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Cooler Reflective Pavements Give Benefits Beyond Energy Savings: Durability and Illumination

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ABSTRACT

City streets are usually paved with asphalt concrete because this material gives good service and is relatively inexpensive to construct and maintain. We show that making asphalt pavements cooler, by increasing their reflection of sunlight, may lead to longer lifetime of the pavement, lower initial costs of the asphalt binder, and savings on street lighting and signs. Excessive glare due to the whiter surface is not likely to be a problem.

Introduction

In an earlier report (Pomerantz & Akbari 1998), the air-conditioning energy and smog reductions that might result from the use of whiter paving materials were estimated. In this paper we consider some of the collateral effects of whiter pavements – on their durability and on illumination they produce. Asphalt pavements are the most common street pavements in cities because they are relatively inexpensive to construct and maintain, and they give acceptable service. Such pavements are dark colored because a dark binder (asphalt) is coated onto stony aggregate in order to glue the aggregate into a rigid paving material. A newly constructed asphalt concrete[1] (AC) pavement thus has the color of the asphalt, which is quite black.

The color of the pavement has several important environmental consequences. AC contributes to sunlight's heating of the air near the surface(Pomerantz et al. 2000). The dark color means that sunlight is not being reflected; the absorbed energy raises the temperature of the pavement and thus the temperature of the air that is near it. This immediately contributes to the heating of the city. When the temperature gets high enough, the modern response is to turn on an air conditioner that further heats the outside air and costs energy. The atmosphere also responds by using the thermal energy to drive the conversion of organic gases and nitrous oxides into smog. There is thus a cost in both energy consumed and degradation of the environment (Rosenfeld et al. 1998). These costs may be lessened by coating the pavement with a light-colored material (Pomerantz et al. 1997).

We suggested in the earlier report (Pomerantz & Akbari 1998), in addition to detrimental environmental effects, the heating of pavements may be bad for the pavements themselves. The properties of asphalt binder are known to be temperature dependent. For example, the stiffness of asphalt decreases exponentially with temperature (Yang 1972).

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[1] In common usage, asphalt concrete is referred to as "asphalt", and Portland cement concrete is called "concrete". We use "concrete" in its technical sense of a composite of a binder (asphalt or Portland cement) with stony aggregate. Thus we refer to "asphalt concrete"; "asphalt" connotes only the binder. Asphalt concrete is about 85% by volume mineral aggregate, which gives it strength; the asphalt binder provides tensile strength, stiffness and all-weather performance.

Likewise, the related property, viscosity, as measured by penetration of a sharp needle, decreases exponentially with temperature (Hunter 1994). The effects of pavement temperature on performance have been recognized by the Strategic Highway Research Program (SHRP) which grades asphalt according to the *pavement temperature* range it will endure (Cominsky et al. 1994). However, asphalt binders that function over wide temperature ranges are more costly. This opens possibilities for additional savings by constructing cooler pavements: by reducing the maximum pavement temperature, a lower grade of asphalt may be acceptable, and/or some failure will be delayed. Ultimately the lifecycle costs of maintenance and disposal of pavements will be reduced.

This paper will investigate these non-energy or non-environmentally related effects of cooler pavements, both the potential benefits and detriments. Such benefits, in addition to longer lifetime, may include better visibility. The danger of glare seems to be negligible for the suggested reflectivity. We also report some measurements on the relationship between the reflectivity of aggregates and chip seals made of them. The evidence suggests that cooler pavements may offer impressive benefits to society, and thus warrant further study.

Effect of Pavement Temperature on Durability

AC pavements fail by a variety of mechanisms, some of which are temperature dependent. Some failures might be delayed or eliminated if the pavements were more reflective of sunlight and their temperatures were thereby decreased. First we establish the order of magnitude of the effect of the reflectivity of a pavement on its temperature. The reflectivity averaged over the solar spectrum is the albedo[2], â. Measurements (Pomerantz et al. 2000b) were made of pavement temperatures in Berkeley and San Ramon, CA. In Berkeley, data were taken at about 3 PM on new, old, and light-color coated asphalt pavements. The data from San Ramon were taken at about 3 PM on four asphalt concrete and one Portland cement concrete (â = 0.35) pavements. In both places, the solar energy fluxes were about 1000 Wm^{-2}. A decrease of about 4 °C (7 °F) was observed for an increase of albedo of 0.1. **(Fig. 1)** (A change in albedeo of 0.25 is the difference between fresh black AC, with â ≈ 0.05, and Portland cement concrete, with â ≈ 0.3.)

