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Paving Materials for Heat Island Mitigation

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Environmental Energy Technologies Division

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Abstract

This report summarizes paving materials suitable for urban streets, driveways, parking lots and walkways. We evaluate materials for their abilities to reflect sunlight, which will reduce their temperatures. This in turn reduces the excess air temperature of cities (the "heat island" effect). The report presents the compositions of the materials, their suitability for particular applications, and their approximate costs (in 1996). Both new and resurfacing are described. We conclude that, although light-colored materials may be more expensive than conventional black materials, a thin layer of light-colored pavement may produce energy savings and smog reductions whose long-term worth is greater than the extra cost.

Key words: pavements, concrete, asphalt, grass, color, reflectivity, albedo, heat islands, safety.

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1. Introduction

The widespread paving of city streets with asphalt has happened only within the past hundred years. The advantages of this smooth and all-weather surface for the movement of bicycles and automobiles is obvious but some of the associated problems are perhaps not so well appreciated. One consequence of covering streets with dark asphalt surfaces is the increased heating of the city by sunlight. A surface is dark because it absorbs light; it gets warmer. The pavements in turn heat the air and help create the "urban heat island". If the urban surfaces were lighter in color, more of the incoming light would be reflected back into space and the surfaces and the air would be cooler. This tends to reduce the need for air-conditioning.

Cooler air, in turn, can reduce the amount of urban smog because the chemical reactions that produce smog slow down as the temperature is reduced. Avoided electricity generation also reduces air pollution. Recent simulations of smog production in Los Angeles(Taha, 1995) show that if a practical reflectivity [1] increase were effected it would lead to a decrease of the ozone exceedance by 12%. In some cases, a city that fails clean-air standards may thus be brought into compliance without drastic changes in lifestyle or infrastructure, such as restricted auto travel or electric cars. In addition to monetary savings, smog reduction improves the quality of life and health.

In addition to the heating caused by replacing cool vegetation by hot pavement, paved surfaces inhibit the entry of rainwater into the earth. This increases the danger of flooding and reduces the amount of water available for drinking or irrigation. We will discuss some porous and grass pavements which improve drainage.

We emphasize in this review those paving surfaces that ameliorate the heat island effect. We describe the chemical nature of the materials, their properties and most suitable applications, and their approximate costs (in 1996). The costs we state will be for the topmost paving material alone, because this is the layer that reflects the sunlight. This is only part of the total cost which may include preparation of the base on which the pavement is laid. We assume that the preparation costs are the same for all roads of the same class, regardless of the wearing surface. It is likely that light-colored surfaces will have higher initial costs than conventional dark materials. The crucial question is the marginal cost difference between dark and light surfaces. Even this marginal cost will decrease if lighter materials become widely used, and economies of scale set in. We cannot be precise about prices of materials because they depend on the size of the job, and the distance between the site and the sources of the materials. The relative costs of different materials may be the most useful information. In a future report we hope to address the important but more complicated issue of the life-time costs of the various surfaces. This is difficult because one needs, in addition to the initial costs, accurate data on the lifetime history of maintenance costs, down times, accident records, and disposal

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[1] The reflectivity over the solar spectrum is also referred to as "albedo", which varies from 0, for perfect absorbers, to 1 for perfect reflectors. Taha's calculation assumes an albedo increase of 0.25.

costs of roads that perform comparable functions in comparable soil conditions and weather.

First we consider new pavements, which require grading of the terrain and a new base course of rock. The thickness of this base and its preparation will depend on the anticipated traffic. We focus therefore on the topmost (wearing) course which is relatively independent of the base and is the important part for the albedo of the pavement. Then we review resurfacing of pavements. The reasonable time to retrofit a street with a light surface is when routine maintenance is being performed. Then the total cost is increased by the marginal difference between light and dark materials; the extra labor and shut-down times are minimized. An analysis of cost vs savings completes the paper. A glossary of terms and a list of units are appended. We also include a list of sources of information.

2. New Pavements

We first consider new pavements that are sufficiently thick that they can support automobile traffic. We assume that the base is the same for each type of pavement and thus focus on the outer wearing course only. There are three main types of new pavements: asphalt concrete, cement concrete and porous paver. In general, a pavement consists of a binder (asphalt, tar, or Portland cement) and aggregate (stones of various sizes down to sand). The function of the binder is to glue the aggregate together. The aggregate provides the strength, friction and resistance to wear, and the binder keeps the stones from dispersing under the forces of the traffic and weather.

a) *Asphalt concrete in new pavements*

Asphalt or bituminous materials are the most common binders of road surfaces(Asphalt-Institute, 1989). The relative amount of asphalt and aggregate is about 1 part in 10 (typically about 7% asphalt by weight, or 17% by volume). This type of pavement is properly called "asphalt concrete", suggestive of its composite nature. The fact that about 80% of roads now in service are made of asphalt concrete is a result of its relatively low initial cost and ease of repair.

Asphalt is derived from petroleum. It is often the residue after lighter components, such as gasoline and kerosene, are fractionated from crude oil. As such, it varies in composition depending on the reservoir of origin and on the fractionating process to which it is subjected. Compared to the Portland cement concrete, bituminous concrete is more flexible. This has the advantage that the wearing surface tends to conform to any movements of the subgrade with less cracking, but too much softness can lead to spreading or rutting of the road. In particular, asphalt concrete softens more than Portland cement concrete at temperatures which roads may attain.

The cost of the bitumen itself is about \$120 per ton (**Table 1**) (or \$0.15 per liter or \$0.50 per gallon). The cost of typical rock aggregate is about \$16 per ton delivered within 25 miles of the quarry, and additional shipping costs about \$0.10 per mile per ton(NSA, 1996). Asphalt concrete (with about 7% bitumen and 93% aggregate by weight) costs about \$25/ton or \$50/yd^3(Means, 1996). (The density of finished mixed asphalt concrete is 1.8 ton/yd^3 = 2.1 Mg/m^3). Thus for a surface 4 in thick, the cost is about \$0.60/ft^2 (**Table 2**). The cost of the bitumen alone in a 4" pavement is about \$0.25/ft^2.

Table 1. Approximate costs and densities of asphalt, asphalt concrete, cement and cement concrete.

