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A Comparison of Six Environmental Impacts of Portland Cement Concrete and Asphalt Cement Concrete Pavements

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Abstract: The current era is characterized by increased concerns about the environment. This trend is evidenced by the governmental, industrial, and consumer concerns for ozone depletion, solid and liquid waste disposal, pollutants, and rain forest depletion. This has led to an increase in marketing of the “environmentally friendly” aspects of products.

This report summarizes a literature survey, investigation, and comparison of six specific topics relating to the environmental impact of portland cement concrete and asphalt cement concrete pavements. These areas include (1) the effects of the pavement color on the microclimate, (2) artificial lighting requirements of the pavements at night, (3) the effect of pavements on vehicle fuel consumption, (4) inclusion of waste and recycled materials in pavements, (5) the potential to recycle pavement at the end of its useful life, and (6) costs during construction, maintenance, and reconstruction.

Situations where either pavement type provides an advantage to the environment are highlighted, and if available, quantifiable data are presented.

Keywords: albedo, asphalt, concrete, construction, costs, environment, environmental life cycle assessment, fuel consumption, life-cycle costs, lighting, microclimate, mileage, pavement, portland cement, recycle, waste

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INTRODUCTION

Environmental concerns are gaining a higher profile as evidenced by the governmental and consumer; concerns for ozone depletion, solid and liquid waste disposal, pollutants, and rain forest depletion. This has led to an increase in marketing of the "environmentally friendly" aspects of products. This report summarizes a literature survey and investigation of six specific areas for which the; environmental impact of portland cement concrete (PCC) and asphalt cement concrete (ACC) paving are compared. For purposes of this publication, PCC is simply defined as a hardened mixture of; hydrated portland cement, sand, and coarse aggregate. ACC, also commonly referred to as "asphaltic concrete," is similarly defined as a hardened mixture of asphalt cement and aggregate.

SCOPE

The scope of this project was limited to the following six topics chosen by the Portland Cement Association (PCA) and the American Concrete Pavement Association (ACPA):

1. Effects of the pavement color on the microclimate.
2. Artificial lighting requirements of the pavements at night.
3. The effect of pavements on vehicle fuel consumption.
4. Inclusion of waste and recycled materials in pavements.
5. The potential to recycle pavement at the end of its useful life.
6. Costs during construction, maintenance, and reconstruction.

For each topic, a literature survey was performed to identify and compare the environmental impacts of PCC and ACC pavements. Situations where either pavement type provides an advantage or disadvantage to the environment are highlighted, and if available, quantifiable data are presented. The "Recommendations" section of this report indicates whether each topic provides an overall advantage to PCC, a disadvantage, or not enough information is available to reach a recommendation.

This paper is divided into six chapters. Each chapter corresponds to a single topic.

CHAPTER 1

EFFECTS OF PAVEMENT COLOR ON THE MICROCLIMATE

BACKGROUND

The effect of materials on the temperature of the localized atmosphere is a rapidly expanding research area. Basic research in this area is directed at the color and composition of materials and their ability to reflect or absorb (and emit) solar radiation. The color and composition of the materials greatly affects the temperature of the material exposed to solar radiation. Heat energy from absorbed solar radiation will eventually enter the surrounding atmosphere, causing localized heating.

ALBEDO

The degree to which a material will reflect incoming solar radiation (all "light" from the sun including, but not limited to, infrared, visible and ultraviolet light) is governed by the material's albedo, a measure of the solar reflectivity of the material. Albedo is, therefore, different than "reflectivity," which is a measure of the reflectance of light in the visible spectrum. Albedo is measured on a scale of 0.0 to 1.0. Materials on the low end of the scale absorb solar radiation, while materials on the upper end of the scale reflect solar radiation. Generally, materials that appear to be light-colored in the visible spectrum have high albedo and those that appear dark-colored have low albedo. Because reflectivity in the solar radiation spectrum determines albedo, color in the visible spectrum is not always a true indicator of albedo.