A theory of maximum pavement temperature versus albedo predicts a decrease in temperature of 3.6 °C (6.5°F) for a 0.1 increase in â, for conditions of insolation, time and low wind-speed roughly similar to the measurements (Solaimanian & Kennedy 1993). Their result is in reasonable agreement with the data of Fig. 1. Other calculations more specific to the conditions of the experiments give similar results (Pomerantz et al. 2000b). Thus it may be possible to reduce the peak pavement temperatures by upwards of 5 °C by increasing the albedo by a practical amount of about 0.2.

The pavement temperature may affect the rate of pavement failures. There are several distress mechanisms of AC that are likely to be influenced by pavement temperature (Yoder & Witzak 1975) including:

- rutting: tires cause channel-like depressions in the pavement
- shoving: the AC is pushed along the direction of tire motion
- aging: asphalt becomes brittle and stiffer with age

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[2] Albedo is the fraction of the incident solar energy reflected by a surface, averaged over the solar spectrum. Perfect reflectors have â = 1, perfect absorbers have â = 0. For opaque materials, absorbtivity is (1 - â).

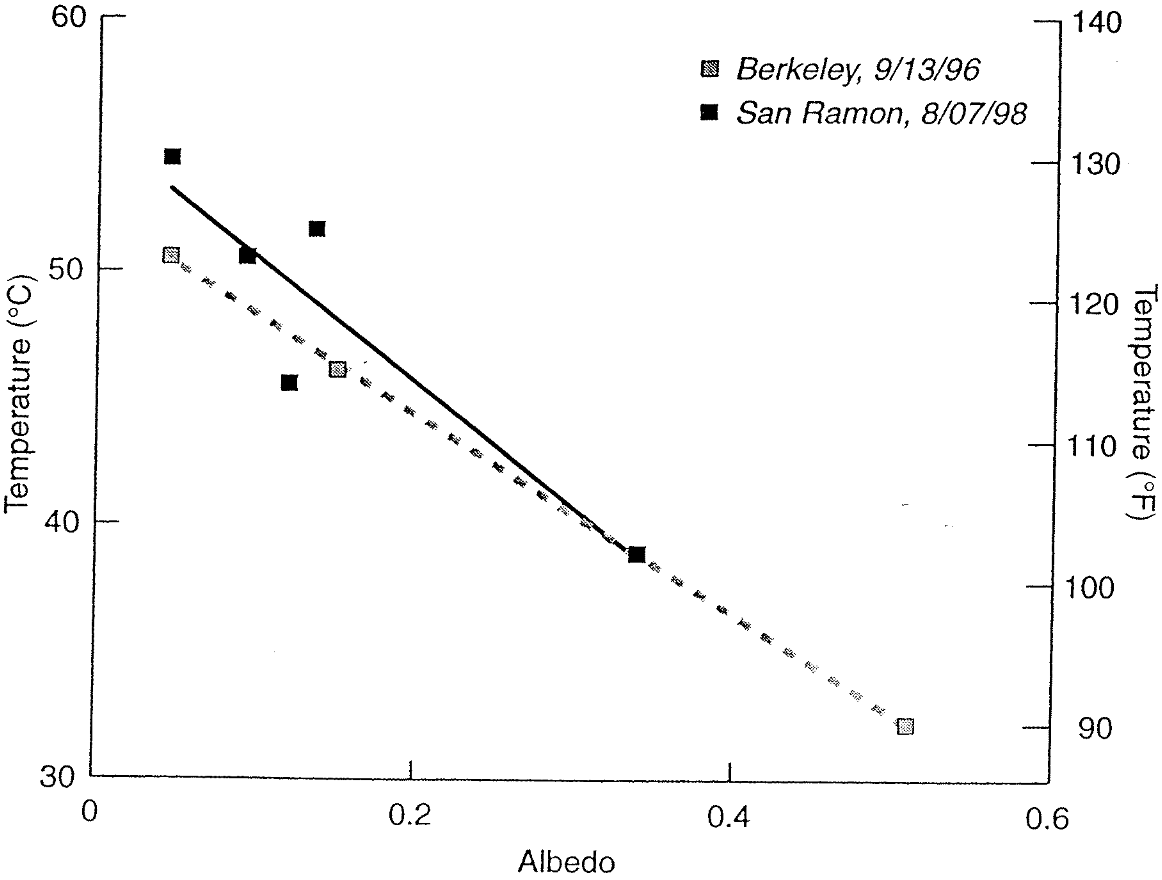

Fig. 1. Example of the Dependences of Pavement Surface Temperatures on Albedo

- fatigue damage: gradual cracking of pavement
- bleeding: asphalt binder accumulates at the surface