Property		Asphalt Concrete		Cement Concrete	
		Asphalt	Concrete	Cement	Concrete
Cost	$/m^3$	130	65	250	72
	$/Mg	130	31	83	30
	$/yd^3$	100	50	190	55
	$/ton	120	28	75	28
Density	Mg/m^3	1	2.1	3	2.4
	ton/yd^3	0.84	1.8	2.5	2

b) *Cement concrete in new pavements*

Cement concrete consists of an inorganic binder, or *cement*, which, after being mixed with water, can harden and hold together stony aggregate. The raw material of the cement contains *lime* (CaO), which is derived from *limestone* (calcium carbonates, $CaCO_3$) or oyster shells. Portland cement contains *clay,* which has iron oxides, silica, and alumina in it. The approximate composition (by weight %) of Portland cements is(Leighou, 1942)lime (60), silica (20), alumina (5), iron oxide (3), magnesia (2), and other (10). Depending on the composition of the starting materials, a suitable mixture of them is ground together. (E.g., limestone contains 52% lime and 3% silica, but slag contains 42% lime and 34% silica, so the amount of clay (57% silica) to be added would differ between limestone and slag based cements to get a final silica content of 20%.)

Concrete pavings are the choice for very heavy traffic loads because the material does not deform as much as asphalt. In dry climates in Texas, for example, concrete is chosen when the traffic exceeds 70,000 cars per day. In wet climates, where the softer undersurface requires a stiffer road, concrete is preferred for traffic of 40,000 per day(Smart, 1994). However, the higher initial cost of concrete and the difficulty of modifying the surface favors asphalt in applications to roads that carry traffic in low volume and low weight, such as in residential areas and parking lots. The initial cost of ready mixed concrete is about \$50 - \$60 per cubic yard(Means, 1996), or about \$30 per ton. Thus the cost is about $1/ft^2$ for a 4" thickness.

Cement is darkened by the presence of iron oxide, which can be reduced to get a whiter cement by using kaolin, instead of ordinary clays. Added titanium dioxide makes it whiter, but manganese oxide, present in slag, makes it browner. Measurements and literature searches(Taha, Sailor et al., 1992), give an albedo, a , of fresh cement concrete of 0.35 - 0.40. As cement concrete ages it tends to get darker, because of dirt, and the a tends toward 0.25 - 0.30. Contrarily, asphalt concrete tends to get lighter as it ages, because the black asphalt wears away to reveal the lighter aggregate. We have measured $a = 0.15$ for an old asphalt pavement.

It is possible to produce concrete with visible reflectivity approaching 68 % by using whiter cements and aggregates(Lehigh-Cement, 1994)[2]. The cement is white because the starting materials are selected to have low concentrations of colored minerals, such as iron oxides. White aggregates, such as white sand, and some limestones are available, but

[2]White cement is available, for example, from Lehigh Portland Cement Co., Allentown, PA 18195

Table 2.

Representative materials for new pavements. Entries refer to the topmost layer; the grading and bases are assumed the same for all the pavements. Prices are merely indicative and average; they will vary with job size, location and time.

Name	Composition	base	thickness cm	(in)	cost for thickness given $/m2	($/ft2)	albedo*/color
Impermeable							
asphalt concrete	7 % asphalt + 93 % aggregate by weight	graded rock	10 cm	(4 in)	$7/m2	($0.60/ft2)	Albedo (new) 0.05 - 0.1, (weathered) 0.15 - 0.2
Portland cement concrete	portland cement/sand/stones (about 1/3/5 by weight)	graded rock	10	(4)	10	(0.9)	a (new) = 0.35 - 0.40, (weathered) 0.25 - 0.30
white cement concrete (Lehigh)	white aggregate + cement which is low in Fe oxides	graded rock	10	(4)	22	(2)	a (new) = 0.70 - 0.80, (weathered) 0.40 - 0.60
Road Oyl (Road Products Corp.,	resin modified emulsion	graded rock	10	(4)	11	(1)	Binder is tan colored
Permeable							
Grasscrete (Bomanite Co.)	concrete lattice, filled with soil.	soil, sand/ gravel	15	(6)	60	(5.5)	a(grass) ≈ 0.2
Grasspave2 (Invisible Structures, Inc.)	lattice of100% recycled rigid polyethylene cylinders, filled with soil	soil, sand/ gravel	3	(1)	$1.5/ft2 for < 10 kft2; $0.50/ft2 for M ft2.		a(grass) ≈ 0.2
Gravelpave (Invisible Structures Inc.)	Same as grasspave, except filled with gravel only.	soil, sand/ gravel	3	(1)	$1.5/ft2		a(gravel) ≈ 0.5
Geoblock (Presto Products)	lattice of 50% recycled, rigid fiber-reinforced polyethylene rectangles, filled with soil	soil, sand/ gravel	3 or 5	(1) (2)	$2/ft2 for more than 40,000 ft2		a(grass) ≈ 0.2
Geoweb (Presto Products)	Flexible polyethylene sheets formed into lattice, filled with soil and grass.	soil, sand/ gravel	>13	(> 5)	$0.95 /ft2 for more than 40, 000 ft2		a(grass) ≈ 0.2

*Albedo data from Taha, et al., 1992.

usually cost more. The price of white dolomite rock is about $30 per ton at the quarry, compared to usual rock at about $4 - 9 per ton at the quarry. Because the quarries for white rock are fewer, they are likely to be further from the final destination, and thus transportation costs may be higher than the usual $6/ton within 25 miles (Filapeck, 1994). Because of the higher costs of both the cement and the aggregates, the cost of white concrete is about $110 - $150/yd^3, or about $ 2 /ft^2 for a 4" thickness.

c) *Tree-resin modified emulsions*

"Road Oyl", a relatively new binder, is tan colored because it is derived from pine tree pitch and resin. When it is mixed with stone or sand, it produces a light colored pavement. In the emulsified form it is water soluble, applied without heating and thus is particularly convenient to apply where access of large equipment is a problem. After drying and setting it is insoluble in water. It is comparable in strength to asphalt concrete in laboratory tests, but has not yet been extensively tested on city streets. RoadOyl costs about $2 per gallon, and comprises about 6% by weight of the finished pavement. It is manufactured by Road Products Corp. of Knoxville, TN.

d) *Coal-tar resins*

In the South Eastern U. S., near coal mining regions, coal - tar resins are used in a manner similar to asphalt binder. Because it is not applied much nation-wide, and it is black, we shall not discuss it any further here.