The ability to reflect infrared light is of great importance because infrared light is most responsible for heating. To illustrate this point, surface temperatures were measured on various materials on a bright clear November day in central California [1-1]†. During the time of the experiment, the ambient air temperature was 55 °F (13 °C). Darker materials such as black acrylic paint attained a maximum temperature of 142 °F (61 °C), while white colors such as white acrylic paint had a temperature of 74 °F (23 °C). Interestingly, a cementitious (portland cement) coating had a temperature of 89 °F (32 °C), while a "white" colored asphalt roofing shingle, which is actually quite dark, had a temperature of 118 °F (48 °C). Reflectivities of select materials are shown in Figure 1. For the cementitious coating, average measured value of reflectivity of visible light was 71 percent, and for infrared light was approximately 60 percent. Average reflectance values for the "white" asphalt roofing shingle ranged from 26 percent in the visible range to approximately 20 percent for the infrared spectra. The average solar reflectivity of a "green" asphalt

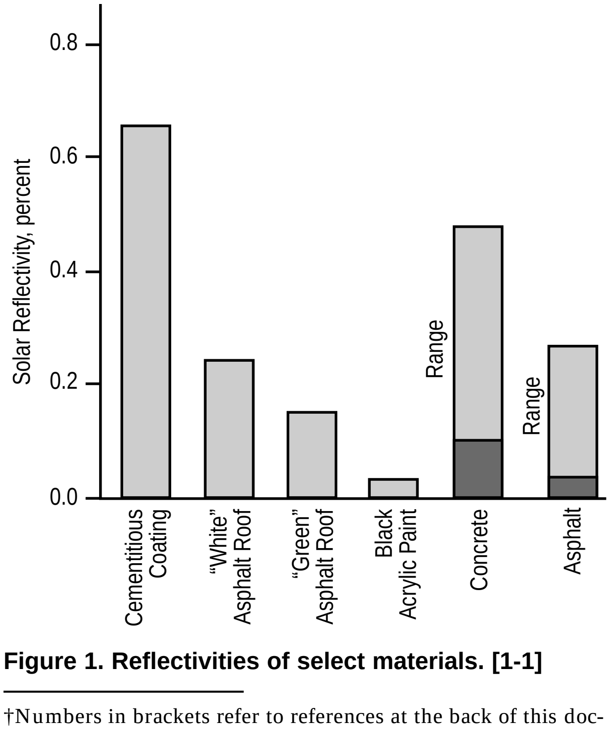

Figure 1. Reflectivities of select materials. [1-1]

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†Numbers in brackets refer to references at the back of this document. References are numbered with respect to the topic under which each first appears. As an example, reference [2-10] is the tenth reference in the second chapter of this report.

shingle and black acrylic paint were 0.14 and 0.05, respectively. Specific tests were not conducted on asphalt concrete; however, it is assumed that values for asphalt fall somewhere between that of black paint and the "white" asphalt shingle. Rough surfaces were shown to reflect less solar radiation, thus heating to a higher temperature.

In a different study of the same nature conducted at noon on a clear calm day in Austin, Texas, surface temperatures were approximately 155 °, 195 °, and 135 °F (68 °, 91 °, and 57 °C) for weathered concrete, black asphalt, and asphalt surfaced with crushed oyster shells, respectively [1-2]. The ambient air temperature at the time of testing was 90 °F (32 °C). Corresponding surface albedos were 0.4, 0.1, and 0.55, respectively. Other reported albedos for ACC and PCC pavements were 0.4 for weathered concrete [1-2], 0.10 to 0.35 for concrete [1-3], 0.15 for asphalt [1-2], and 0.05 to 0.20 for asphalt [-3]. Figure 2 shows a PCC sidewaLk with new and weathered concrete. Figure 3 shows weathered and new ACC pavements. The albedo of new concrete will vary depending on the constituent materials in the concrete and the surface finishing techniques.

Figure 2. New PCC section in weathered PCC sidewalk.

EMISSIVITY

In addition to albedo, a surface temperature is affected by the material's emissivity. While albedo is a measure of the solar radiation reflected away from the surface, emissivity is the ability of the material to emit, or "let go of'' heat. A white surface exposed to the sun is relatively cool because it has a high reflectivity and a high emissivity. A shiny metal surface is relatively warm because it has a low emissivity even though it has a high albedo (reflectivity).

Figure 3. New ACC pavement on left, old ACC pavement on right.

