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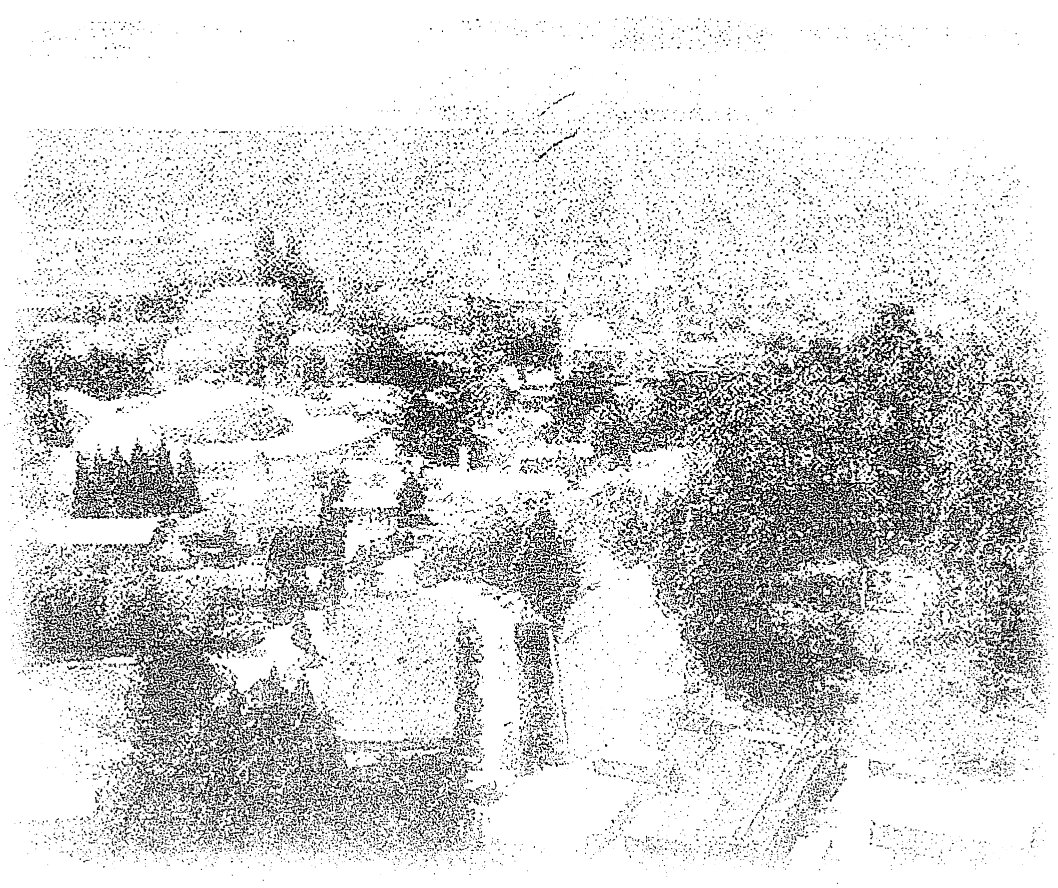

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## Abstract

A semi-quantitative connection between the albedo of pavements and its effect on the diurnal variation of air temperature in large cities is presented. Measurements of albedos and temperatures of a variety of asphalt concrete pavements in the eastern San Francisco Bay Area of California were made. The albedos correlate with pavement age. The time dependence of the pavement temperature is measured and calculated. Measurements show that the albedo of a chip-seal is about 70% of the albedo of the aggregates from which it is constructed. A formula to approximate the reduction of the peak air temperature by higher albedo pavement is derived and compared favorably to simulations.

## I. Introduction

Heating of pavements by sunlight has been suggested as one of the causes of "urban heat islands," the excess heating of cities compared to their surroundings. The reasoning is that pavements of most cities are made of asphalt concrete[1] (AC) which is quite dark. This means that it absorbs most of the visible light that falls on it. (Asphalt pavements similarly absorb the invisible infrared solar radiation.) Thus the energy in the absorbed sunlight becomes heat in the pavement. Because AC is one of the darkest sur-

[1] "Asphalt" is the black binder that holds together rocky aggregates to form a composite, generically called concrete. The composite is commonly called "asphalt," but is properly called "asphalt concrete," abbreviated AC. In the other common type of paving material, the binder is Portland cement, which serves to bind aggregate into a concrete. This composite is properly called Portland cement concrete but is commonly called "concrete." In this paper we adhere to the strict usage and refer to *binders* as "asphalt" and "cement" and the *composite* of binder and aggregate as "concrete."

faces in the city, it is likely to be one of the hottest. In turn, the air is heated by the pavement. In hot cities, this contributes to the need for air conditioning. The hotter air also contributes to the production of smog (ozone). Cities might not warm as much if the pavements absorbed less sunlight. In this report we make semi-quantitative connections between the albedos[2], â, of existing pavements and their effects on air temperature.

There exists some documentation about the albedos of pavements actually extant in cities and the temperatures to which they are heated by sunlight. The literature reports values of AC pavement albedos from 0.05 to 0.15 (Bolz *et al.* 1973) with aging suggested as the explanation of the variation. The air and pavement temperatures at various times of day have been measured (Yang 1972; Asaeda *et al.* 1995) and peak temperatures have been calculated (Solaimanian *et al.* 1993). Starting from the results of a meteorological simulation of Los Angeles (Taha 1997), it was estimated (Pomerantz *et al.* 1997) that if the sunlight absorbed by all the pavements were reduced from 90% to 65%, the peak air temperature would decrease by about 0.6°C (1°F) (population-weighted and on a hot day in August).

The goal of this paper is to elucidate the effect of pavements on the air temperatures of large cities. By "large cities," we mean that the air temperature in most of the city is determined by the surfaces within the city and not much affected by wind flow from the outside.

We begin with a survey of the albedos of streets that we measured in the eastern San Francisco Bay Area of California and consider these as a function of the age of the pavements. We also show some measured daytime variations of pavement temperatures and compare them to the variation of sunlight and air temperatures. We then calculate this time course of the pavement temperatures; the agreement with measurements suggests that we understand the major causes of the phenomena. These data confirm the hypothesis that the pavement albedo strongly influences the pavement temperature. We then consider one means of increasing the albedo, resurfacing with a "chip seal." We report measurements of the ratio of the albedo of chip seals to the albedo of the aggregates from which they are constructed. Combined with the above results, this gives a sense of the degree to which pavements can be whitened and made cooler. The ultimate goal is to re-

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[2]Albedo is defined as the reflectance of a surface, averaged over a hemisphere and the solar spectrum. A perfect solar reflector has â = 1, and a perfect absorber has â = 0.

duce air temperatures. To this end, we make a simple semi-quantitative estimate of the contribution of pavements to the diurnal change in air temperature. In sum, given the albedo of the aggregate chosen for a chip seal, we can very simply predict the approximate maximum cooling of a large city.