It is well known (Croney & Croney 1998) that the stiffness of asphalt depends strongly on temperature. The exponential dependence of viscosity on temperature results in about an order of magnitude decrease in viscosity for a 10°C increase in temperature. The stiffness of AC also decreases exponentially as its temperature increases: a 10°C increase in temperature can cause a factor of 2 decrease in the stiffness of AC. Stiffness is thought to be an indicator of pavement resistance to rutting and fatigue, which would suggest that the lifetime of the pavement might increase if the temperature of the pavement were lowered (Pomerantz & Akbari 1998). We have conducted experiments to measure this effect.

Experiments on the Effect of Pavement Temperature on Rutting

Fig. 2 shows the results of our rutting measurements made with the Heavy Vehicle Simulator at the Institute of Transportation Studies (ITS) of the University of California, Berkeley. A standard single-axle load with a wide-base single tire was repetitively driven at a speed of 7 km/hr, without wander. The pavements, dense-graded AC, were held at different temperatures by heating the ambient air and shining infra-red lamps. The temperatures were measured by thermocouples embedded at various depths. The rut depths were measured from the top of the extruded material to the bottoms of the ruts. There is a striking increase in the ability of the road to resist rutting as the temperature was decreased. At a surface temperature of 53 °C (127 °F) the rut depth exceeded the failure criterion (12.5 mm ≈ 0. 5 inch) in fewer than 20, 000 repetitions. By lowering the temperature by about 10 °C, to 42 °C (108 °F), the road did not reach failure until about 270, 000 cycles, a more than 10 fold increase in pavement life.

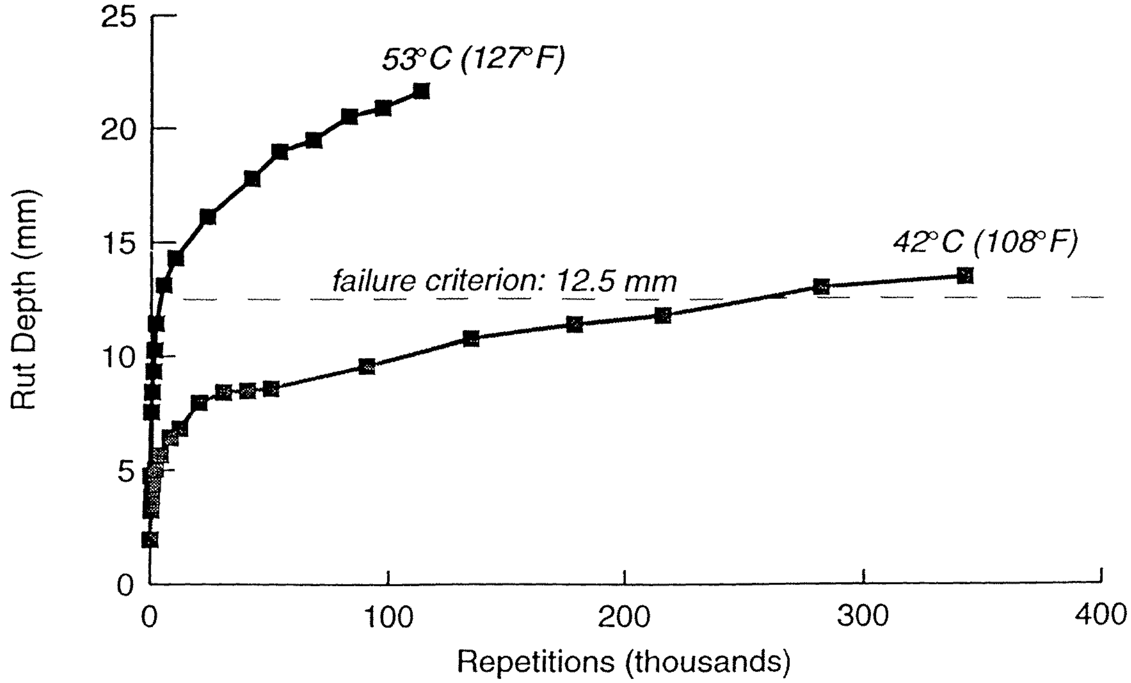

Fig. 2. Depth of Rutting vs Number of Repetitions of a Standard Axle Load, Wide-base Single Tire, at Pavement Surface Temperatures of 42°C and 53°C