URBAN HEAT ISLAND EFFECT

A material's albedo and emissivity is important when many materials are massed together, as in a city. Cities are constructed of concrete, asphalt, glass, steel, and other building materials. These materials heat up from solar radiation during bright sunny days. Heat collected by these materials radiates into the local atmosphere, thus increasing the local temperature. At night, when the ambient air temperature typically decreases, objects with large amounts of heat energy radiate the heat for a considerable length of time. This can keep the local atmosphere from cooling to its maximum potential.

Research has shown the average temperature of urban areas is between 2 ° and 8 °F (1 ° to 4 °C) warmer than surrounding rural areas [1-3]. This is termed the "urban heat island effect." Many factors effect this phenomena; however, replacing grass and natural vegetation with concrete asphalt, and other building materials is the most significant cause of the urban heat island effect. In a rural environment, a large portion of the solar energy evaporates moisture from vegetation. In the urban environment, this energy is absorbed to a certain extent by the building materials. The net effect is that the rural area remains cooler during the day and quickly cools at night, while the urban area becomes hotter during the day, and is slower to release its heat at night.

Los Angeles has been used to study the "urban heat island effect." Research has shown that the average temperature of Los Angeles has risen steadily over the past half century, and is now 6 ° to 7 °F (3 ° to 4 °C) hotter than 50 years ago [1-4]. The increased temperature is only partially due to surface color. Researchers currently estimate that approximately one-third to one-half of the "heat island effect" is due to a lack of trees [1-5].

Temperature data from other cities throughout the world also confirm the "urban heat island effect." Urban temperatures in the United States during summer afternoons have increased 2 ° to 4 °F (1 ° to 2 °C) in the last 40 years [1-3, 1-4]. This daily temperature rise on hot days results in an increase in the peak energy consumption in all major cities due to an increase in the air conditioning load [1-3]. It is estimated that 3 to 8 percent of the electricity demand in cities with populations greater than 100,000 is used to offset the heat from the heat island effect [1-4]. In Los Angeles, for every 1 °F (0.6 °C) of temperature rise, an additional 300 megawatts per hour of power are consumed, which is an increase of approximately 1.7 percent per degree Fahrenheit [1-3]. Similar data are available for many cities around the United States, including cities in more temperate climates such as Washington, D.C. The implications of the heat island effect for the entire United States are tremendous. The cost of electricity used to offset the peak temperatures from the heat island effect in U.S. urban areas is estimated to be one million dollars per hour or approximately one billion dollars per year [1-3].

SMOG

Smog levels have also been correlated to temperature rise [1-3]. Thus, as the temperature of urban areas increases, so does the probability of smog and pollution. In Los Angeles, the probability of smog increases by 3 percent with every degree Fahrenheit (°F) of temperature rise [1-2]. Studies for Los Angeles and 13 cities in Texas have found that there are almost never any smog episodes when the temperature is below 70 °F (21 °C). The probability of episodes begins at about 73 °F (23 °C) and, for Los Angeles, exceeds 50 percent by 90 °F (32 °C). Reducing the daily high in Los Angeles by 7 °F (4 °C), the amount resulting from the heat island effect, is estimated to eliminate two-thirds of the smog episodes [1-2].

Smog and air pollution are the main reasons for the EPA (United States Environmental Protection Agency) creating and mandating expensive clean fuels for vehicles and reduced particulate emissions from industrial facilities such as cement plants and asphalt production plants. The EPA now recognizes that air temperature is as much a contributor to smog as NO_X (the various oxides of nitrogen) and volatile organic compounds, the contributing emissions [1-6]. The effort to reduce particulates in the industrial sector alone costs billions of dollars per year, whereas reduction in smog may be directly related to the colors of the infrastructure that surround us.

MITIGATING THE HEAT ISLAND EFFECT

One method to reduce the "urban heat island effect" is to change the albedo of the urban area This is accomplished by simply replacing darker colored materials with materials of higher albedo. In one study, a computer model was used to predict the effects of changing the albedo of Los Angeles [1-2, 1-7]. Aerial photographs were used to identify areas where the albedo could be increased. Areas identified for albedo modification were roofs and pavements, with equal areas available for modification. Roofs were lightened through the use of lighter colored shingles and white coatings, and roads were changed from asphalt to weathered concrete. The study indicated that the lightening of the city would decrease average mid-afternoon temperature by 4 °F (2 °C), thus eliminating a significant amount of smog and energy usage.