e) *Porous pavers for new pavements*

Porous pavements are defined in this paper as pavements that deliberately allow water to pass through them. Permeability has the advantages of permitting rain water to be stored in the earth and reducing the problems of flooding. A road surface made of grass has the added desirable qualities that the grass evapotranspires and thus cools the air above it, and it is decorative. However, a grassy field as a parking lot or access road is soft when it is wet and is easily rutted permanently. These defects can be alleviated by enclosing the soil in a lattice structure that provides lateral containment. The lattice structure thus serves as a binder for the soil or gravel. We refer to such porous pavements as "grass pavement". All grass pavements must have sufficient water year round, which, depending on the location, may entail a cost. In Los Angeles, e. g., watering may cost $0.01/ft^2-yr. Grass pavers are best suited for occasional use where perhaps one or two cars a day traverse it (e.g., parking for employees, sports facilities, overflow), or as fire lanes, because grass cannot survive frequent traffic. Also, it is advisable to minimize walking on the surface for safety reasons because the footing may be somewhat irregular. The lattices supporting the grass pavers are made either of concrete or plastic.

Another type of porous pavement is formed of concrete (asphalt(Brown, 1996) or cement) which is loosely packed so that water can percolate through it. We now present some examples of these permeable pavements.

(i) Concrete-lattice grass pavement: The lattice of cement concrete can be either prefabricated or poured in place. Typical prefabricated units are 2 ft x 2 ft and 6" thick, with 3" or 4" diameter through-holes. The prefabricated pavers suffer from possible differential settling of one unit with respect to another, particularly in rainy conditions. At a greater cost per area, a large area can be covered with a poured-in-place type. For example, "Grasscrete", (Bomanite Corp., Madera, CA) is made of a grid of steel-reinforcing bars about which concrete is poured into forms to a thickness of at least 5". The bars are 6" apart, and when the concrete is in place it forms a pattern of roughly square blocks. There is space for soil between the blocks so that about half the area is filled with soil. When the grass is fully grown, from a distance it looks like a continuous lawn. The installation of Grasscrete requires more labor than does a simple concrete pavement. Thus in addition to a materials cost of about \$2.50 per ft^2, there is an extra labor cost of about \$2.00 per ft^2, which gives a total cost of about \$ 5.50 per ft^2.

(ii) Plastic-lattice grass pavement: A lattice can be made of hard or soft plastic. A typical panel of the hard type is about 2 x 2 ft^2. The units can be connected together to inhibit differential movement, and cover large areas. The vertical walls of the cells of the lattice are about 1" tall, 0.25" thick, and spaced about 3" apart. Thus, most of the area is soil. In one product, "Geoblock®", (Presto Products Co., Appleton, WI) the areas of the cells are rectangles 6.9 cm x 7.1 cm (2.7 in x 2.8 in); in another, "Grassspave2" (Invisible Structures, Inc., Aurora, CO) the cells are 6 cm (2.4") diameter cylinders connected on 10 cm (3") centers by spokes. The costs of these products (including the soil, grass, and the rigid forms) range upward from approximately \$1.5/ft^2 for areas about an acre. For areas approaching 100 acres (4 million ft^2) the price may decrease to about \$0.5/ft^2. Asphalt concrete prices, by comparison, seem not to depend as much on the scale of the job; they may decrease by about 20% for jobs over 1 acre. Thus for areas approaching 100 acres the prices of grass pavements are similar in cost to new asphalt concrete.

There is also a flexible plastic form, called "Geoweb®" (Presto Products Co., Appleton, WI). It is thin strips of plastic many feet long and about 8" tall, bonded together to form a lattice. When filled with earth it is strong enough to support an automobile.

Instead of filling the lattices with grass, one may substitute gravel or crushed stones. This will lead to lower maintenance costs and yet is still environmentally beneficial by allowing a path for rain water entry and having potentially light color, if the stones are chosen with this in mind. A possible combination might be access roads and lanes finished with white stones (which can withstand repeated traffic), and parking spaces finished with grass.

(iii) Porous pavement of asphalt or cement concrete: To construct a permeable pavement entirely of asphalt or cement concrete, the aggregate is chosen to be a single size, usually about 3/8 in. (so-called "open-graded" aggregates.) In the absence of fine aggregates and sand, the stones pack so loosely that there are channels through which moderate flows of water can filter(Asphalt-Institute, 1974). This porous pavement is usually placed over a solid pavement for strength, and is domed such that the water leaks out the sides of the roadway. Blockage of the pores by dirt, and fracture by freeze-thaw cycles may be problems. The porous surface has a safety advantage of avoiding standing water that can lead to aquaplaning by fast autos. Another benefit that is welcome in cities is that these surfaces tend to suppress tire noise(Hugues, *et al.*, 1995; Lefebvre, *et al.*, 1995).

3. Resurfacing of pavements

a) *Asphaltic coatings*

Asphalt and asphalt based materials are the most common for repair and resurfacing roads(Raza, 1995). Asphalt adheres well to both older asphalt and to cement concrete. For large jobs, conventional hot-mix asphalt concrete at least an inch thick is commonly used. The price of hot ready-mix asphalt concrete is indicated in Table 1. The prices of resurfacing are shown in **Table 3**.

Keeping asphalt in a fluid state is accomplished by having oil-fired heaters onboard the spreaders. For small repair jobs, room temperature bituminous binders have been developed. One such binder is asphalt dissolved in kerosene or creosote. This is called a

Table 3.
Materials for resurfacing pavements. Costs are for the materials only for the given thicknesses. They are merely indicative as they vary with location, time and size of the job.

