a volume of 4.95 L (0.0172 ft^3) of aggregate, of mass 12.4 kg, and 1.05 L (0.00364 ft^3) of binder. Using units of \$/kg for the cost of aggregate, A, and \$/liter for the cost of binder, B, the price, P, of material for 1 m^2 of 6mm thick pavement is P (6 mm) = 12.4A + 1.05B. Note that the costs of pavements are proportional to their thicknesses in this approximation of constant cost of application[3].

If one buys more expensive aggregate, at a cost change of ΔA, and binder at a cost change of ΔB, the *changes* of the price of the pavement, ΔP, can similarly be written:

$$\Delta P\ (6\ \text{mm}) = 12.4\Delta A + 1.05\Delta B, \quad (\$/\text{m}^2) \qquad (1)$$

From Eq. 1, we can determine the maximum price *increases* of aggregate and binder for a 1/4 " thick pavement that are paid for by the cooling savings, ΔP. This is shown in **Fig. 1**. The increases in aggregate prices and binder prices below the outermost line result in cost increases less than the savings of \$0.36/m^2 (\$0.03/ft^2). For example, a binder more costly by as much as \$1.10/gal is affordable (if the aggregate is unchanged). Or, aggregate costing up to \$22/ton more can be used (and the binder stays the same). It is likely that very white aggregate can be bought at this price. Of course, intermediate choices between

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[2]This ignores the possibility that the light-colored aggregate may be recycled in subsequent resurfacings. In that case the effective lifetime of the material is greater, the present value multiplier will be larger than 5, and the savings will be larger than calculated here.

[3] In English units, the price of the one square foot of same thickness (6 mm or 1/4 in.) is given by P= 0.00135A + 0.0273B, where A is the cost of aggregate in \$/ton and B is the cost of binder in \$/gal. To check the accuracy of this equation, note from earlier work (Pomerantz et al. 1997, Tables 2 and 3), that the least expensive materials for pavement are aggregate at about \$15/ton (delivered) and asphalt at about \$0.50/gal. We find the cost P to be about \$0.04/ft^2 for a 1/4" thick pavement. Scaled up to a 4" thick asphalt pavement, this predicts a 16 fold greater cost of \$0.64/ft^2. This agrees with a 4" thickness costing \$0.60/ft^2 (Dalmaso 1995). Asphalt slurry coats use binder costing about \$1/gal, and aggregate at about \$15/ton. They give a coating about 1/4" thick and Eq. 1 predicts a cost of about \$0.06/ft^2. This is close to the value of \$0.063/ft^2 (\$0.57/yd^2), reported by Means (Means 1996). The equation for the cost of materials thus gives reasonable estimates of actual costs for thick pavements. For thin pavements the estimate is lower than what contractors quote, probably because installation is a relatively larger fraction of the cost compared to the materials.