Available literature has numerous cost-conscious suggestions for lightening pavements [1-3]. Most of the literature stressed switching to a light colored pavement when the current pavement needs to be renovated or replaced. Costs are minimized when a high albedo material is introduced at the time of replacement to meet other needs. This minimizes the cost of the lightening process. Ideas for lightening pavements include: white topping roads with light colored PCC when the road is in need of an overlay, paving with PCC in urban areas, placing a finishing layer of white sand or crushed oyster shells on new ACC pavements, and developing a light-colored asphaltic slurry seal. A more expensive option is to use white cement in the PCC rather than ordinary portland cement.

One area of concern for lightened pavements is the long-term color stability. As light colored pavements age, they become darker. Although oil drips, pavement scrapes, tire marks, debris, and dirt decrease the albedo of a light colored surface such as PCC or a light colored ACC, one study states that this is not a great concern [1-4]. This study also states that this issue has not been thoroughly addressed. Data for aged white roofs may be comparable. Studies have shown that although a portion of the reflectivity is lost within the first year, the residual reflectivity is still much greater than the reflectivity from a darker colored material [1-3].

In contrast to PCC, the albedo of ACC pavements increases with age because the asphaltic binder on the surface wears away revealing the aggregate. In general, the degree of lightening of the pavement depends on the color of the aggregate, and the rate of lightening depends on the amount of traffic, the total hours of solar radiation, and other factors.

HIGH ALBEDO IN THE HEATING SEASON

Because light colored surfaces reflect solar radiation, high albedo surfaces may increase winter heating bills. However, the effect of light colored horizontal surfaces in winter is estimated to be one-tenth of those in summer due to less solar radiation, shorter days, and the increased possibility of overcast skies. Therefore, the beneficial effects of cool materials in the summer are not necessarily a large disadvantage in the winter in U.S. climates.

Dark colored pavement surfaces may provide some benefits in cold weather climates. Although no quantifiable research was identified, pavement color may effect the quantity or frequency of deicer chemical applications. In certain situations, dark pavements are warmer and appear to shed snow and ice more quickly than light colored pavements.

IMPLEMENTING AND PROMOTING COOL SURFACES

Standard test methods and a method of rating the benefits of high albedo are required to implement incentive plans to encourage the use of high albedo surfaces. An ASTM subcommittee of Committee E-6 on Performance of Buildings, E06.42 on Cool Construction Materials, was formed to promote standards development for high albedo surfaces used to cool urban areas. Standards are required for the following areas:

1. Solar reflectivity and emissivity of new materials.
2. Surface temperatures of fresh materials under standard conditions such as clear hot summer days, high and low wind speed, and in several climate regions.
3. Longevity of high reflectivity. Standards for addressing aging of materials must take into account such factors as the accumulation of dust and dirt on white roofs over time, the accumulation of dirt and grease on PCC pavements over time, the wearing of asphalt binder on ACC pavements over time, resistance to mold build-up, and washability.
4. Service life.

ASTM Subcommittee E06.42 proposes a rating system to assess the ability of a surface to stay cool when exposed to sunlight. The temperature rise on a surface will be calculated based on measured reflectivity and emissivity of an insulated surface exposed to sunlight. The formula for the temperature rise can be determined from the equations on page 26.5 of the ASHRAE Handbook 1993 Fundamentals [1-8] and will be correlated to a “Cooling Index” [1-6]. Agencies or organizations could then perform modeling to determine the energy-saving and pollution-reducing effects of various materials with various “Cooling Indices” for different roofs and roadways in a range of climates. The modeling efforts could be used to quantify benefits and encourage high albedo surfaces in codes, utility rebate programs, and pollution control strategies. The thermal mass effects of PCC and ACC paving materials will make their reflectivity measurements, emissivity measurements, and temperature rise calculations more complicated than those for painted surfaces.