## II. Measurements of pavement albedos and temperatures

The albedos of pavements were measured following ASTM Standard E1918-97. To measure the solar radiation we used an Eppley PSP Precision Pyranometer. This is faced downward to measure the reflected solar radiation from a surface and upward to measure the incident radiation. The ratio is the albedo of the surface.

The temperatures of pavement surfaces were measured at several points separated by a few meters. (This is necessary because there may be underground sources of heating or cooling such as steam or water pipes.) We measured the pavement temperatures with a Raytek infrared thermometer. It provided the temperatures accurately and rapidly compared to contact surface thermometers that are slower to come to equilibrium. All the pavement temperatures were measured with the Raytek instrument set to an emissivity, $\varepsilon$, of 0.9. (We did not make measurements of the emissivities of each pavement, but 0.9 is a typical value for most insulators.) At each site we also measured the air temperature using a mercury thermometer set in the shade.

Pavements for measurement were selected by two criteria. One was to obtain a wide range of samples of AC pavements with the goal of investigating the albedos of existing pavements. The second was to check the influence of aging on albedos of pavements. AC pavements are a composite of asphalt binder with mineral aggregate in typical proportion (by volume) of about 15% and 85%, respectively. The asphalt is black, with an albedo of about 0.05, and it coats the aggregate particles (typically lighter in color) in order to bind them together. A new pavement is thus quite black, but as the asphalt wears off, the aggregate shows. As the pavement wears, the albedo approaches the albedo of the aggregate. Also the asphalt itself becomes lighter due to oxidation.

To ensure that we included pavements spanning a range of ages, we obtained from Departments of Public Works their records of street resurfacing. Included were the California cities of Berkeley, Concord, Oakland, Pleasant Hill, San Ramon, and Walnut Creek. We also inquired about the kinds of aggregates used and included all of them in our sample. We then measured the albedos and temperatures of pavements whose ages were known. In addition there was a resurfacing of streets and parking lots immediately around our offices at LBNL in September 1996. We had made measurements then, and we repeated them in September 1998. The results for the albedos of roads from new to 18 years old are shown in **Figure 1**.

The data indicate that a fresh AC pavement has an albedo of about 0.04 to 0.05. Pavements that are more than five years old have an average albedo of 0.12 ± 0.03. The two oldest pavements in our sample have albedos lower than this range, which does not fit the rule. This points to the fact that our sample is real-life pavements whose constructions are subject to change over time and whose histories of exposure to traffic, moisture, shade, dirt, etc. were uncontrolled. But, for all of the aging and the vagaries they may have experienced, these ordinary AC pavements do not have albedos higher than about 0.16.

The distribution of albedos we measured is shown in the histogram of **Figure 2**. Pavements usually are resurfaced about every ten to fifteen years, depending on the deterioration they suffer. The albedos of the pavements we measured cluster about 0.12.

Several authors (Yang 1972; Asaeda *et al.* 1995) report the temperatures of pavements as a function of time during the day. We made our own measurements because we wanted to do a careful comparison taking account of other parameters, such as sunlight and pavement albedo, which were heretofore usually not all specified. In **Figure 3** we show hourly values of temperatures measured on two pavements of differing albedos: $\hat{a} = 0.04$ (upper curve) and $\hat{a} = 0.16$ (lower). The data were all collected on the same day, September 17, 1998, a distance of 2.6 kilometers (1.6 miles) apart.

The peak surface temperatures are about 56°C (133°F) for the lower-â pavement and 47°C (117°F) for the higher-â pavement. Calculations to be detailed below indicate that the difference in albedo alone is not sufficient to explain the temperature difference. The difference in the peak temperatures is about 9°C (16°F), or an apparent dependence of the change in temperature on the change in albedo of $\Delta T/\Delta\hat{a} = -7°C/0.1$ (-13°F/0.1). This ratio is larger than others we have measured in more controlled circumstances. For example, in **Figure 4** we show data measured at a site outside our offices in Berkeley at which we had three adjacent pavements, a new one with $\hat{a} = 0.05$, an old one with $\hat{a} = 0.15$, and one with an experimental coating with $\hat{a} = 0.51$. The proximity means that the history of heating by sunlight and cooling by winds were quite similar for these pavements. (Unlike the situation in Concord where the pavements were 2.6 km (1.8 mi) apart, whose shading and wind patterns might be quite different.) For the Berkeley pavements we find $\Delta T/\Delta \hat{a}$ = -3.9°C/0.1 (-7°F/0.1). In Figure 4 we also display data measured in San Ramon. In this case also we had a light-colored cement concrete pavement with $\hat{a}$ = 0.33 adjacent to an AC pavement with $\hat{a}$ = 0.1. Again the thermal histories are similar to each other, and we obtain the dependence $\Delta T/\Delta \hat{a}$ = -5.3°C/0.1 (-9.6°F/0.1).

We remark that the heating of the pavement does not follow immediately the intensity of sunlight; the peak of sunlight is always between noon and 1 PM (standard time) but the pavement temperature does not reach its peak until at least an hour later. We shall explain and discuss this time lag in detail in the next section.

## III. Discussion and calculation of pavement temperatures

The temperature of the air near the ground, which is what directly affects humans, is dependent on the absorption of sunlight by solid surfaces (Gedzelman 1980). It then follows that reducing the absorption of sunlight can reduce the temperature to which the pavements rise. This is one way to mitigate heat islands. We now discuss some evidence that the solid surfaces are the primary cause of heating of the air.

The solar constant—the solar energy flux arriving at the top of the atmosphere—is 1353 $W/m^2$ (Siegel *et al.* 1981); at sea level the maximum is about 1100 $W/m^2$. This is about a 30% reduction due to the entire atmosphere whose thickness is about 5 km (3 mi) at sea level pressure. The air within, say, 30 m (100 ft) of the surface directly absorbs its proportional fraction of the 30% total atmospheric absorption; about 0.2% of the incident power. The direct surface-air absorption is thus negligible compared to pavements that absorb up to 95% of the insolation (and then heat the surface air).