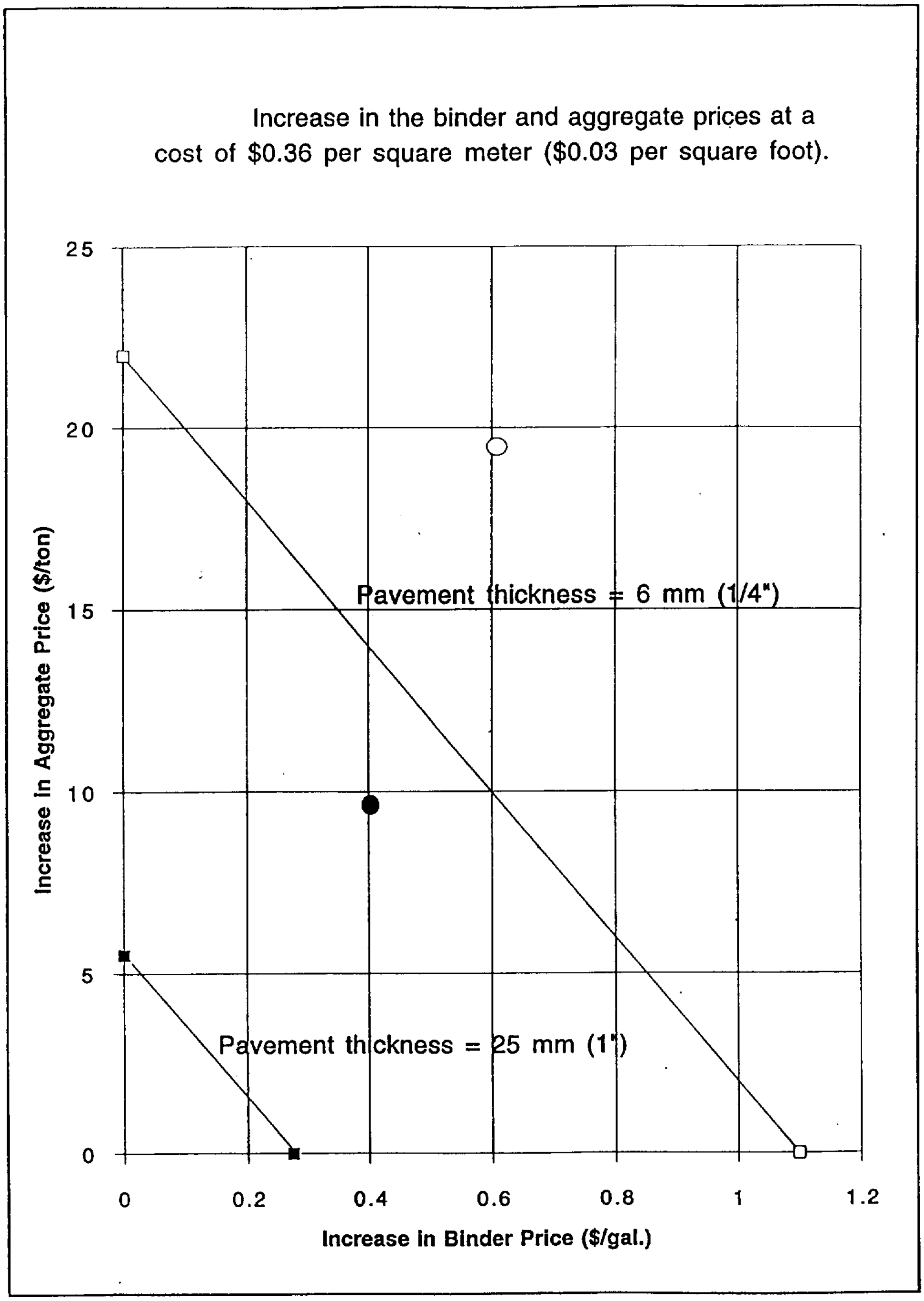

Fig. 1. The region below the outermost line indicates the combinations of increases in costs of binder and/or aggregate that do not raise the price of a 6 mm resurfacing more than $0.36 per m^2. The black circle exemplifies one economical choice, in which the cost increase is paid for by the savings. The cost increase for the white circle is too high. For a thicker resurfacing, 25 mm, the costs that do not raise the price more than $0.36 are restricted to the (smaller) region below the lower line. See the text for further explanation.

these extremes are possible. One needs only to stay below the outermost line in Fig. 1. For example, an increase in cost of aggregate by $10 and an increase of binder by $0.40 per gallon, indicated by the filled (black) circle in Fig. 1, would be an economical choice for a 6 mm thick resurfacing. But increases of $20/ton for aggregate and $0.60/gal for binder would not be paid for by the benefits (the empty circle representing these increases lies above the line).

To demonstrate the effect of the layer thickness, we repeat this analysis for a thicker layer, say 25 mm (1") thick. Since four times as much material is used than for the 1/4" pavement, the coefficients of Eq. 1 are simply multiplied by 4. The affordable price increases of aggregates and binders (that cause a price increase equal to the cooling saving of $\$0.36/m^2$ or $\$0.03/ft^2$) lie below the lower line of Fig. 1. In this case, one could afford an increase of up to $0.27/gal in binder price, or an increase of $5.5/ton in the aggregate price. As expected, a thinner layer is more likely to be economical.