CHAPTER 2

ARTIFICIAL LIGHTING OF PAVEMENT AT NIGHT

Darkness increases the potential for hazards on roadways because driver visibility is decreased. The night-time fatality rate is approximately three times greater than during the daylight hours, adjusted for the proportional number of vehicles travelling during these times [2-1]. Artificial lighting of pavements during the night can reduce the fatality rate, but this represents an additional cost to society. Estimated costs of lighting vary depending on location, type of light, etc. Data from a 1986 report [2-2] for typical roadway lighting arrangements provide first cost estimates in the range of $44,000 to $78,000 per mile ($27,000 to $48,000 per kilometer). This is based on a cost of $2,000 per lighting unit including the pole, concrete foundation, luminary, pole wire, erection, and testing. Energy costs range from $1,100 to $2,000 per mile per year ($680 to $1,240 per kilometer per year). Maintenance costs are estimated to range from $1,300 to $2,300 per mile per year ($810 to $1,430 per kilometer per year).

LUMINESCENCE AND REFLECTANCE

Current lighting practices allow for the reflectivity of the pavement to be considered when designing roadway lighting [2-1]. This method, called the “Luminance Method” is based on the light that the driver actually sees [2-3]. In this method of lighting, design pavements are classified as one of four types ranging from R1 to R4, with required luminescence increased from type R1 to type R4. New PCC pavements generally fall under type R1, while new ACC pavements typically fall under type R3.

ACC pavements are penalized by the luminance method due to their poor reflectance. More lights are needed per unit length of ACC pavement to achieve the same illumination as PCC pavement. This is illustrated in Figures 4 and 5. More illumination is needed on ACC pavements because ACC pavements reflect light mainly in a specular fashion. Specular reflection can be likened to bouncing a ball off of a floor at an angle. When the ball strikes the floor at a 38 degree angle, it rises at a 38 degree angle. Light is mainly diffusely reflected from PCC pavements. This is similar to bouncing a ball off a pool of water. Regardless of the angle of incidence, the water will splash at all angles in a similar fashion as diffusely reflecting light.

Figure 4. Light from automobile on PCC pavement. (S-38072)

Figure 5. Light from automobile on ACC pavement. (S-38073)

COST SAVINGS

Many examples exist [2-1 through 2-6] on the advantages of artificially lighted conventional PCC pavements compared to conventional ACC pavements. One study of a major road in a commercial area estimated decreases in costs for lighting PCC in comparison to ACC, shown in Figure 6. Using PCC rather than ACC, the initial cost of purchasing the lights would be reduced by $24,000 per mile ($15,000 per kilometer), energy costs would be reduced by $600 per mile per year ($370 per kilometer per year), and maintenance costs would be reduced by $576 per mile per year ($358 per kilometer per year) [2-2]. These cost savings represent a 31 percent decrease in initial, energy, and maintenance costs for lighting PCC versus ACC pavement. These costs were calculated in 1985 dollars for the Chicago metropolitan area assuming that the ACC pavement was type R3 and the PCC pavement was type R1.

UNCERTAINTIES

Current lighting technology allows designers to chose from a variety of more energy-efficient lighting that may minimize the differences in costs between lighting ACC and PCC pavements by reducing the total number of lights needed to provide adequate illumination. New technologies provide illumination at a lower cost which may minimize the cost difference between lighting PCC and ACC pavements. This will mainly affect total reconstruction jobs and the construction of new 5 roads. For reconstruction, does a PCC road with a new ACC overlay require additional lighting; and if so, are more lights needed or are there other solutions? The advantages of PCC over ACC in terms of lighting may be minimized, however, these advantages will most likely remain unchanged.

Some uncertainty exists in the values of reflectance for worn PCC and ACC pavements. One study in Canada [2-7] measured the lighting requirements of ACC and PCC pavements at different ages with different aggregates and surface textures. The study classified ACC and PCC pavements in all categories from ranging from type R1 to R4 and concluded that, over time, ACC pavements lighten and PCC pavements darken (See Figures 2 and 3). Furthermore, aggregates which are polishable will cause the pavement reflectance to shift from diffuse to more specular. These studies raised the question of the appropriate categories for worn ACC and PCC pavements. Other reflectance studies conducted in Australia [2-8] had similar conclusions.