The first step in the process of heating the air is thus the heating of the surface. The effect of increasing pavement albedo on pavement surface temperature can be calculated by applying the law of conservation of energy to the heat flows into and out of the surface (Incropera *et al.* 1985). After sunlight is absorbed (in proportion to solar absorptivity, $\alpha = (1 - \hat{a})$, and the solar power density, I) heat flows into the surface. Heat is lost by radiation to the cooler sky, according to the Stefan-Boltzmann law, $\varepsilon\sigma T^4$. Heat is also convected into the air above the pavement, proportional to the convection coefficient, $h_{conv}$, and the temperature difference between the pavement surface and the air, $(T_s - T_{air})$. Heat is conducted from the surface at z = 0 downward toward the deep earth, assumed to maintain a constant temperature over the period of interest. The equation expressing the conservation of energy for a dry surface, is

$$(1-\hat{a})I = \varepsilon\sigma(T^4_s - T^4_{sky}) + h_{conv}(T_s - T_{air}) - \kappa(dT/dz)|_{z=0} \quad (1)$$

The heat conduction through the solid pavement is governed by the one– dimensional heat equation

$$d^2 T_s/dz^2 = (\rho c/\kappa)dT_s/dt \quad (2)$$

Equations 1 and 2 were solved simultaneously for $T_s$, using values of emissivity $\varepsilon = 0.9$, $T_{sky} = 283$ K = 10°C = 50°F, thermal conductivity of the pavement $\kappa = 1.7$ W/K·m, $h_{conv} = 6$ W/K·m$^2$, specific heat c = 0.74 kJ/kg·K, density $\rho = 2.3$ gm/cm$^3$ and a deep-earth temperature $T_i = 293$ K. Using the time dependence of the insolation and the air temperatures for the same date and a location similar to the pavement site in Concord, CA (we chose September 17, 1997, in San Jose) we calculate the time dependence of pavement surface temperatures shown in **Figure 5**. The qualitative agreement with the measurements of Figure 3 gives confidence that we understand the main thermal processes.

To isolate the effect of albedo on pavement temperature, the calculation was repeated for values of â from 0.1 to 0.4. Note that for the calculations we shall discuss only the peak temperatures. From the results (**Figure 6**) we derive $\Delta T_S/\Delta\hat{a}$ = -3.7°C/0.1 (-6.7°F/0.1) at the peak pavement temperature; this is close to what is observed in Figure 4 (about -4.4°C/0.1 or -8°F/0.1). Others (Solaimanian *et al.* 1993) have calculated the change in peak pavement temperature, $\Delta T_S/\Delta\hat{a}$ = -3.5°C/0.1 (-6.3°F/0.1) for a particular set of parameters. Their values of â, $\varepsilon$, $h_{conv}$, and $\kappa$ are similar to ours, but their insolation and air temperatures are larger. Nevertheless we obtain similar results, which is satisfying. However, these calculated values are rather less than the measured ones we obtained in Figure 3. We suspect that the discrepancy may arise from the difference in wind speed, or other local factors such as shading, between the two sites measured for Figure 3. Thus we repeated calculation for a higher convection, $h_{conv} = 24$ W/°C·m$^2$, corresponding to a wind speed of about 10 km/hr. For better comparison with Figure 3, we used the exact albedos measured in Figure 3 but with two values of $h_{conv}$ for the higher-â pavement. The maximum difference between the upper and lower curves of **Figure 7** gives a result $\Delta T_S/\Delta\hat{a}$ = -13°C/0.1 (-23°F/0.1). This is deceptively large because there are both higher albedo and larger convection but only albedo was measured. Thus, if the wind were stronger at the higher albedo pavement, the pavement would remain cooler than the increased reflectivity alone would produce.

## IV. Albedos of chip seals

The next question is how to achieve the higher albedo of pavements, at a reasonable cost and with practical methods. In an earlier report (Pomerantz *et al.* 1997) we concluded that the most economical approach is to apply a thin light-colored topping on the pavement. This assumes that the light-colored material is more expensive than the ordinary material and thus is to be used as sparingly as possible. The light-colored toppings known to us include chip-seals[3] and Portland cement concrete white-topping. Portland cement white-topping is currently being developed (ACPA 1998); cement concrete is whiter than asphalt concrete because the cement binder is not as black as asphalt. Since white topping is less common at this time, the discussion below will focus on chip-seals based on asphalt binders.

One way to use asphalt as the binder, and still achieve a light color is to cover the binder with a whiter material, as is done with chip-seal resurfacing. The method consists in first spreading a thin layer of asphalt binder. Before that hardens, a layer of aggregate is spread. This is followed by rolling of the aggregate into the binder. The aggregate is partly exposed and thus the chip-seal has an albedo somewhere between that of the aggregate and the asphalt. We have conducted some experiments to estimate the final albedo of a chip seal constructed from aggregates of varying albedos.

The binder we used was an SS 1-H anionic emulsion, which is 60% petroleum asphalt and about 40% water when spread. The aggregates were of approximately uniform size about 6 mm diameter, typical of chip-seals. The albedos were measured using a Solar Spectrum Reflectometer made by Devices and Services Company. First the albedos of the aggregates alone were measured. They are listed in the second column of Table I, as A. Then asphalt emulsion was spread to a depth of about 3 mm in eight shallow containers. Onto the surface of the emulsion in each container was spread one of the aggregates to a depth of one stone. The aggregates were pressed into the binder and the sam-

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[3]Chip seals are sometimes referred to as "surface treatments," but "surface treatment" may signify other methods (Asphalt-Institute 1989). "Chip-seal" is a clearly descriptive term, so we prefer it.

ples were allowed to harden. The excess aggregate was removed and the samples were measured with the reflectometer. The results are listed in the third column of Table 1, under C. The ratios of the albedos of the chip seal, C, to that of the aggregates, A, are given in the fourth column. The average ratio of albedos of chip seals to their aggregates is 0.67 with a scatter of about 0.11. As a rough guide, we estimate that the albedo of a chip seal will be about $^2/_3$ of the albedo of the aggregate from which it is composed. Thus to obtain a pavement albedo of 0.35 we estimate that an aggregate with albedo of about 0.5 should be used.

| Sample | Albedo of Aggregate = A | Albedo of Chip-Seal = C | Ratio = C / A |
|---|---|---|---|
| Asphalt emulsion only | No aggregate | 0.05 (asphalt) | |
| "Blue Rock" basalt from Syar quarry. Thin binder. | 0.10 | 0.082 | 0.82 |
| "Blue Rock" basalt from Syar quarry. Thicker binder. | 0.10 | 0.081 | 0.81 |
| Pamy pebbles (Soil Products Co.) | 0.21 | 0.12 | 0.57 |
| "Sierra White" granite (Soil Products Co.) | 0.28 | 0.16 | 0.57 |
| "Sierra White" granite (San Ramon Pub. Wk.) | 0.26 | 0.20 | 0.77 |
| Standard chips (Kaiser Sand and Gravel) | 0.17 | 0.094 | 0.55 |
| Smaller chips (Kaiser Sand and Gravel) | 0.18 | 0.11 | 0.61 |

Table 1. Albedos of asphalt, aggregates and the chip seals made of them.