Reduction in Pavement Costs Caused by Cooler Materials

It has long been known that the temperature of a pavement affects its performance (Yoder & Witzak 1975). This has been emphasized by the new system of binder specification advocated by the Strategic Highway Research Program (SHRP). Beginning in 1987, this program brought pavement experts to the task of researching and then recommending the best methods of making AC pavements. A result of this study is specifications of the asphalt binder. The specification form, reproduced in **Fig. 2** from a SHRP report (Cominsky et al. 1994), shows that a primary consideration is the temperature range that the pavement will endure. The performance grade (PG) is specified by two temperatures: (1) the average 7-day maximum temperature that the pavement will likely encounter, and (2) the minimum temperature the pavement will likely achieve. Note, importantly, that it is the *pavement* temperature and not the *air* temperature that is considered. There is a rule of thumb in the industry, "Rule of 90", that when the sum of the absolute values of these temperatures is greater than 90 C, some kind of modifcation of the asphalt will be needed; this adds to the cost. For example, if a binder is specified as PG 58-22, it is intended to function between 58 C and minus 22 C. The sum of the absolute values, 58 + |-22| = 80. An ordinary grade of asphalt will suffice; its cost is about $125 per ton. If, however, the pavement must function between 76 C and -16 C, or PG 76-16, the sum 76 + |-16| = 92, and the price of such a binder is about $165 per ton(Bally 1998), a 30% increase in price. The Rule of 90 arises because ordinary asphalt has difficulty in performing over wide temperature ranges. Additives, such as polymers, are needed to attain this performance. The use of higher albedo materials presents the industry with the opportunity to compress the temperature range that pavements will suffer by decreasing the maximum temperature. The criteria of wide temperature swings and high maximum temperatures are likely to be met in southerly regions, particularly desert areas such as Phoenix.

In **Fig. 3** we show some measurements of the effect of albedo on pavement temperature[4]. These were not extreme conditions, because the data are from September, but they indicate clearly that significant modification of the pavement temperature can be made. The data show an 18 F (10 C) decrease in temperature for a 0.25 increase in albedo. This suggests that the pavement grade's maximum temperature specification

[4]Measured by H. Akbari, M. Pomerantz, and H. Taha at Lawrence Berkeley National Laboratory, Berkeley, CA, on new, old, and white coated asphalt concrete, at 3PM in Sept. 1996, using an IR thermometer.

PERFORMANCE GRADE	PG 46-			PG 52-							PG 58-					PG 64-					
	34	40	46	10	16	22	28	34	40	46	16	22	28	34	40	10	16	22	28	34	40
Average 7-day Maximum Pavement Design Temperature, °C[a]	<46			<52							<58					<64					
Minimum Pavement Design Temperature, °C[a]	>-34	>-40	>-46	>-10	>-16	>-22	>-28	>-34	>-40	>-46	>-16	>-22	>-28	>-34	>-40	>-10	>-16	>-22	>-28	>-34	>-40
ORIGINAL BINDER																					
Flash Point Temp, T48: Minimum °C	230																				
Viscosity, ASTM D4402:[b] Maximum, 3 Pa•s, Test Temp, °C	135																				
Dynamic Shear, TP5:[c] G*/sinδ, Minimum, 1.00 kPa Test Temp @ 10 rad/s, °C	46			52							58					64					
ROLLING THIN FILM OVEN																					
Mass Loss, Maximum, percent	1.00																				
Dynamic Shear, TP5: G*/sinδ, Minimum, 2.20 kPa Test Temp @ 10 rad/s, °C	46			52							58					64					
PRESSURE AGING VESSEL RESIDUE (PP1)																					
PAV Aging Temperature, °C[d]	90			90							100					100					
Dynamic Shear, TP5: G*sinδ, Maximum, 5000 kPa Test Temp @ 10 rad/s, °C	10	7	4	25	22	19	16	13	10	7	25	22	19	16	13	31	28	25	22	19	16
Physical Hardening[e]	Report																				
Creep Stiffness, TP1:[f] S, Maximum, 300 MPa, m - value, Minimum, 0.300 Test Temp @ 60s, °C	-24	-30	-36	0	-6	-12	-18	-24	-30	-36	-6	-12	-18	-24	-30	0	-6	-12	-18	-24	-30
Direct Tension, TP3:[f] Failure Strain, Minimum, 1.0% Test Temp @ 1.0 mm/min, °C	-24	-30	-36	0	-6	-12	-18	-24	-30	-36	-6	-12	-18	-24	-30	0	-6	-12	-18	-24	-30

[a] Pavement temperatures are estimated from air temperatures using an algorithm contained in the Superpave software program, may be provided by the specifying agency, or by following the procedures as outlined in PPX.