Another form of rutting is shoving, where the tires apply large forces in the direction of motion during braking. There are recent data from the ITS in Berkeley on the effect of temperature on the permanent distortion under simple shear stress as a function of temperature. In these repetitive simple shear tests (RSST), disks of AC were subjected to pulsed shear stresses, S, in the form of a haversine in time, $S = S_0 (1\text{-}\cos 2\pi ft)/2$. The inverse of the time (0.1 sec.) during which the stress is applied is denoted by f, i.e., f = 10/sec. Each pulse of stress is followed by 0.6 sec of recovery time. The repeated application of this unidirectional shear stress is similar to the pushing by tires that happens most strongly during stopping and starting. **Fig. 3** shows that the number of repetitions required to produce a permanent strain of 0.01 was increased 100 fold by reducing the temperature from 60 °C to 40 °C, i. e., an average of about an order of magnitude for a 10 °C reduction in pavement temperature. (The stress amplitude, S_0 = 84 kPa =12 psi in Fig. 3). An effect of similar magnitude is observed at lower stress S_0 = 56 kPa (8 psi). Preventing a pavement from getting too hot evidently enhances its resistance to failure by shoving.

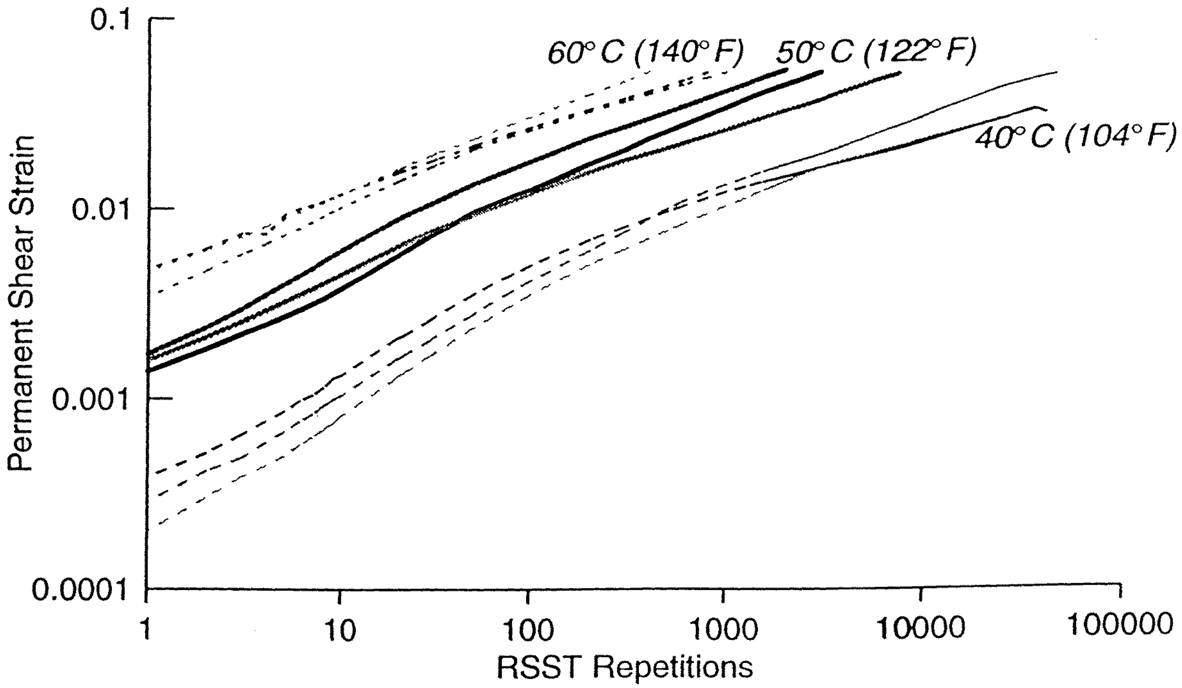

Fig. 3. The Effect of Pavement Temperature on the Permanent Shear Distortion Caused by Repeated Simple Shear Test (RSST) with a Peak Shear Stress of S_0 = 84 kPa

The data indicate that pavements at temperatures higher than about 40°C tend to rut faster. Relevant questions are how much of the time are roads at these temperatures, and how much traffic is present at those times?