## V. Estimate of pavement contribution to air temperature

Thus, there are practical ways to increase the reflectivity of pavements and thereby lower the pavements' temperature. The goal for energy and smog reduction is, however, to reduce the air temperature. We now estimate the order of magnitude of the effect of change in albedo of pavements on air temperature.

Considerable effort has gone into finding the change in temperature by simulating the complete meteorological effect of surface modifications. For example, the change in air temperatures in Los Angeles (LA) resulting from whitening both pavements and roofs was calculated (Taha 1997). The result is a predicted decrease of 1.5°C (2.7°F) averaged over the modified urban area. In a linear interpolation of this result[4], the decrease in air temperature due to an increase of pavement albedo is 0.6°C (1.1°F) (Pomerantz *et al.* 1997). Such detailed simulations are important, but there is some benefit in being able to make a quick estimate of the amount by which higher albedo surfaces reduce air temperature increases.

The goal here is to estimate the contribution of pavement temperature to the air temperature by using readily available data on the diurnal air-temperature increase, the extent of pavement, and the albedos. Our approach is based on the assumption that the major part of the diurnal cycle in local air temperatures is caused by the heating of solid surfaces in that locality. We express this as a proportionality between the *observed swings* in daily air and surface temperatures:

$$T_{aM} - T_{am} = \gamma(T_{sM} - T_{sm}) \quad (3)$$

or

$$\Delta T_a = \gamma(\Delta T_s)$$

where $\Delta T_a = T_{aM} - T_{am}$ is the diurnal change in air temperature from its minimum, $T_{am}$, to its maximum, $T_{aM}$. Similarly, the diurnal change in surface temperature, $\Delta T_s$, is the difference between $T_{sm}$ and $T_{sM}$, the minimum and maximum surface temperatures, respectively. Pavements contribute an amount $\Delta T_{ap}$ to the air temperature change. In the Appendix we derive the effect of whitening the roads, i.e., changing the pavement absorptivity to a lower value, $\alpha_{pL}$, from a higher value, $\alpha_{pH}$. According to Eq. A.14, the whiter pavement contributes less to the air-temperature change by $\partial\, \Delta T_{ap}$, where

$$\partial\, \Delta T_{ap}/\Delta T_a \approx (A_p/A) \cdot (\alpha_{pL} - \alpha_{pH})/\langle\alpha\rangle \quad (4)$$

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[4]Taha's calculation had equal areas of roofs and pavements. Increases in albedo were: 0.35 (roofs) and 0.25 (pavements). These albedo changes produce temperature decreases of $^5/_{12} \cdot -2.7°F = -1.1°F$ (for pavements) and $^7/_{12} \cdot -2.7°F = -1.6°F$ (for roofs).

Here $<\alpha> \equiv \sum\alpha_j \cdot (A_j/A)$ defines the mean absorptivity of all the surfaces, j, in the city, weighted by their fraction of the city's area, $A_j/A$. $(A_p/A)$ is the fraction of the city's area that is paved.

As an example of Eq. 4, for southern cities far from the cooling effects of water, such as Phoenix and Dallas, the daily average temperature change, $\Delta T_a$, is about 12°C (22°F) in the summer (USAstatistics 1994). If we consider only sunny days, in order to assess the maximum effect, the average maximum $\Delta T_a$ is closer to 14°C (25°F). Evaluating Eq. 4 with $\Delta T_a$ = 14°C (25°F), $<\alpha>$ = 0.8, and the same parameters as in Taha's work on the L.A. Basin (Rosenfeld *et al.*, 1998)—$A_p/A$ = 0.125, $\alpha_{pL}$ = 0.65, and $\alpha_{pH}$ = 0.9—we obtain the maximum *air* temperature change due to cooler pavements $\partial\, \Delta T_{ap} \approx$ -0.55°C (-0.98°F). This confirms the result deduced from Taha's simulation, $\partial\, \Delta T_{ap} \approx$ -0.61°C (-1.1°F).

Note that Eq. 4 relies on several assumptions:

a) the temperature of the air in a region is determined only by the surfaces within that region. Thus the region chosen must be large enough that effects at its edges are negligible. Eq. 3 is wrong for cities that are windy or near large bodies of water. This assumption gives the maximum effect of local changes of albedo on local air temperature, since wind will only mask the effects of albedo modifications. (To prove windlessness requires the full meteorological simulation á lá Taha. In the case of LA, Taha finds that cooler surfaces influence temperatures no more than 5 km downwind, so our assumption applies to the LA basin.)

b) additivity of the effects of the various surfaces of the city. Taha *et al.*'s (Taha *et al.* 1997) simulation has demonstrated that the rise in air temperature is the sum of the effects of impermeable surfaces and trees.

The conditions in LA satisfy the assumptions and indeed the estimate is in agreement with the simulation. Taha *et al.* have now simulated the effects of increased vegetation and higher albedo of all impermeable surfaces in ten cities (Taha *et al.* 1999). The results for most cities is -1.0°C (-1.8°F), of which about half (0.5°C, 0.9°F) is due to the impermeable surfaces. Applying Eq. 4, with Taha *et al.*'s parameters (an average absorbtivity of 0.8, decreased by 0.15, and a modified area $(A_i/A)$ = 0.25), we find maximum temperature lowered by 14°C · 0.25 · (-0.15/0.8) = 0.66°C due to all impermeable surfaces. This is reasonable semi-quantitative agreement with the complete simulation and gives support to the approximate formula.

## VI. Conclusions

We have sampled the albedos of asphalt concrete pavements in our area and found them to be similar to what has been reported in the literature. The albedo of new asphalt pavements is about 0.04. Pavements that are about 5 years old have albedo of about 0.12 ± 0.02. This is probably due to the wearing off of the black asphalt binder which exposes the lighter-colored aggregate, oxidation of the asphalt, and soiling with lighter-colored dirt.

Experimentally we find that an increase in albedo by 0.1 produces a change in pavement surface temperature of about -4 ± 1°C (-7 ± 2°F) for an insolation of about 1000 $W/m^2$ when there is little wind. By calculation, we find that the maximum pavement temperature changes by about -4°C (-7°F) for an increase in albedo of 0.1. Increasing wind speed lowers the surface temperature and diminishes the influence of the change in albedo.

We measured the pavement surface temperatures during the course of a day. We also calculated the surface temperature, using as inputs the insolation and air temperature of a similar locality. The agreement indicates that we understand the main processes of heating of pavements.