[b] This requirement may be waived at the discretion of the specifying agency if the supplier warrants that the asphalt binder can be adequately pumped and mixed at temperatures that meet all applicable safety standards.

[c] For quality control of unmodified asphalt cement production, measurement of the viscosity of the original asphalt cement may be substituted for dynamic shear measurements of G*/sinδ at test temperatures where the asphalt is a Newtonian fluid. Any suitable standard means of viscosity measurement may be used, including capillary or rotational viscometry (AASHTO T201 or T202).

[d] The PAV aging temperature is based on simulated climatic conditions and is one of three temperatures 90°C, 100°C or 110°C. The PAV aging temperature is 100°C for PG 58- and above, except in desert climates, where it is 110°C.

[e] Physical Hardening — TP1 is performed on a set of asphalt beams according to Section 13.1, except the conditioning time is extended to 24 hrs ± 10 minutes at 10°C above the minimum performance temperature. The 24-hour stiffness and m-value are reported for information purposes only.

[f] If the creep stiffness is below 300 MPa, the direct tension test is not required. If the creep stiffness is between 300 and 600 MPa the direct tension failure strain requirement can be used in lieu of the creep stiffness requirement. The m-value requirement must be satisfied in both cases.

Fig. 2. A page of the Performance-Graded Asphalt Binder Specification, as recommended by the SHRP Superpave mix design manual (Cominsky et al. 1994).