Pavement temperatures will depend on the climatic conditions.[3] A variety of pavements were measured in the East Bay Area of San Francisco (Pomerantz et al. 2000b); afternoon temperatures in the summer ranged upward from 120 °F (49 °C) to 150 °F (65 °C); 130 °F (54 °C) was about the average peak. Roads in sunny, southerly latitudes get higher than 50 °C regularly. The theory of Solaimanian and Kennedy (1993) which agrees with our measurements, predicts that the maximum pavement temperature at lower latitudes will exceed the maximum air temperatures by about 25 °C (40 °F). This is confirmed by data (Dempsey & collaborators 1995) for Reno, NV which shows a difference of 22.5° C (40.5°F) between maximum pavement surface temperatures and maximum air temperatures on sunny days during the summer of 1991. In southern regions, where air temperatures often reach 35 °C (95 °F), maximum surface temperatures of 60 °C will be common. Measurements (Asaeda, Ca & Wake 1995; Pomerantz et al. 2000b) have shown that the pavement surface temperature peaks from one to two hours after the solar noon and then gradually falls. Roads will be hotter than 50 °C for a considerable part of the afternoons. At these times, when the roads may be susceptible to damage, there tends to be heavy commuter traffic.

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[3] Some data(Yang 1972) report that at Newark (NJ) Airport the highest pavement temperature reached in Aug. was about 100 °F (38 °C). These temperatures seem too low, since we have measured pavement temperatures about 120 °F (49 °C) in Berkeley in Sept. (See Fig. 1).

It is desirable to have additional direct measurements of test sections of actual roads with different albedos because theories tend to neglect the effects of vehicles on the road temperatures. Vehicles will both heat the roads with their tires, and cool them with shade and by stirring the air. Also, in real traffic the tires wander on the road. In the rutting and RSST experiments described above the strains stayed in a single track.

Effect of Temperature on Aging

Aging of pavements is also believed to involve chemical and physical reactions that are speeded by higher temperatures. As a pavement ages the asphalt becomes stiffer and more brittle. This can lead to cracking. The following is some evidence on the effects of high pavement temperature on aging.

Measurements on asphalt extracted from test sections of pavements (Page et al. 1985) showed that the viscosity increased with age. This "hardening" might be thought to enhance lifetime since "stiffness" is believed to be beneficial for thick pavements. Stiffening is not good for thinner pavements where flexibility prevents cracking. Embrittlement leads to cracking in sudden, single events. The cause is a loss of volatile hydrocarbons, and some oxidation and polymerization. It has been observed that the embrittlement increases with temperature and the intensity of ultraviolet light (Kumar & Goetz 1977); the oxidation rate doubled for every increase of 10 °C (Dickinson 1980).

Tests in various climates in California showed that desert conditions lead to relatively rapid decreases in ductility, as well as increased viscosity (described as "hardening") (Kemp & Predoehl 1981). **Fig. 4** shows the dramatic effect of weathering in a hot and sunny desert climate. The average viscosity of several asphalts exposed to a desert climate with an annual average air temperature of 23° C (73 °F) for about 4 years is 10 times higher than when the average temperature was 17° C (63°F). The dependence on temperature seems to be non-linear; the hardening rate accelerates when the average air temperature exceeds about 13°C (55°F). In these studies, the embrittlement that contributes to road failure is assumed to be due to the same mechanism that increases the viscosity. Thus the embrittlement is likely to decrease if the temperature of the pavement could be decreased. The authors correlate their results with *air* temperatures but they recognize that it is the *asphalt* temperature that is crucial and controllable. They conclude that the durability of asphalt can be improved by "the insulating of the asphalt concrete mat with a cover such as a reflective chip seal in hot areas." A reflective seal has the benefits of both lowering the asphalt temperature and reducing the ultraviolet light damage.

Thus, the durability of roads against various modes of failure can be enhanced by preventing the pavement temperature from becoming too high.

Cost and Benefits of Increased Durability of AC

The evidence cited above indicates the importance of the pavement temperature in determining the lifetime for several failure mechanisms. There remains the question of whether the cost of cooling the road is less than the lifetime cost savings of such a road.

There are not sufficient direct data to provide a complete answer, but the following considerations indicate that cooler roads could be economical.