Name	Composition	Base	Thickness cm	Thickness (in)	Cost ($/m2)	Albedo or Color
Chip seal/Seal coat Surface treatment	aggregate pressed into emulsified asphalt	previous pavement stony or soil subbase	1	(0.4")	0.8	depends on aggregate
Sand seal	sand pressed into asphalt emulsion, cement	previous pavement	0.2	(0.08")	0.6	depends on aggregate
Hot-mix overlay (Blacktop)	hot asphalt, various aggregates mixed before spreading	previous pavement	1.3	(0.5")	1	*0.1 (new); 0.2 (weathered)
Slurry	asphalt emulsion, cellulose fibers, color agents, aggregate (3/8 in.)	previous pavement	0.7	(0.3")	0.7	*0.1
Microsurfacing	*polymer-modified* asphalt emulsion, crushed mineral aggregate, mineral filler, water, and field additives as needed.	previous pavement	0.7	(0.3 ")	1.4	*0.1
Fog coat, or tack coat	asphalt emulsion	previous pavement	0.013	(0.005")	0.01	*0.1
Petroleum resin (Pavebrite)	petroleum resin + white fine aggregate + pigment	rock, previous asphalt or concrete + pavebrite tack coat	1.3	(0.5")	10	add TiO2 for whiteness
Pine resin (Road Oyl)	tree resin modified emulsion	graded rock	>10.2	(> 4")	10	Binder is tan colored
Cement concrete	portland cement and aggregates	pavement	>5.1	(> 2")	6.5	*0.4 (new); 0.3 (weathered)
Acrylic	acrylics, dyes, fillers	previous pavement	0.2	(0.06)	3.4	^0.5 (new)

*Albedo data from Taha, et al., (1992).
^Unpublished measurements by Berdahl and Wang, LBNL (1996).

"cutback" asphalt. The solvent evaporates over a "curing" time, after which the asphalt is hard. The emission of the organic solvents, however, has adverse effects on the environment, so the cutback asphalts have been superceded by water-soluble asphalt emulsions(AEMA 1995). Here the bitumen is ground to small particles and chemically treated with an emulsifier so that it remains in suspension in water. The emulsifier is chosen anionic or cationic to facilitate the wetting of the particular mineral aggregates that are mixed with the emulsion. After the spreading of the emulsion and aggregate, the water separates ("breaks") and evaporates harmlessly. The asphalt coats and binds the aggregate to form an asphalt concrete. Asphalt emulsions cost from 15% to 100% more than bulk asphalt; costs of more than $1/gal(Reed 1997), and an average of about $1.50 per gal are quoted(Raza 1995; Means 1996). Emulsions have drying times of as little as a few hours, resulting in minimal disruption of traffic. A newer type of binder is formed by adding polymers to asphalt emulsions; this is called "micro-surfacing". We emphasize in Table 3 the costs of the materials alone, but it should be borne in mind that as the repaving gets thinner, the relative costs of the material, compared to costs of labor and equipment gets smaller. For example, the costs (¢ per square yard) of the thinnest layer of asphalt emulsion, a "tack coat", are broken down(Means 1996) to 8 (¢/yd^2) for the material, 15 for the labor and 28 for equipment, for jobs of 1000 square yards. For thicker resurfacing, such as "slurry seals", the costs for small jobs breaks down to 57 (¢/yd^2) for material, 46 for labor and 43 for equipment; material is a more significant component. For larger jobs, however, economies of scale set in for labor and equipment, but less so for material. Thus, materials are a larger component for large jobs. For example, for tack coats of 10,000 square yd, the labor and equipment costs decrease from 15 and 28 (¢/yd^2) to 4 and 7 (¢/yd^2) respectively, but the material cost remains the same at 8 (¢/yd^2).

There are two general approaches to the repair or resurfacing of an existing pavement(Hunter 1994). In both cases the new surface is a composite of binder and aggregate; the difference is whether these components are mixed after or before the binder is spread on the old surface. If the binder is spread first and then the aggregate is dropped on top of it and then pressed into the binder, it is called a "chip" seal or a "sand" seal. Otherwise, the aggregate and binder are premixed and then spread. The mixing is often done onboard the spreader vehicle just before the mixture is applied to the pavement. The premixed pavements are known as "overlays", "slurry coats", "microsurfaces", and "fog coats" depending on the binder and the size of aggregate; they have different suitabilities.

(i) Chip seal: The binder in a chip seal is usually a fast-drying emulsified asphalt. As soon as possible after the binder is spread, uniform aggregate is dropped and rolled into the binder. The typical surface is about 1/4" thick. When the chip seal is used to resurface an existing pavement it is sometimes(AEMA 1995) referred to as a "seal coat", which may be confused with the same word applied to a slurry coat containing fine aggregate. (Cf. below). When the chip seal is applied to a stony or soil surface it may be referred to as a "surface treatment"(AEMA 1995).

Chip seals are usually applied to low-use roads, such as in rural areas. The rough aggregate on the surface is problematic in residential areas where children play and fall, and loose aggregate thrown by car tires may be more dangerous. The color of the surface is strongly influenced by the color of the aggregate. When white limestone is used, as in Texas where it is abundant, a quite white surface results. The average cost of chip seals is about $0.75/m^2 (Raza 1995).

(ii) Sand seal: This provides a thin coating for surfaces which have small need of repair. It consists of a emulsified asphalt onto which sand is spread. Sometimes cement and other materials are added to the mix, but the aggregate particles must be smaller in diameter than about 0.04". The preliminary preparation of the surface is relatively simple. Deposits of grease and oil must be removed or sealed over. Otherwise, the surface must be thoroughly cleaned of loose dirt or paving particles. The surface is then dampened with water, and the slurry is applied in a smooth coat. For one coat, the amount of asphalt applied(Asphalt-Institute 1989) is about 0.6 liter/m^2, and about 4 kg/m^2 of sand, which produces a layer about 1mm (0.05") thick. The thickness of the binder is about 0.6 mm (0.03"). Sand seals cost about \$ 0.50/m^2 (\$0.06/ft^2)(Means 1996). (Note that the term "seal coat" is sometimes applied to chip seals on pre-existing pavements.)

The color of the binder is basically gray, and is normally made darker by the addition of carbon black. Even when the carbon black is omitted, the gray surface has an albedo of 0.05, as measured by P. Berdahl at LBNL. To lighten the color, rutile (titanium dioxide, TiO_2) powder can be added. This increases albedo to 0.10 with no loss of structural quality. An emulsion designed to rejuvenate asphalt, Reclamite(Erickson 1989), is often followed by a coating with sand. Thus a lighter color is achievable if white sand is used.

The more common pre-mixed asphaltic resurfacing methods, in the order of decreasing thickness are:

(iii) Hot-mix overlays: For roads needing considerable repair or that must support large stresses, such as near stop signs where acceleration and turning are frequent, a sturdy repair can be done with a hot mix containing aggregate from 3/8" to 1/2" in maximum diameters. Typical(Raza 1995) dense hot-mix applications are about 35 kg/m^2 for each layer. At 2 ton/yd^3 (2.3 Mg/m^3), this is about 0.5" thick. At a cost of \$30/Mg (\$25/ton), the unit price is about \$1/m^2 (\$0.1/ft^2) for a 5,000 ft^2 job.