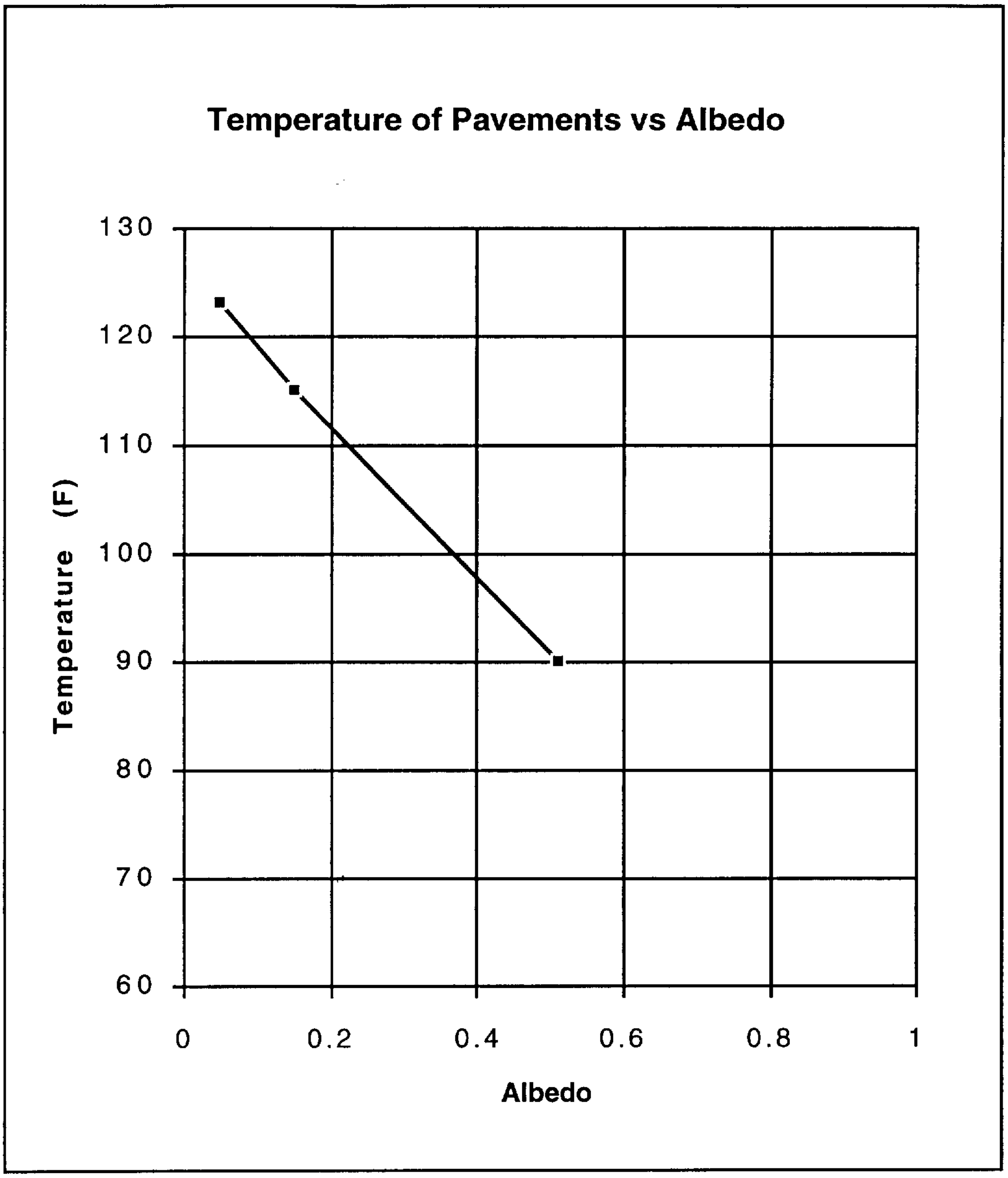

Fig. 3. The dependence of pavement surface temperature on albedo. Data taken on Sept. 1996 at about 3 PM in Berkeley, CA, on new, old and light-color coated asphalt pavements.

could be decreased by perhaps 10 C. For example, if a grade of PG76-16 were required, now PG66-16 would suffice. By the "Rule of 90", this grade does not entail a surcharge. Thus the cost of \$2.60 per m^2 for higher grade asphalt could be reduced to the usual \$2.00 per m^2 , for a saving of \$0.60 per m^2.

The next question is whether a coating can be found that increases the pavement albedo at a cost less than \$ 0.60 per m^2. On a national average (Means 1996), the materials for a *chip seal* , consisting of an asphalt emulsion onto which uniformly sized aggregate is pressed, costs about \$0.63 per m^2 for a large area. Thus, for a 4 in thick pavement it would cost about as much to apply a chip seal rather than going to a higher grade asphalt. If the pavement were thicker the savings would be greater than for the 4 in. thickness. For a new pavement it might be possible to dispense with the additional asphalt emulsion and merely spread the aggregate on the hot mix before the final rolling. This makes the light-colored topping even less expensive. Chip seals, or as they are sometimes called "surface treatments", are the preferred resurfacing in such places as Chula Vista, CA (Maruffo 1998). There are some reservations about their use in cul de sacs, where tires are turned hard and loosen the aggregate. Sometimes aggregate is thrown by tires, but when installed properly this seems to be rare.

Another potential cost saving is the increase in lifetime of a pavement. A source of pavement failure is "tertiary creep", which is the rapid increase of plastic deformation after many repetitions of stress at high temperatures (Cominsky et al. 1994, p. 102 et seq). Pavements gradually accumulate permanent distortions as tires roll over them repeatedly. "Tertiary creep" refers to the phenomenon of accelerated rate of distortion after many such repetitions. This signals gross failure of the pavement. We now estimate how much a decrease in pavement temperature may increase the lifetime of a pavement. **Fig. 4** (Fig. 4.3 of the cited report) shows how to determine the "control temperature", i.e., the one temperature at which to test for creep, depending on the number of design load repetitions, N, and the "effective temperature", T_{eff}. The effective temperature is the one temperature which, if maintained for a year, would give the same permanent deformation as the actual range of temperature in that locality. It is defined (eq. 4 - 2 of Cominsky, et al)

$$T_{eff}\,(PD) = 30.8 - 0.12Z_{cr} + 0.92MAAT_{des},$$

where Z_{cr} = critical depth (in mm.), to account for temperature decrease with depth (typically 25 mm. for the surface course),

$MAAT_{des} = MAAT_{av} + K\sigma_{MAAT}$ = air temperature for the design

$MAAT_{av}$ = average mean annual air temperature in that locality, from historical records

K = factor for reliability specified in the design.