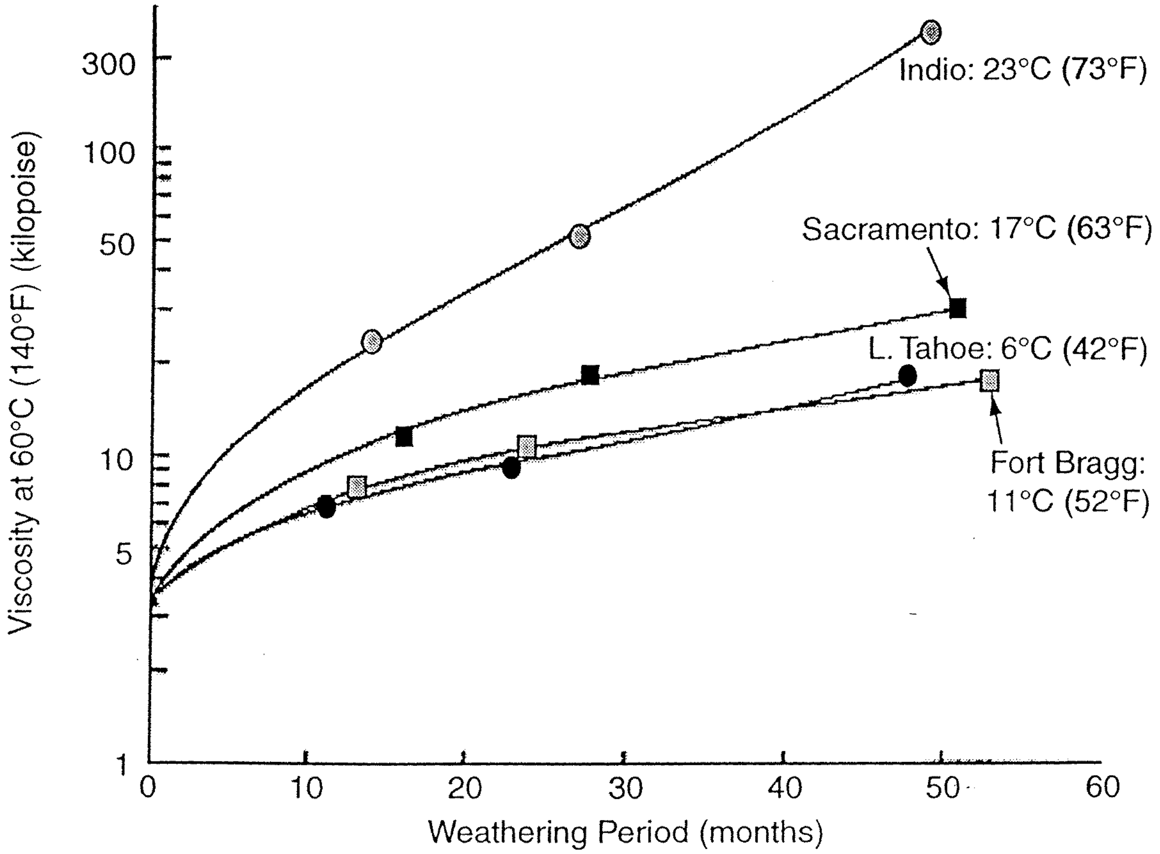

Fig. 4. Effect of Air Temperature on Hardening of Asphalt as a Function of Time (from Kemp and Predoehl, 1981)

The cost will depend on how much the albedo must be reduced to achieve a desired temperature change. The data of Fig. 1 indicates that the slope of the curves, dT/dâ, is about -4 °C per 0.1 increase in albedo with an insolation of about 1000 W/m^2. This maximum magnitude will depend on the thermal conductivity of the pavement structure, the wind speed, and other factors.

There are several methods to construct more reflective roads, including hot-mix AC with light-colored aggregate, cement concrete, chip seals, slurry seals, microsurfacing, sand seals, etc.(Pomerantz et al. 1997) To decrease the surface temperature one need only cover the surface with a reflective layer. The cost is minimized because the layer of the (probably expensive) whiter aggregate is thin.

A well-known method of resurfacing is a "chip seal". Onto the faulty pavement, a layer of asphalt emulsion is spread and, before it dries, a layer of aggregate of uniform size (typically about 3/8 ") is placed on top. The aggregate is pressed into the surface by rollers and also by the traffic. This technique is appropriate when it is time for maintenance, since it adds life to the road and is cooler. Placing aggregate on the binder has heretofore been used as a repair technique, but we suggest that it could also be used as the final treatment of a new road. The additional cost of adding this final layer can be estimated from experience in applying chip seals. Typically, labor plus equipment cost about \$0.34 / m^2 more for a chip seal than for a simple single spreading of emulsion(Means 1996), due to the extra costs of spreading the aggregate, rolling and sweeping. But suppose that a lower temperature were thereby achieved. A lower grade of asphalt might be used where the SHRP specifications call for a higher grade of asphalt. The savings of \$0.60 / m^2 in binder cost could be applied against the additional costs of the equipment, labor and materials, allowing \$0.26 / m^2 toward the cost of the required 0.016 tons/m^2 of aggregate[4]. This allows for a cost of \$16/ton of extra aggregate. This is a typical cost of aggregate; white aggregate would likely cost more.