One method of constructing higher albedo pavements is chip-sealing. The procedure is to spread a thin layer of asphalt binder, cover it with a layer of aggregate and then press the aggregate into the binder. Our experiments show that the resulting chip-seal has an albedo about 67 ± 10% of the albedo of the aggregate. Thus a chip-seal with an albedo of 0.35, approximately that of fresh cement concrete, might be achieved with aggregate which has an albedo of 0.5. The availability of appropriate and inexpensive aggregate depends on the location.

The ultimate goal is to reduce high summertime air temperature and thereby save energy and reduce pollution. A direct way to achieve this is to reduce the temperatures of the surfaces that are the cause of the hot air. We derive an approximate formula for the change in the peak air temperature that would be caused by a change in the albedos of the surfaces. The result, Equation (4), should apply to cities in which the winds do not mix the air from outlying areas. (The effects of albedo changes will be washed out where the wind is high.) The agreement with detailed simulations is good for all appropriate cases. In typical cases we find that the increase of pavement albedo from 0.1 to 0.35 in the whole city will result in a decrease in air temperature of about 0.6°C (1°F).

Because we have control of the reflectivity of man-made surfaces, we can in principle make urban areas even cooler than the natural environment by making the albedo higher than that of the native ground. The evaporation of water from the ground is another factor that could be beneficial if the surface is permeable and can hold water. But if one must have impermeable surfaces—such as roofs and pavements—their effects on temperature increases can be minimized by making their albedos as high as possible.

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## Appendix: Derivation of an approximate formula for the contribution of pavements to the air temperature increase

Because the air-temperature change is caused by changes in surface temperatures, as explained above and represented by Eq. 3,

$$\Delta T_a = \gamma(\Delta T_s) \qquad \text{Eq. 3 and (A.1)}$$

$$T_{aM} - T_{am} = \gamma(T_{sM} - T_{sm})$$

we first seek a simple expression for surface temperatures. We approximate Equation (1) by replacing the temperature gradient, a differential, by a difference between $T_s$ and the temperature in the interior of the pavement, $T_i$, at a distance $\Delta z$. Also, we factor the difference of fourth powers of the temperatures. These give

$$\alpha I = (1 - \hat{a})I \approx \varepsilon\sigma(T^2_s + T^2_{sky})(T_s + T_{sky})(T_s - T_{sky}) + h_{conv}(T_s - T_{air}) - \kappa(T_s - T_i)/\Delta z \qquad \text{(A.2)}$$

We approximate $(T^2_s + T^2_{sky})(T_s + T_{sky}) \approx 4T^3_{sky}$.

All the terms on the right hand side of Eq. A.2 then have the form of differences from $T_s$ so we rewrite them as

$$\alpha I \approx k(T_s - T_{eff}) \qquad \text{(A.3)}$$

This gives

$$kT_s = 4\varepsilon\sigma T^3_{sky}T_s + h_{conv}\, T_s - (\kappa/\Delta z)\, T_s, \qquad \text{(A.4)}$$

which defines

$$k \equiv 4\varepsilon\sigma T^3_{sky} + h_{conv} - \kappa/\Delta z. \qquad \text{(A.5)}$$

$k$ represents heat flows by radiation, convection, and conduction. $T_{eff}$ is defined by

$$T_{eff} \equiv (4\varepsilon\sigma T^4_{sky} + h_{conv}T_{air} - (\kappa/\Delta z)T_i)/k. \qquad \text{(A.6)}$$

It is an effective temperature toward which the surface temperature is relaxing. From Eq. A.3, the surface temperature is

$$T_s \approx (\alpha/k)I + T_{eff} \quad (A.7)$$

Substituting Eq. A.7 in Eq. A.1 we obtain

$$\Delta T_a \approx \gamma\{(\alpha/k)I + (T_{eff} - T_{sm})\} \quad (A.8)$$

To estimate the relative magnitudes of the terms on the right, we insert values appropriate to Fig. 5: $\varepsilon = 0.9$, $4\varepsilon\sigma = 2 \cdot 10^{-7}$ $Wm^{-2}K^{-4}$, $T_{air} = 297$ K, $T_{sky} = T_{air} - 10$ K $= 287$ K, $h_{conv} = 6$ $Wm^{-2}K^{-1}$, $\kappa/\Delta z = 1.7$ $Wm^{-1}$ $K^{-1}$ / 0.1 m = 17 $Wm^{-2}$ $K^{-1}$, $T_i = 291$ K. This gives values of $k \approx 29$ $Wm^{-2}K^{-1}$, and $T_{eff} \approx 291$ K. Thus, with $\alpha = 0.9$, $I = 800$ $Wm^{-2}$ and $T_{sm} = 283$ K, we get $(\alpha/k)I = 24$ K, and $(T_{eff} - T_{sm}) = 8$ K. To about a 30% error, we neglect $(T_{eff} - T_{sm})$ compared to $(\alpha/k)I$. This reduces Eq. A.8 to the simple form of a linear dependence of $\Delta T_a$ on $\alpha$:

$$\Delta T_a \approx \gamma(\alpha/k)I \quad (A.9)$$

Because the city is composed of various surfaces, Eq. A.9 should be generalized to express the total temperature change as the sum of the changes produced by each type, j, of surfaces. We assume the fraction of air temperature increase caused by each type of surface, $\Delta T_{aj}$, having area, $A_j$, is proportional to its fraction, $A_j/A$, of the total area A, and its contribution to the air temperature change, which by Eq. A.9 is proportional to its absorptivity $\alpha_j$. Thus, the total change in air temperature is the sum of the contributions of all the solid surfaces:

$$\Delta T_a = \Sigma \Delta T_{aj} \approx \gamma I \Sigma(\alpha_j/k_j)\ A_j/A \quad (A.10)$$

To focus on the absorptivity, we make the approximation that all the $k_j$ have the same value $= k$. Then Eq. (A.10) simplifies to

$$\Delta T_a \approx (\gamma I/k)\Sigma\alpha_j A_j/A = \gamma I\langle\alpha\rangle/k \quad (A.11)$$

This defines the mean absorptivity $\langle\alpha\rangle \equiv \Sigma\alpha_j \cdot (A_j/A)$. Eq. A.11 has the intuitively correct properties that the diurnal temperature-swing increases with the intensity of the sunlight and the mean absorptivity of the surfaces, and is inversely proportional to the total conductivity.