(iv) Slurries: For surfaces with medium need of repair and that carry considerable traffic, resurfacing may be done with a mixture of asphalt emulsion and aggregate. The size of the aggregate and the formulation of the emulsion are determined by the expected traffic and the climate. The typical aggregate is about 1/4" maximum diameter (ISSA 1991). The slurry is spread at about 7 kg per m^2 (1.4 lb/ft^2). At a density of about 2.1 Mg/m^3 (specific gravity of 2.1) this gives a thickness of about 0.4 cm or 0.2 in. (one rock thick). The cost of materials is about \$ 0.70 per m^2 for large jobs(Means 1996).

(v) Microsurfacing: When polymers are added to slurry binders the product is called "microsurfacing"(Raza 1994). The polymer confers greater resistance to wear. In addition, it becomes possible to apply a layer in multistone thicknesses; it can be more than 1.5 times thicker than the largest aggregate. It can be used for layers down to 0.3". At a cost of about \$110/Mg or tonne (\$100/ton) and a material application rate(Raza 1994) of 13 kg/m^2, the cost of materials is about \$1.40/m^2 (\$0.13/ft^2).

(vi) Fog coat: A thin layer of diluted asphalt emulsion is spread on an existing pavement. It can be used as a protective layer, but also to change color. The typical amount of asphalt applied is about 0.06L /m^2 (0.03 gal/yd^2)(AEMA 1995). This results in a coating about 0.005" thick. The cost of the labor would dominate the total cost because the amount of material is so small.

b. Petroleum resin coatings

A petroleum product that is not an asphalt is manufactured by Neville Chemical Co., Pittsburgh, PA, and sold as "Pavebrite®"(Willockl 1995). Similar products are distributed in Europe by the French Shell Oil, as "Mexphalte C" and by Total as "LSC", (Liants Synthetiques Clairs). These are synthetic resins derived from lighter fractions of petroleum, and chemically modified. The pure material is tan in color, but coloring additives can achieve bright colors. The color of the aggregates must be chosen to not interfere with the desired color, as well as to provide the required mechanical strength. The aggregates are fine graded, meaning they all pass a # 8 mesh (about 0.1") screen. This is necessary in order to prevent the color of the aggregate from becoming significant as the pavement wears, if one desires that the color pavement stay the color of the binder. For the purposes of a whiter road, a white binder could be mixed with white rock of any desired sizes. The mechanical properties of the paving is reported to be at least as good as comparable asphaltic pavings.

The typical use in the U. S. has been for pavements at least 1/2" thick. In Holland there is some experience in using the binder in slurries. The cost of this product is currently about \$8/gal. and the complete mixture with aggregate and pigments is about \$350/ton. A ton occupies about 15 ft^3. When used for a 1/2" pavement, it requires one ton to make 36 yd^2 and thus cost about \$1/ft^2.

c. *Tree resin coatings*

A resinous material derived from pine trees, known as RoadOyl®, is used for roads and dust-suppression. In Marshall stability tests, it is reported to perform at least as well as asphalt(SSC, 1995). It has not yet been completely evaluated as a slurry binder. Its cost is about \$2/gal.

d. *Cement concrete coatings ("white-topping")*

Layers of concrete as thin as 2" have been used for resurfacing roads. The procedure is still somewhat experimental and the long-term behavior and proper practice are still under study.

e. *Acrylics*

These are synthetic polymers which can be highly colored. They are expensive, and are thus far have been used mostly for special applications such as tennis courts. Recently, Reed and Graham, Inc., San Jose CA, produced experimental materials based on acrylics mixed with pigments, that proved to have acceptable structural strength(Lungren, *et al.*, 1996) as a roadway, and solar reflectivities of about 50%(Berdahl, *et al.*, 1996). The effect of the high albedo on the temperature of the pavement was measured(Pomerantz, *et al.*, 1997) by comparison of a new asphalt concrete pavement, of albedo 0.05, an old asphalt pavement, a = 0.15, and an old asphalt pavement coated with the white overcoat, a = 0.50. On a sunny September afternoon in Berkeley, CA, the measured pavement temperatures were as shown in Fig. 1. A considerable effect of albedo on temperature is evident.

The cost is estimated at \$8 per gallon. At the recommended coverage of 25 ft^2 per gallon, the cost is about \$0.3 per ft^2, or \$3.4/m^2 .