The question then arises, how white does the aggregate have to be? We made test samples of chip seals by spreading aggregates onto an asphalt emulsion (Pomerantz et al. 2000). We measured the albedos of the aggregates alone, and then when they were incorporated into the chip seals. The albedos of different aggregates ranged from 0.10 to 0.28; we observed chip seal albedos from 0.08 to 0.20. On average the albedo of the chip seal was about 70% of the albedo of the aggregate. Extrapolating this to higher albedos, to obtain a chip seal with the albedo of cement concrete (0.35) would require aggregate with albedo of 0.5. The cost of such a high-â aggregate depends on the nearness to quarries from which such aggregate is available. The cost of shipping aggregate is about \$0.10 per ton-mi.

Savings might also accrue for resurfacing of pavements. Some engineers find that chip seals last longer than simple black slurry seals, by about 25% (Donelly 1998). But the extra labor and equipment costs of a chip seal makes it about 20% more expensive than a slurry seal (Means 1996). The longer pavement life may pay for the additional cost.

It should be mentioned that chip seals can have undesirable properties. In places where tires are repeatedly turned, such as in cul de sacs, the aggregate tends to be dislodged. It can then be thrown by tires, or tracked into homes. The practice is thus not to use chip seals in such locations (Donelly 1998; Maruffo 1998). Constructing a chip-seal requires the coordination of a precise three-step process and is a little more expensive than simple slurry seals. Part of the resistance to light-colored pavement is that it is often associated with being old or worn (Donelly 1998). Sometimes carbon black is added to asphalt to make it look even blacker (and newer). This attitude does not exist where chip seals are used extensively (Maruffo 1998). In some up-scale communities, black roads are disfavored because they look too much like cities. Such matters of taste may be modified by education in the practical and aesthetic advantages of lighter-colored pavements. Development of low-cost, highly-reflective, surface treatments without the negative aspects of chip seals should be investigated.

Effects of Reflective Pavements on Illumination

If pavements are more reflective, illumination at night is enhanced by the light reflected off the pavement. Thus both traffic signs and pedestrians may become easier to see. According to the International Commission on Illumination (CIE 1984) "In order to make asphalt pavements lighter, some countries (e. g. Denmark) stipulate the inclusion of a proportion of white stones in the bituminous concrete. In Belgium, the use of light-colored stones for chip..sprinkling..is obligatory on the major roads of the State network." The need for better lighting will become greater because of the aging of the population. A consequence

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[4] The amount of aggregate needed can be estimated from the example of Chula Vista, CA, where chip seals on 10, 500 m^2 of pavement require about 170 tons of aggregate or 0.016 ton / m^2(Maruffo 1998).

of the aging of drivers is that it becomes more important that traffic signs and their supports be larger and clearer, increasing their costs. Enhanced visibility due to reflective pavements will help avoid accidents and reduce the costs of automobile insurance. In addition, better illumination probably reduces auto theft and other street crimes.

We made a quantitative estimate of the contribution of pavement reflectivity to the illumination of a subject for the geometry of **Fig. 5**. Part of the illumination of a subject is by light directly from the luminaire, and partly by light reflected off the pavement.