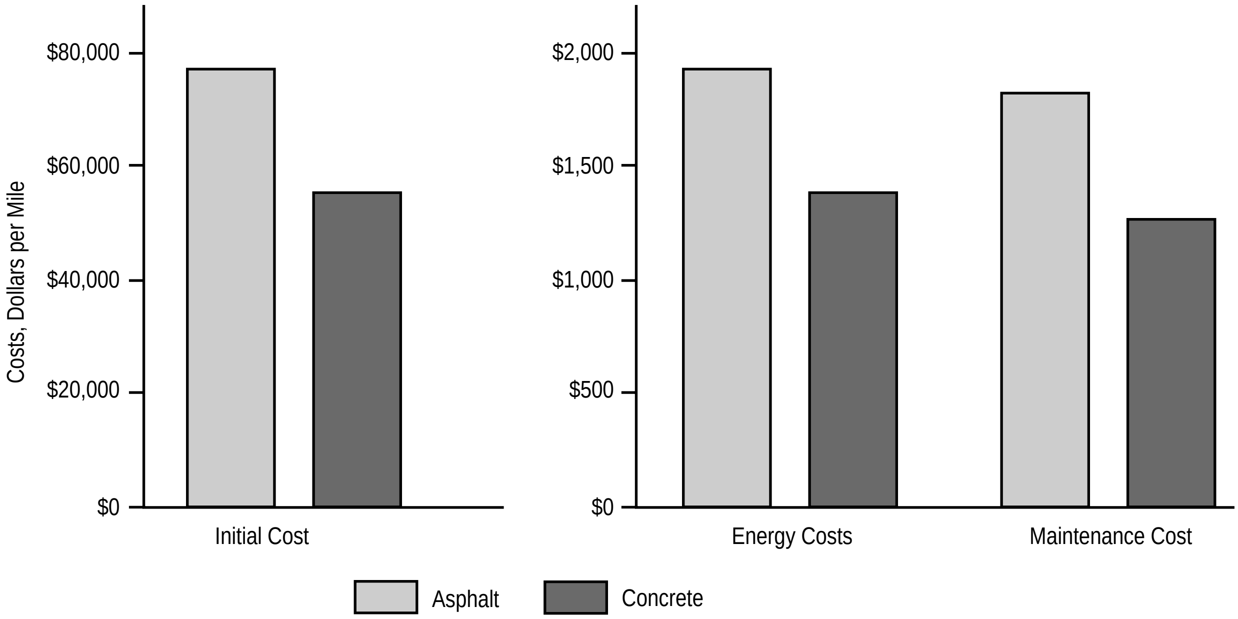

Figure 6. Example of initial cost, energy, and maintenance savings for lighting PCC versus ACC pavements. [2-2]

CHAPTER 3

THE EFFECT OF PAVEMENT ON VEHICLE FUEL CONSUMPTION

On a per vehicle basis, heavy trucks travel the greatest distance, use the most fuel, and cause the most road wear. Various aspects of truck traffic on ACC and PCC pavements are investigated in the following sections.

BACKGROUND

In the U.S., all trucks (including light duty and pick-up trucks) accounted for 440 billion highway miles (708 billion kilometers) and consumed 51 billion gallons (190 billion liters) of fuel in 1985 [3-1]. In 1992, the total number of "highway truck miles" increased to 629 billion miles (1.01 trillion kilometers). Over this distance, trucks consumed 58 billion gallons (220 billion liters) of fuel [3-2].

The average "combination" (semi-tractor trailer) truck consumed 10,695 gallons (40,485 liters) of fuel and travelled an average of 5.6 miles per gallon (2.4 kilometers per liter) in 1992. The average fuel economy of all trucks in 1992 was 10.84 miles per gallon (4.61 kilometers per liter). This is a decrease of approximately 1.2 percent from the 1991 average truck mileage of 10.97 miles per gallon (4.66 kilometers per liter). The decrease in mileage is apparent for all vehicles except motorcycles. This may be due to a number of factors including increased traffic congestion and the use of cleaner burning oxygenated fuels [3-2].

Between 1991 and 1992, vehicle registrations increased by approximately 1 percent, and the average number of miles (kilometers) traveled per vehicle increased by 2 percent. Also during this time approximately 0.33 percent more miles (kilometers) of federally funded roads were constructed. Data for urban interstate traffic volume indicates congestion actually decreased during this period. However, historical data indicates twice as many traffic jams in 1992 as in 1975 [3-2].