σ_{MAAT} = standard deviation in the distribution of MAAT.

The control temperature increases as the T_{eff} increases, at constant N. T_C also increases as N increases at T_{eff} = const. Thus, we interpret T_C as a measure of the resistance of the material to permanent deformation. Viz., it is more demanding that the pavement does not fail at higher T_C than if it did not fail at lower T_C. Thus along a curve of constant T_C a pavement is of constant quality. We can then ask, for a constant quality, or T_C, how does the lifetime vary with the temperature of the pavement? As the *change* in pavement temperature is the same as the *change* in air temperature(Kennedy et al. 1994), we can read the effect of *change* of pavement temperature on change of lifetime directly from Fig. 4, as follows:

The curves are of the form $\log N = c - kT_{eff}$ at const T_C. Thus for high and low effective temperatures, T_{eh} and T_{el}, the lifetimes at high and low temperatures, N_h and N_l, are given by:

$$\log N_l - \log N_h = \log (N_l / N_h) = k(T_{eh} - T_{el})$$

or

$$N_l / N_h = 10^{k(T_{eh} - T_{el})}$$

From the curves, we find k = 0.14. Thus for a 1 °C change in $T_{eh} \rightarrow T_{el}$, $N_l / N_h = 10^{0.14}$ = 1.4. This says there is a 40% increase in lifetime for 1 °C decrease in temperature. A 10 °C decrease gives a 25 fold increase in N_l / N_h, which is so large that we suspect it is an overestimate. The derivation of Fig. 4 needs to be examined to find its limitations.