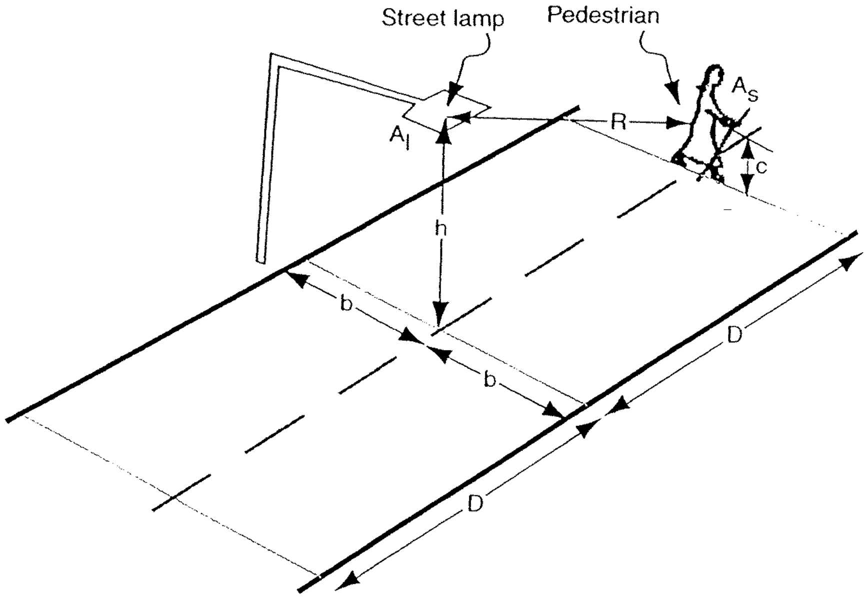

Fig. 5. Geometry of a subject illuminated by a street lamp (luminaire) and a pavement

In a more detailed paper (Pomerantz *et al.* 2000a), we show that the ratio of the light reflected off the pavement, q_r, to the light arriving directly from the street light, q_d, is

$$q_r / q_d \approx \mathcal{R} \qquad (1)$$

where $\mathcal{R}$ is the reflectivity for the spectrum of *visible* light emitted by the lamp[5]. For a $\mathcal{R} = 0.1$, the contribution of reflected light is about 10%; if $\mathcal{R} = 0.3$ the reflected light increases to about 30% of the direct light. This offers the possibility of using fewer or less powerful street lamps, or leaving these unchanged and receiving greater illumination. Our estimate of about 20% reduction in the required strength of the light sources by changing reflectivity from 10% to 30% is similar to the results of a rather different calculation of the number of light fixtures needed to achieve a desired level of illumination with different pavement reflectances (Stark 1986).

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[5] For visibility we are concerned with the reflection of only the visible light emitted by the luminaire. Thus, we use the letter $\mathcal{R}$ to distinguish it from the albedo, which is the reflectivity over the solar spectrum.

The actual visibility depends not only on illumination but also on contrast, which is not an issue here because it depends on the background, which is uncontrolled.

Higher reflectivity does not imply unacceptable glare. The maximum albedos contemplated here are about 0.35, similar to cement concrete. Cement concrete roads are in widespread use around the world; the reader of this article has likely ridden on some. One does not hear that the users of such roads are suffering from glare. It seems likely that AC pavements with such reflectivities will not cause problems from glare.

Conclusions

That high pavement temperatures lead to more rapid deterioration of roads is anticipated by civil engineers. The concept is embodied in the Superpave specifications for the choice of the grade of asphalt binder: one of the criteria for the grade of asphalt is the highest temperatures the pavement is expected to endure. The experiments with the Heavy Vehicle Simulator reported here show quantitatively that at pavement temperatures greater than 40 °C the amount of rutting increases dramatically. Similarly, under simple shear stress, samples suffer larger permanent shear distortion when their temperatures are elevated. Temperatures greater than 50 °C, at which the pavements degrade more rapidly, are known to occur in actual roads even in temperate climates. The traditional means to strengthen pavements is to use a modified or high-grade asphalt binder. An alternative is to make the pavement cooler by reflecting the sunlight before it is absorbed. If the surface of the pavement is kept cooler, the gradient of the temperature inside the pavement will obviously be smaller. The peak pavement temperature can be reduced by about 4°C for each increase of 0.1 of albedo.

One suggested method of increasing the albedo is to cover the pavement with a single layer of aggregate. When used as a repair technique this procedure is known as a chip-seal. Our experiments show that the albedos of chip-seals are about 70% of the albedos of the aggregates. A similar technique may also be applicable to *new* AC construction – by spreading white aggregate as the final layer and rolling it into the pavement. In cases where a high grade or modified asphalt is called for, it might be cheaper to place an additional layer of aggregate. The possibility of covering a road with a thin layer of cement concrete- thin white topping – is being researched in the industry.

More-reflective pavements have the benefits of adding to the effectiveness of street lighting and automobile headlights. Our result for a representative case is that the ratio of reflected light to direct light is approximately equal to the visible reflectivity. Changing from surfaces that are 10% reflecting to 30% would result in 20% more light from luminaires reaching a subject in the middle of a street.

Our laboratory findings indicate that cooler pavements may be considerably more durable against rutting and embrittlement. We believe that tests should now be made on actual functioning roads. Then the effects of time dependent temperatures and flows of traffic will be revealed. The possible benefits of more reflective, cooler pavements are worthy of this serious attention because this might lead to significant reduction in the huge expenditures on the nation's roads.

Acknowledgments

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