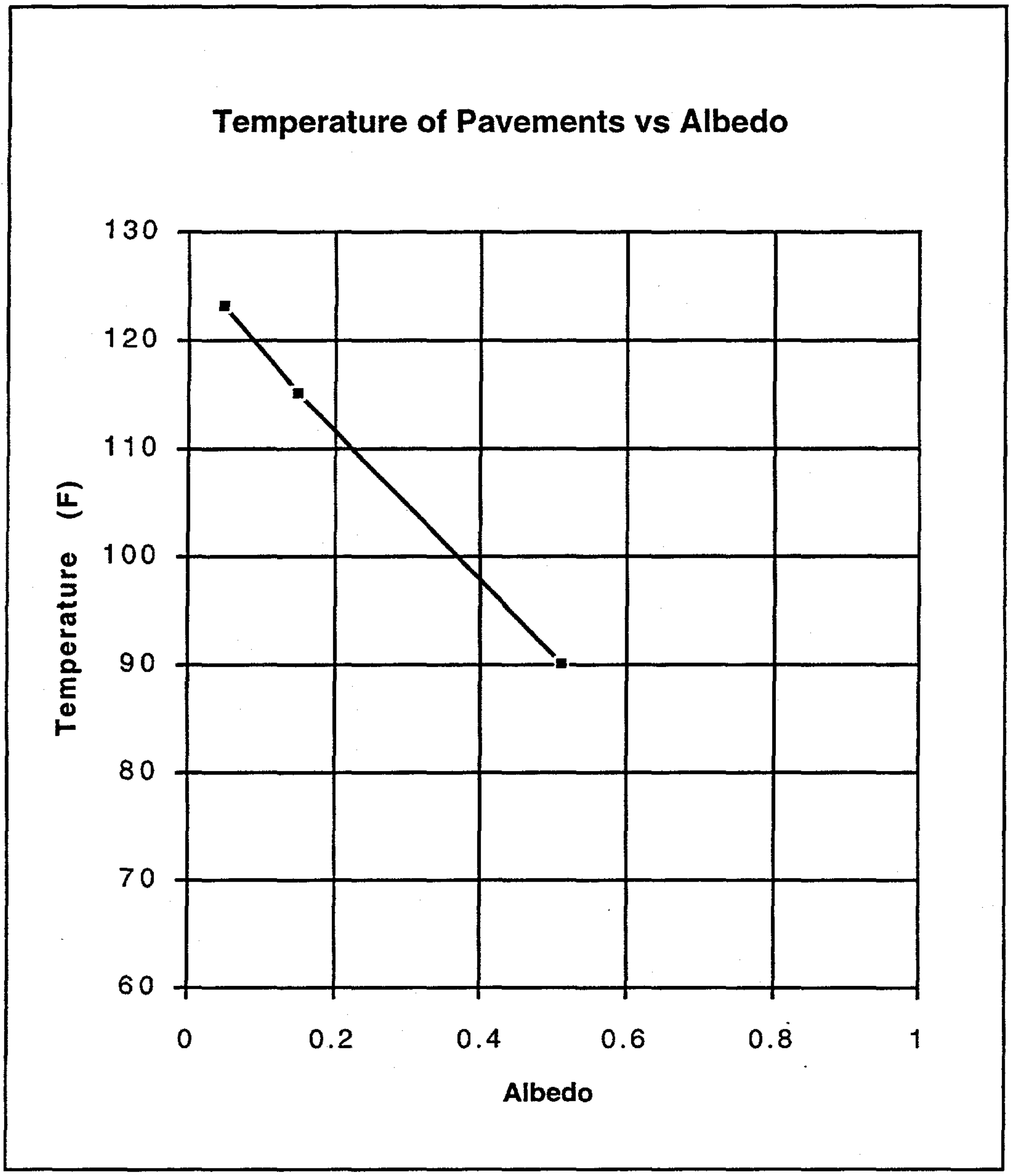

Fig. 1. Dependence of pavement temperature on albedo, on an afternoon in September, in Berkeley, CA.

4. Costs and savings of reflective pavements

We now address the question of whether the higher cost of high albedo pavements can be compensated by the savings produced by cooler surfaces. An estimate of the cost savings to society can be deduced by finding the temperature decrease that would result if a city were resurfaced with more reflective materials. Lower temperature has two effects: reduced demand for electricity for air conditioning and 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 published elsewhere (Rosenfeld, Romm et al., 1996).

a. *Electric power savings in Los Angeles*

Simulations of Los Angeles show that for a practical change in albedo a noticeable decrease in temperature can be achieved. A simulation of Los Angeles predicted a 1.5 °C (2.7 °F) decrease in temperature of the downtown area(Taha, 1995). (The model assumes that all roofs (1250 km^2) have albedo increased by 0.35 and all pavements (1250 km^2) have albedo increased by 0.25.) 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. The energy consumptions of typical buildings were then simulated for the original weather and also for the modified weather. The differences are the energy-demand changes due to the ambient temperature decrease. The result is a city-wide annual saving of about \$71 M, due to combined albedo and vegetation changes. The temperature changes due to albedo came out to be the same as due to trees. Pavements give rise to about 21% of the total saving since their area is the same as the roof area, but their albedo change is assumed to be 0.25 compared to roof-albedo change of 0.35. Thus the savings attributable to the pavement is \$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. The power plants required to handle this peak load need not then be built, which saves money, resources, and pollution.

We can estimate the savings due to grass parking lots from the result for trees. Planting 11 million trees reduces the temperature by about 2.7 F (1.5 C), similar in magnitude as albedo changes(Taha, 1996). Thus trees cause about half of the total saving of \$71 M per year, or \$35 M per year. Each of the 11 million trees thus saves about \$3 per year, or \$23 present value. (The present value multiplier is 7.5 because it takes about 10 years for the tree to reach full size(Rosenfeld, *et al*., 1997). A mature tree has an area of about 50 m^2 or 538 ft^2. A typical parking stall has an area of 300 ft^2, included lanes. If it is assumed that the area of grass is as effective at cooling the air as the same area of tree, a grass parking stall will save 0.56 as much as a tree, or about \$1.7/stall -yr. Unlike a tree, grass is effective in its first year. Thus its present-value multiplier for a 10 year life is 8.5, giving a present value of \$14.5/stall.

b.*Smog savings in Los Angeles*

The production of ozone (O_3) in smog requires precursors (nitrous oxides (NO_x) and volatile organic hydrocarbon gases), sunlight and heat to drive the reactions. These reactions occur more rapidly as the temperature is increased, known as "cooking the smog". The influence of temperature is demonstrated by the dramatic dependence of smog incidents on the daily maximum temperature in Los Angeles. 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(Taha, 1995). 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, 1995). It has been estimated(Hall, *et al*., 1992) that people would 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).

It was estimated(Rosenfeld , *et al.*, 1997) that the cooling by trees can lower the air temperature in Los Angeles sufficient to reduce smog and save \$180 M. The savings of grass parking areas, by analogy with trees, as in the previous section, has a present values of about \$75/stall. Thus a grass stall in LA can cost an extra \$89 and be economical. These estimates depend on the simulations of LA. For other cities a similar analysis needs to be performed.

c. 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, again, 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.*, 1997). Thus, the potential savings are worth \$1.08/m^2 (\$0.10/ft^2) at present. Table 2 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 will now be estimated. The lifetime of resurfacing is only about 5 years, so that the present value is 5 times greater than the annual savings[3]. Thus 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 our survey of asphalt-based pavements, 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 , of which 17.5% by volume is binder (the density of aggregate is about 2.5 times greater than asphalt). Thus, in this volume, 0.00495 m3 (0.0172 ft^3) is aggregate and 0.00105 m^3 (0.00364 ft^3) is binder. Other units for the amount of aggregate are 0.00495 m^3 <=> *12.4 kg*. Other units for the amount of binder are 0.00105 m^3 <=> 1.05 kg <=> *1.05 liters* . Thus, 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[4].