By Eq. A.10, the contribution to the air temperature rise due to the pavement (indicated by subscript p) is:

$$\Delta T_{ap} \approx (\gamma I/k)\alpha_p(A_p/A) \qquad (A.12)$$

where the fractional area of pavement is $(A_p/A)$. The fractional contribution of pavements to the total increase is thus the ratio of Eq. A.12 to Eq. A.11:

$$\Delta T_{a,p}/\Delta T_a \approx (A_p/A) \cdot (\alpha_p/<\alpha>) \qquad (A.13)$$

If the pavement absorptivity is changed to a lower value, $\alpha_{pL}$, from a higher value, $\alpha_{pH}$, there is a change in the pavement contribution to the air temperature, $\partial\, \Delta T_{ap}$. The result for the change in air temperature due to a change in pavement albedo:

$$\partial\, \Delta T_{ap}/\Delta T_a \approx (A_p/A) \cdot (\alpha_{pL} - \alpha_{pH})/<\alpha> \qquad (A.14)$$

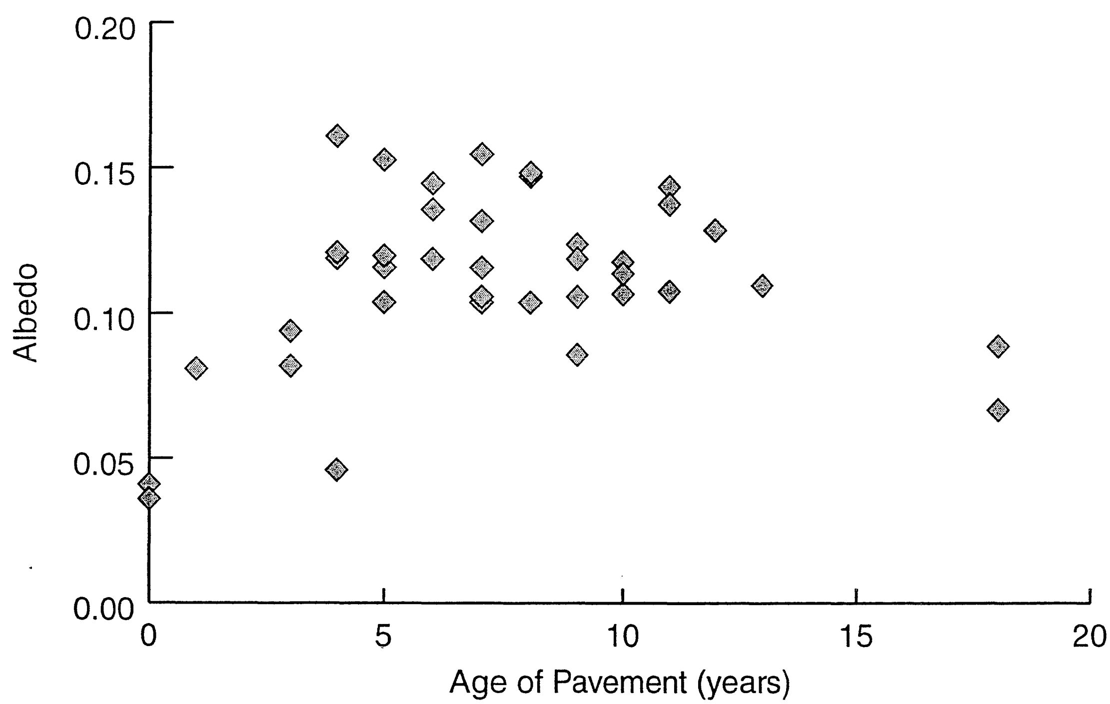


Figure 1. Age dependence of albedos of asphalt concrete pavements in the East Bay Area of San Francisco, CA.

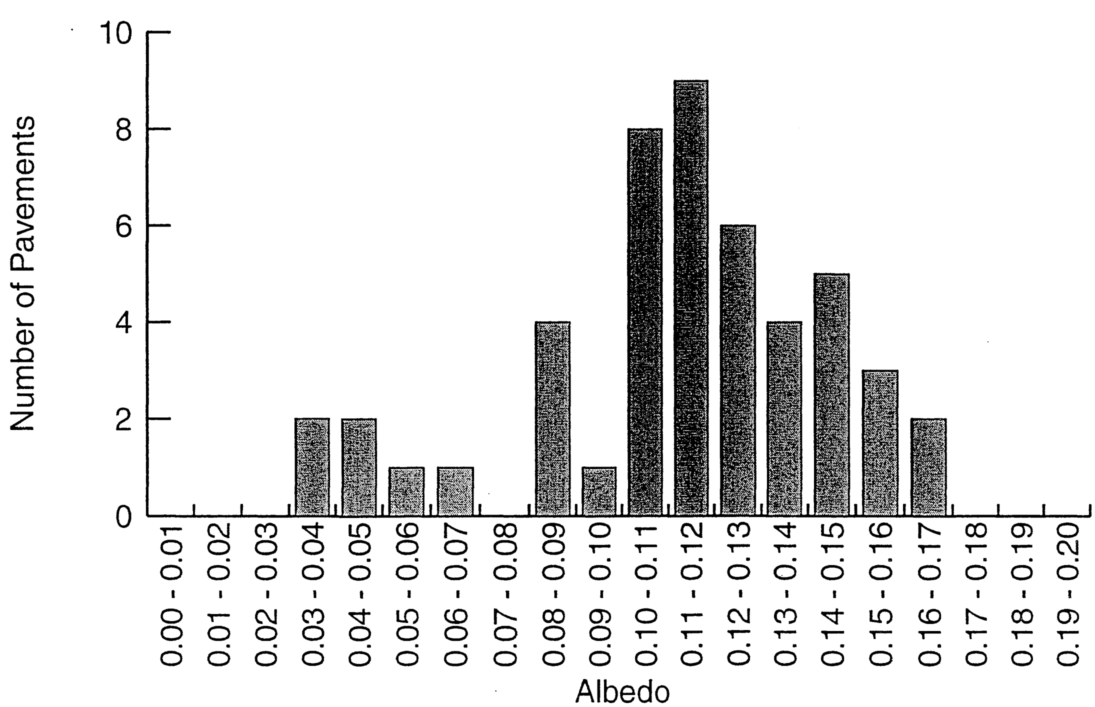


Figure 2. Histogram of the number of pavements vs. their albedos.