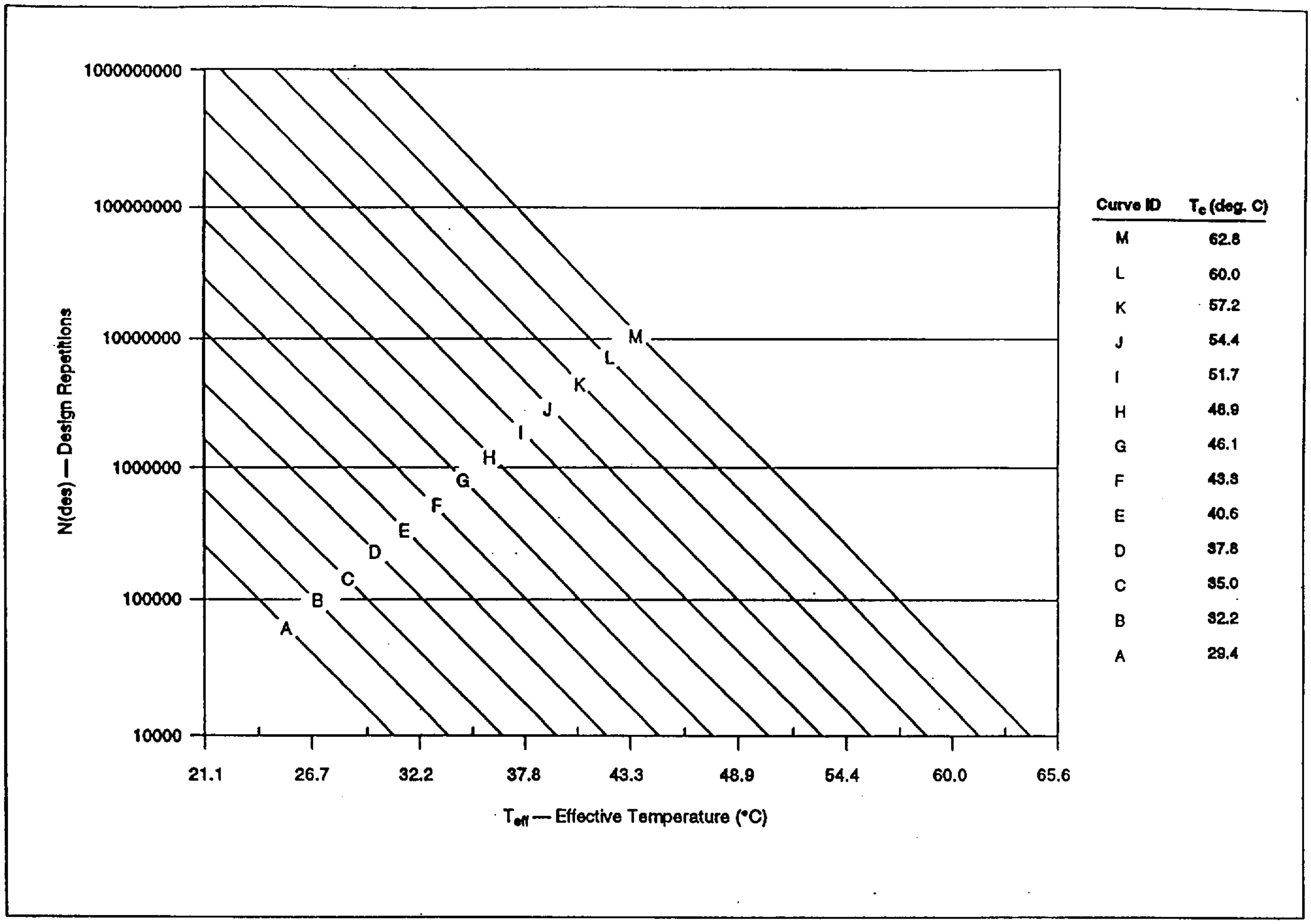

Fig. 4. Graphs for selecting the "approximate control temperature" for testing for tertiary creep (Cominsky et al. 1994). This temperature is a surrogate for stability of the pavement against destructive plastic flow, hence the graphs are used in the text to estimate the benefits of cooler pavement temperatures on increased lifetimes, at a constant stability.

Other Benefits of Cooler Pavements

Reflectivity of pavements is also a safety factor in visibility at night, and reduces the demand for electric lighting for streets. Street lighting is more effective if the pavements are more reflective, which can lead to greater safety, or lower cost if some lighting becomes excessive. These benefits have not yet been monetized. A suggested drawback of high reflectivity is glare but this does not appear to be a problem. The change we suggest is to go from resurfacing with black asphalt, with albedo of about 0.1, to a resurfacing with an albedo of about 0.35, which is like that of cement concrete. The experiment to test whether this will be a problem has already been done: every day millions of people drive on cement concrete roads, and we rarely hear of accidents caused by glare, or people even complaining about the glare on such roads. Thus every reader of this paper likely knows the answer from experience.

Conclusions

It is obvious that the heat island effect can be mitigated by increasing the albedo of pavements. The question of whether it is economical seems to be answered in the affirmative in some cases. We show in this report that in Los Angeles in particular, a thin coating of reflective material is inexpensive enough to be paid for by the savings in electric power and smog. Los Angeles may be special because it has a particularly severe smog problem; indeed most of the saving is predicted to come from smog reduction. More studies of other cities are underway, so each unique situation can be evaluated.

In addition to the environmental benefits, cooler roads can be cheaper to construct, and may also last considerably longer than roads that are not coated with light colored toppings. The predicted possibility of enormously large effects should be tested directly. An increase in lifetime by even 30% represents a huge saving in construction, maintenance, convenience and disposal. One type of inexpensive cool surface, chip seal, is standard in the pavement industry. Again, each climate will determine the magnitude of the benefit. In hot cities where there is large air-conditioning demand it is likely that it is sunny enough to cause the roads to be even hotter, which contributes to that demand and also damages the roads.

The policy issue that remains is who shall take the lead in actualizing these benefits. The electric power industry, environmental protection and the city street departments all need to act in order that the benefits accrue to society.

Acknowledgments

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