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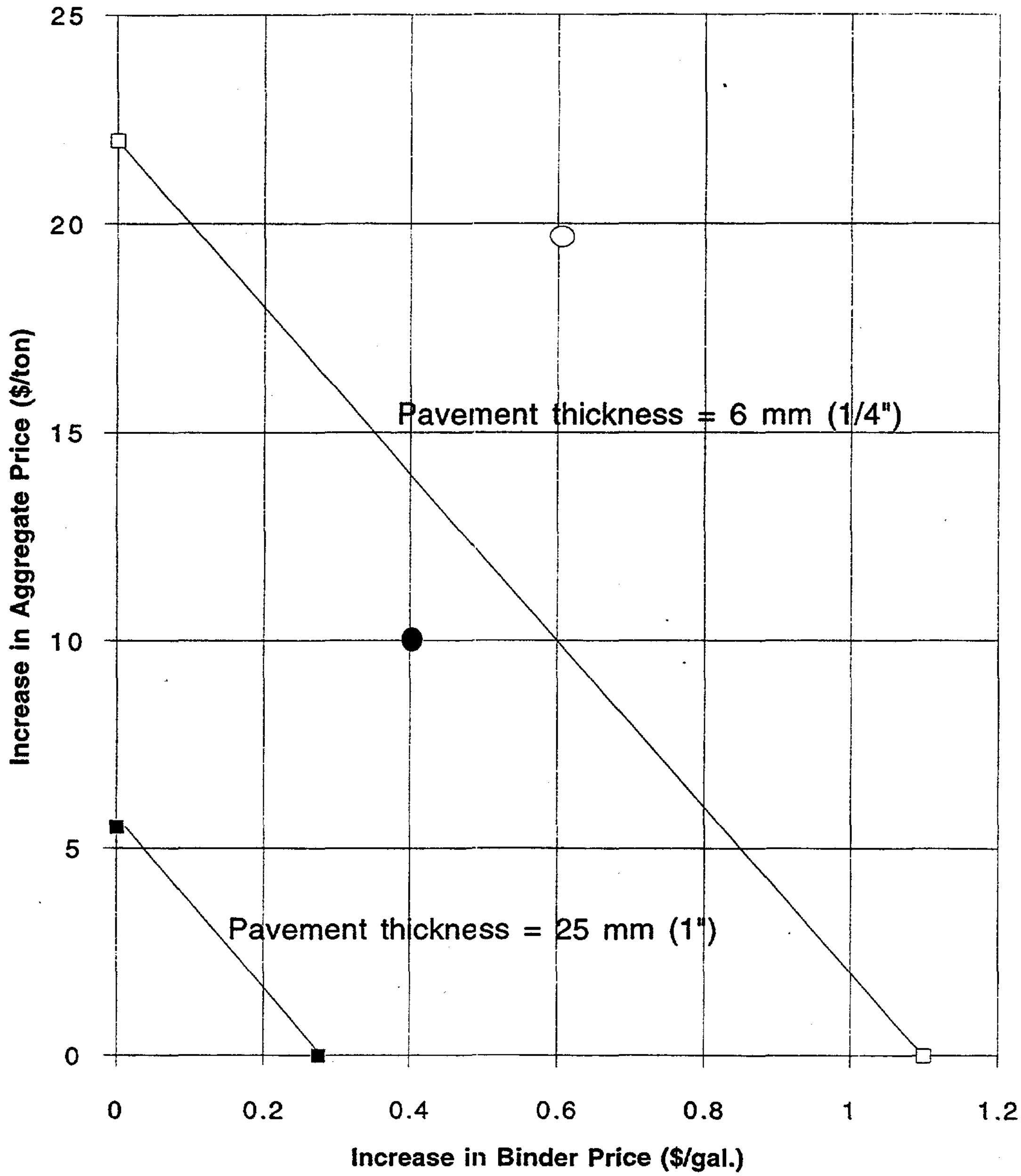
[3]This ignores the possibility that the light-colored aggregate may be recycled in subsequent resurfacings. In that case the effective lifetime of the material is greater, the present value multiplier will be larger than 5, and the savings will be larger than calculated here.

[4] 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

Fig. 2. Increase in the binder and aggregate prices at a cost of $0.36 per square meter ($0.03 per square foot).



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

$\Delta P(6\ mm) = 12.4\Delta A + 1.05\Delta B$, $(\$/m^2)$ (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. 2.** The increases in aggregate prices and binder prices below the line that passes through the open squares 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 these extremes are possible. One needs only to stay below the line drawn through the open squares in Fig. 2. For example, an increase in cost of aggregate by \$10 and an increase of binder by \$0.40 per gallon, indicated by the full circle in Fig. 2, 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 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, Eq. 1 becomes

$\Delta P(25\ mm) = 49.6\Delta A(\$/kg) + 4.2\Delta B(\$/liter)$ $(\$/m^2)$ (2)

or in English units:

$\Delta P(1"\ thick) = 0.00540\Delta A(\$/ton) + 0.109\Delta B(\$/gal)$ $(\$/ft^2)$

The affordable price increases of aggregates and binders (that cause a price increase equal to the cooling saving of $\$0.36/m^2$ or $\$0.03/ft^2$) are shown by the line through the filled squares of Fig. 2. 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. Clearly, a thinner layer is more likely to be economical.

5. Conclusions and future work

The first conclusion is that one should consider the thinnest layers possible. As the layers get thinner their costs decrease, and the extra costs of the lighter material also decrease. The benefit from higher albedo does not decrease with the thinness until the base shows through. Thus, one should use only enough of the more expensive coating to achieve the maximum albedo and sufficient mechanical strength. Significantly, with thin enough layers, quite white surfaces may be affordable. In LA, for example, the savings in air conditioning costs and smog abatement repay an extra cost of as much as \$22/ton for aggregate; the whiter aggregate available at this additional price pays for itself.

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cost of binder in \$/gal. To check the accuracy of this equation, recall from 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 $\$0.63/ft^2$ ($\$0.57/yd^2$), 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.

There are other benefits of higher albedo beyond electricity costs and smog which need to be investigated in the future.

1. Because the surface stays cooler there is less softening of the asphalt, and thus there is less rutting due to traffic(Loustalot, *et al.*, 1995). The lifetime of the road is thereby extended. There are some preliminary laboratory tests of the relationship of durability and temperature of the asphalt-aggregate sample(Monismith, *et al.*, 1994). If the asphalt road is cooler, the chemical reactions that make the asphalt more brittle proceed at a slower rate and thus the desired flexibility is maintained for longer times. Longer lifetimes save on maintenance and replacement costs, including the disposal of old roads.