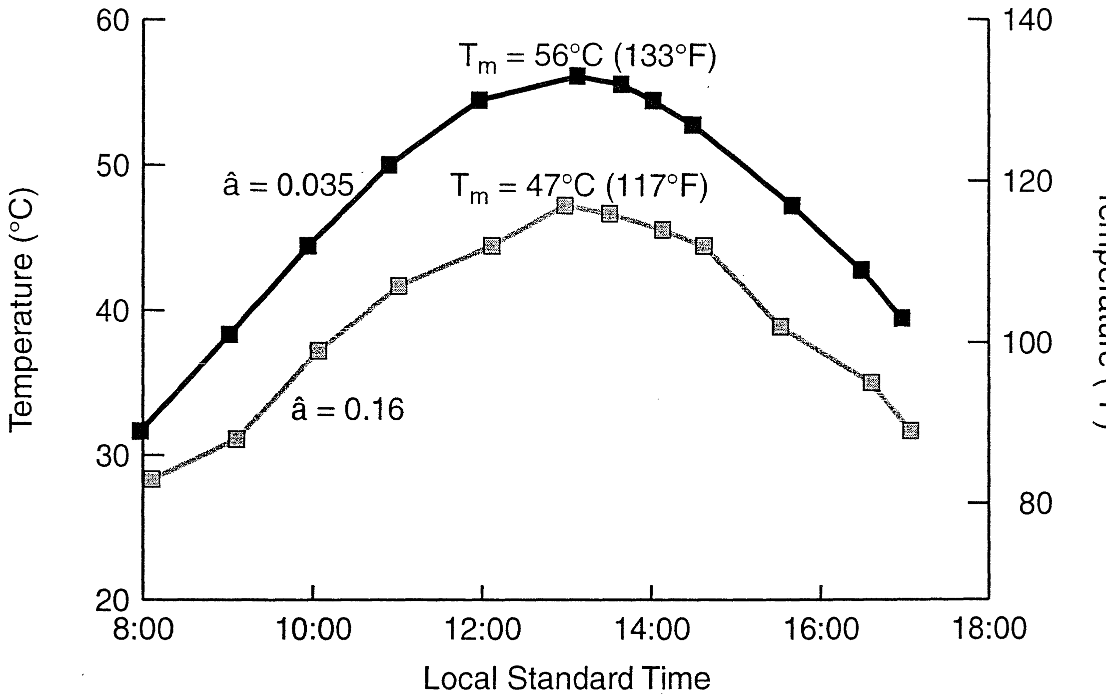


Figure 3. Time dependence of the surface temperatures of asphalt concrete pavements of different albedos measured at different locations in Concord, California, on September 17, 1998.

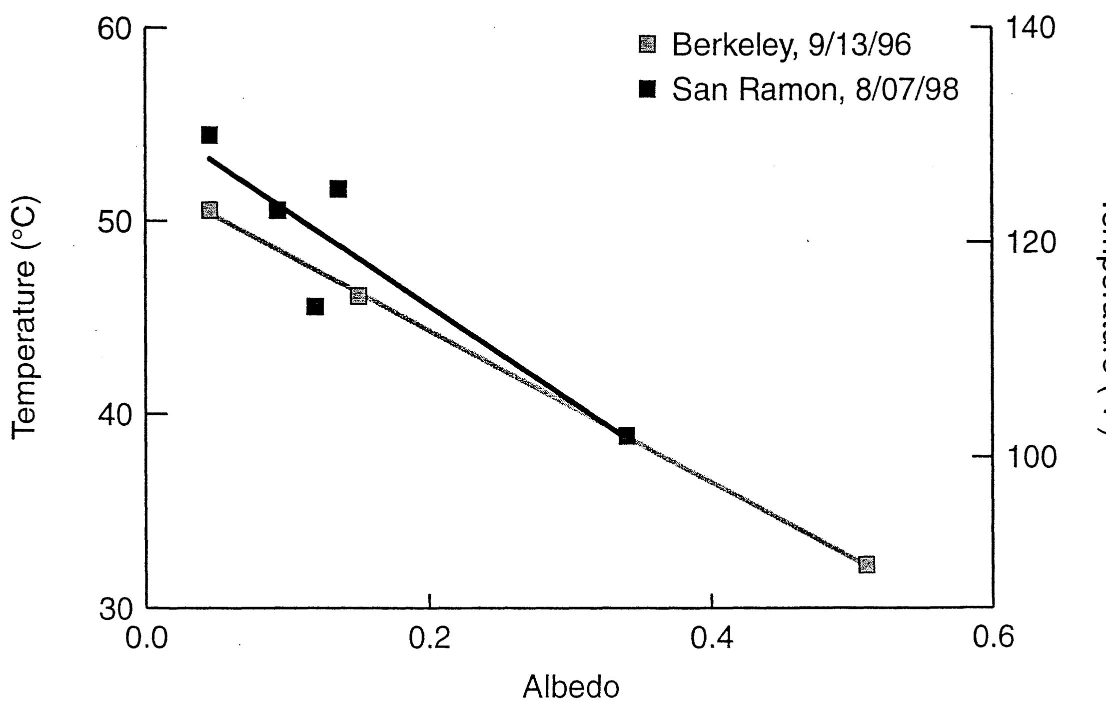


Figure 4. Pavement surface temperatures vs. albedos in Berkeley and San Ramon, California. At both locations, the different pavements were close together.

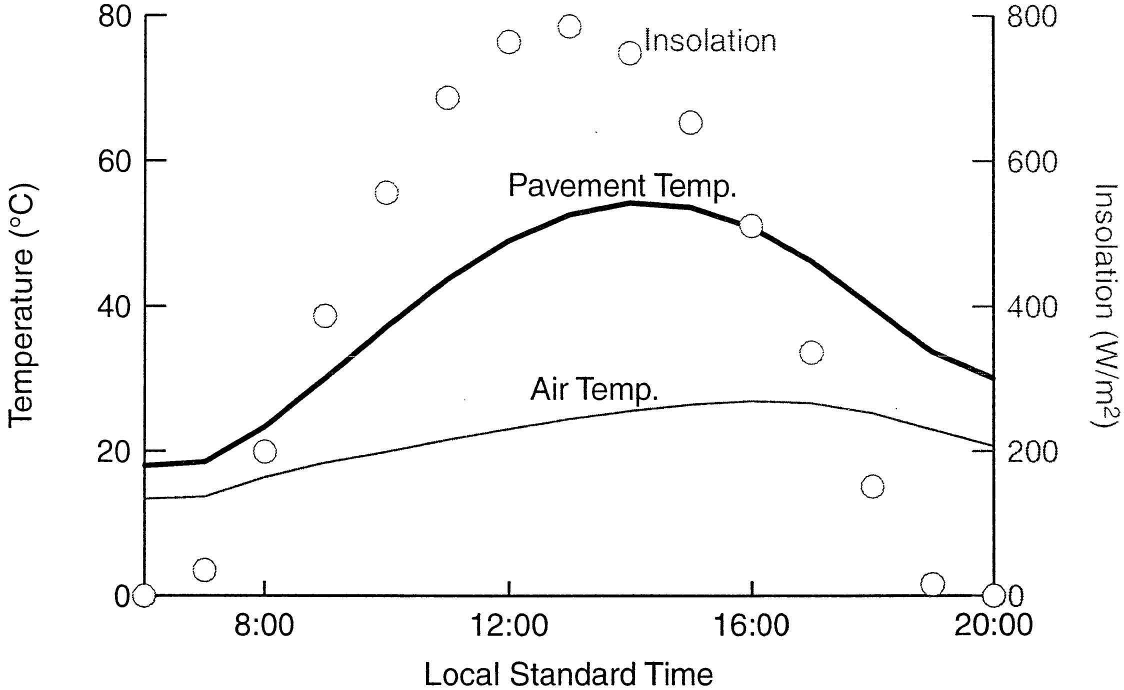


Figure 5. Calculated time dependence of surface temperature. Also shown are the insolation and the air temperatures measured in San Jose, California, on September 17, 1997, that were used in the calculation. Other input data are given in the text.

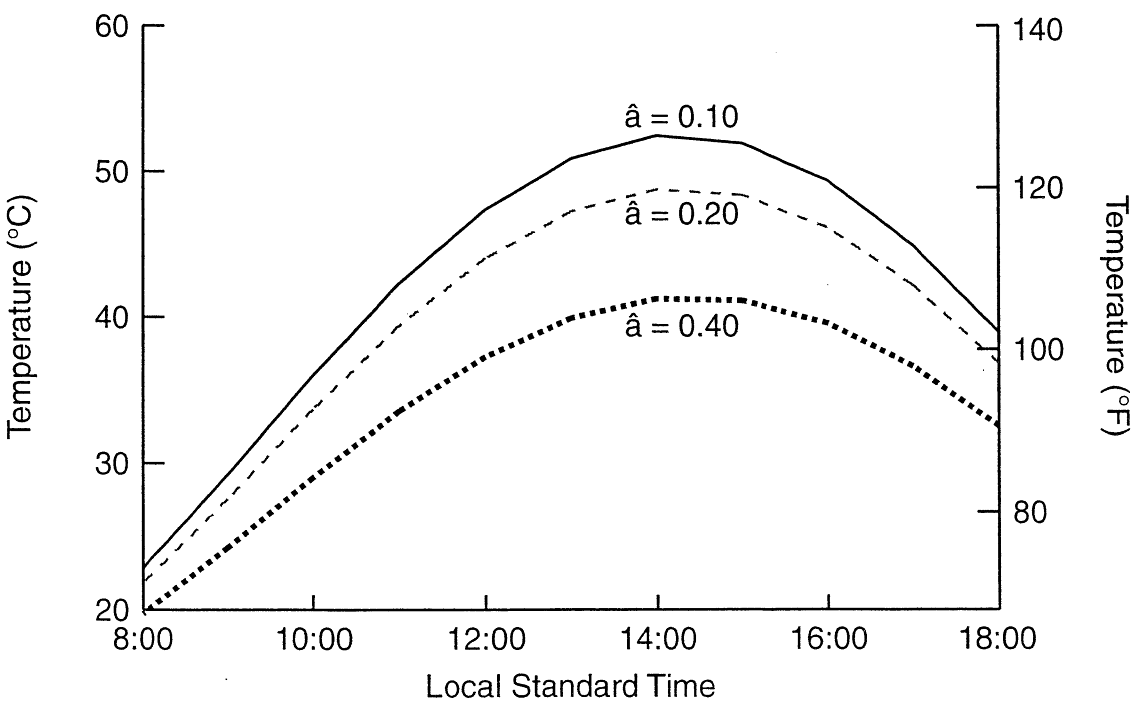


Figure 6. Calculated time dependences of pavement surface temperatures for three values of albedo: 0.1, 0.2, and 0.4. Other inputs are the same as in Figure 5.

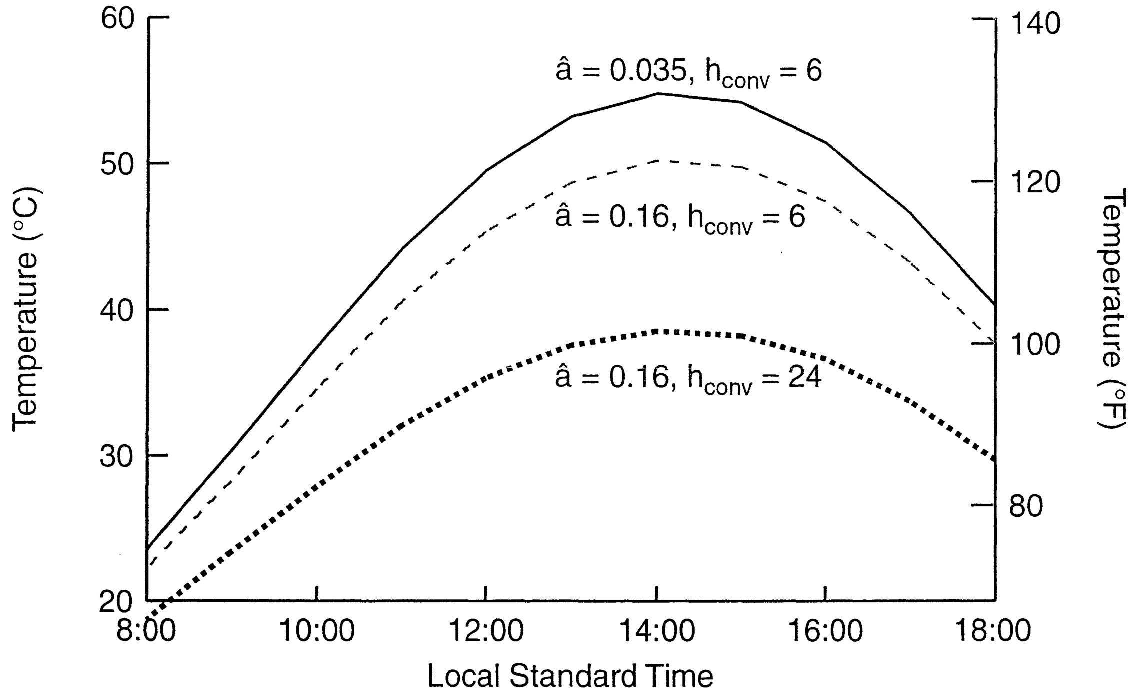


Figure 7. Calculated time dependences of pavement surface temperatures, for the albedos of Figure 3, for two different convections (units of W/m²C). Other parameters are the same as in Figure 5.