2. If fewer resurfacings are made there is less emission of the volatile asphalt fumes which feed smog.

3. If roads are cooler, softer (presumably cheaper) grades of asphalt may be used.

4. Whiter road surfaces require less night-time artificial lighting while maintaining visibility of pedestrians. Thus, safety and crime prevention will cost less.

The quantification of these effects requires further research.

Possible problems with light-colored pavements are that there may be excessive glare with extremely reflective pavements, which may make some people uncomfortable or unable to see well. The reflectivity of fresh cement concrete (about 35%) seems to be no problem, however. Also, in locales where there is thin snow on the pavements for part of the year, the snow may melt slower on a whiter road. This disadvantage may be compensated by the longer lifetime of the road due to less frequent freezing and thawing, which is a major cause of deterioration of roads. These factors need to be checked in controlled field situations in order to be quantified.

Disclaimer

The mention in this report of specific suppliers of materials does not represent an endorsement of the company or the product by the authors or by the DoE. It is only meant to indicate the commercial availability of the kind of product discussed.

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Appendix A. Glossary of some pavement terms:

Aggregate: A hard material used in pavements to bear the weight and provide skid resistance. It can be sand, rock, gravel, ceramics, etc.
Asphalt: A petroleum product used as a binder in asphalt concrete pavements and coatings. It is solid at room temperature. It is often the remainder after the refinement of crude oil has removed other liquids such as gasoline and kerosene.
Binder: A general term for the component of a pavement that adheres to aggregate, holding it together to prevent its spreading under the action of traffic. Common forms of binder are cements (such as Portland cement) and asphalt.
Cement: The inorganic binding material used to hold together sand (in mortar) or sand and rocks (in concrete). Cement is distinguished from asphalt which is an organic (hydrocarbon) binder.
Chip seal: A method of resurfacing a pavement that involves covering the pavement with a binder, such as asphalt, and then spreading aggregate ("chips") such as rocks or sea shells, and pressing the aggregate into the binder and the older surface.
Concrete: The general term applied to a composite of binder and aggregate to form a pavement. The major distinction among concretes is the binder used; the aggregates are often similar. Common examples are Portland-cement concrete and asphalt concrete.
Cut - back bitumen: Bitumen to which a volatile solvent, such as kerosene or creosote has been added. These are used when small amounts of binder are needed and it is inconvenient to heat the viscous bitumen.
Emulsion: A material in which an oily substance is mixed with an ionic substance such that they do not segregate. In the case of an asphalt emulsion, the asphalt is ground to a size less than 50 micrometers. It is then treated with an emulsifier, a molecule that has an oily end, which attaches to the asphalt. The other end is ionic and is repelled by the asphalt but is attractive to water. Thus the asphalt particles present a water-seeking coating which allows them to remain in suspension in water.
Hot mix: Asphalt that is melted and mixed with aggregate before being spread for pavement.
Macadam: Type of road construction in which the base (under the wearing surface) is of compacted rock. The surface is contoured for drainage .
Marshall stability test: The maximum compressive force that a sample 102 mm (4 in.) in diameter and 64 mm (2 1/2 in.) in height can support before rupturing, under specified conditions of compaction, temperature, rate of deformation, and direction of force(Asphalt-Institute, 1989).
Microsurfacing: Resurfacing method employing an polymer-modified emulsion binder that also contains crushed stone aggregate, and mineral filler (e.g., Portland cement), and water.
Overlay: A resurfacing material which is a hot mix, containing aggregate of about 3/8 or 1/2 in. diameter.
Portland cement: A mixture of calcium-bearing minerals, clay and water which is a binder when it solidifies.
Seal coat: A mixture of emulsified bitumen, water and a fine aggregate, used to resurface a pavement with a thin (less than 1/32 in) layer. Sometimes the term is used to refer to a chip-seal placed on an existing pavement.
Slurry coat: A mixture of emulsified bitumen, water and a gritty aggregate, used to resurface a pavement with a layer about 1/8 to 1/4 in. thick.

Appendix B. Units and conversions

The units used in this report are abbreviated as follows : inch = " or in., foot = ft, square foot = ft^2, cubic foot = ft^3, yard = yd, square yard = yd^2 , cubic yard = yd^3, square meter = m^2, cubic meter = m^3. Because this review is intended for people in the United States pavement industry as well as the research community, we use both the common U. S. units of length, weight and temperature, as well as metric units. The conversions we use are:

1 yd = 3 ft = 0.914 m

1 yd^2 (square yard) = 9 ft^2 = 0.836 m^2; 1 m^2= 10.76 ft^2

1 yd^3 (cubic yard) = 27 ft^3= 0.765 m ^{3}

1°F = 5/9 °C. Temperature of 65 °F corresponds to 18 °C

1 lb <-> 0.454 kg <-> 0.12 gallons of water (or asphalt)

1 ton (short - 2000 lb) <-> 907 kg = 0.907 Mg

To convert kg/m^3 to lb/yd^3 , multiply it by 1.69.

Appendix C. Trade associations and sources of information

American Portland Cement Association (APCA), Suite 300, 1225 Eye Street N.W., Washington, D.C. 20005 (202) 408-9494 - fax- 0877

American Concrete Pavement Assoc, 3800 N. Wilke Rd, Suite 490, Arlington Heights, Ill 60004-1268, (708) 966-2272, fax- 394-5610

Asphalt Emulsion Manufacturers Association, #3 Church Circle, Suite 250, Annapolis, MD 21401, (410) 267-0023, fax-7546 - manufacturers of various emulsions, microsurface.

Asphalt Institute, Research Park Drive, P. O. Box 14052, Lexington, KY 40512-4052, (606)288-4960 - fax -4999

Asphalt Sealcoat Manufacturers Assoc., P. O. Box 511, Elk Grove, CA 95759-0511

International Slurry Surfacing Assoc. 1200 19th Street, N. W., Suite 300, Washington, D. C. 20036-2401 (202) 857-1160, fax 223-4579. Represents contractors who apply slurry seals.

Federal Highway Research Report Information System, R &T Report Center (703) 285-2144, fax-2919

National Asphalt Pavement Assoc., 5100 Forbes Blvd., Lantham, MD 20706 - 4413 (301) 731-4748, fax-4621 (Gary Fore)

National Ready Mixed Concrete Assoc., 900 Spring Street, Silver Spring, MD 20910, (301) 587-1400, fax 585-4219

National Stone Association, Washington, D.C. 800/342-1415. Represents suppliers of aggregate.