PAVEMENT CONDITION

Pavement condition in 1992, in general, was better than pavement condition in 1991 [3-2, 3-3]. This is based on the reports by state Departments of Transportation (DOTs) using the present serviceability rating (PSR). This scale rates roads on a scale of 5.0 for new roads to 0.1 for pavements in extremely poor condition. The 1992 average condition of all interstate roads, expressways, major arterial roads, and minor arterial roads was in the "good" range, with the average ratings of each individual type of road being between 3.5 to 3.7 on the PSR index.

Deteriorated roads have a negative impact on fuel consumption. Numerous studies have correlated pavement condition to fuel consumption [3-4]. In one study, as pavements deteriorated from new to very poor conditions, the cost for operating a small car increased from $0.35 to $0.48 per mile ($0.22 to $0.30 per kilometer). The cost to operate a five-axle combination truck (semi) increased from $0.77 to $1.07 per mile ($0.48 to $0.66 per kilometer). This 1983 study considered only the costs of fuel, oil, maintenance, and depreciation [3-4]. Secondary costs such as lost time or lessened productivity were not considered. Operating costs specifically comparing deteriorated PCC and ACC pavements were not available.

PAVEMENT TYPE

Data compiled by the Federal Highway Administration (FHWA) shows that, from 1991 to 1992, total miles (kilometers) of flexible and composite pavements increased 2 percent, and the total miles (kilometers) of rigid highway pavement increased by slightly more than 1 percent. Rigid pavements account for slightly less than 10 percent of all highway pavements. By the FHWA definition, a rigid highway pavement is a PCC pavement with or without a 1 inch (25 mm) or less ACC overlay. Flexible highway pavements are defined to be ACC pavements on a flexible base with a combined surface and base thickness of 7 inches (180 mm) or more. This definition also includes brick and block pavements as well as asphalt overlays of brick and block pavements. Composite highways, approximately 9 percent of all highways, are defined to be ACC overlays (greater than 1 inch [25 mm]) on a rigid base, where the overlay and base materials are greater than 7 inches (180 mm) [3-2].

FUEL CONSUMPTION BY PAVEMENT TYPE

Studies have shown that consumption of fuel varies on the type of pavement as the weight of the vehicle increases [3-5, 3-6]. Data indicate that fuel consumption of automobiles is not affected by the type of pavement surface. Pavement type greatly affects the fuel consumption of trucks, as illustrated in Figure 7. As truck weight increased, the fuel consumption on ACC pavements dramatically increases as compared to fuel consumption on PCC pavements. For a combination truck (semi-tractor trailer), fuel mileage on PCC was 1 mile per gallon (0.43 kilometer per liter) better than on ACC. Because the combination truck averaged 4.5 to 5.5 miles per gallon (1.9 to 2.3 kilometers per liter), this represents a 20 percent energy savings. The same study indicates 25 percent better mileage for a three-axle truck and 11 percent better mileage for a two-axle truck (pick-up trucks and vans) on PCC pavement [3-5].

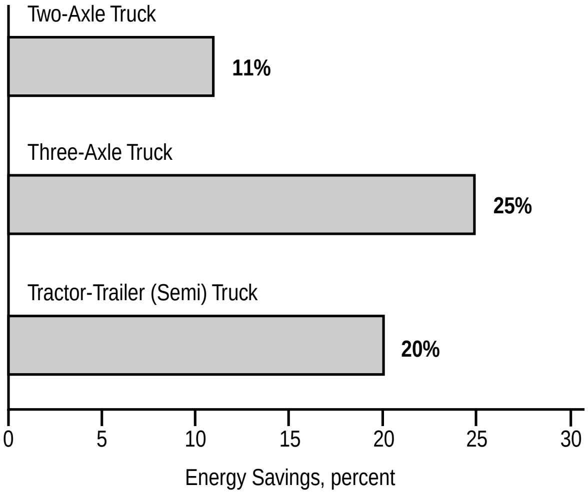

Figure 7. Energy savings of trucks on PCC pavement in comparison to ACC pavements. [3-5]

Another study, measuring rolling resistance on different pavement types, indicated that ACC compared to PCC pavements increase fuel consumption by 5 percent at 30 miles per hour (19 kilometers per hour) for large trucks [3-7]. At 40 miles per hour (25 kilometers per hour), fuel consumption increases by 7 percent on ACC surfaces compared to PCC surfaces. The ACC pavement used in this study was relatively new, and the PCC pavement was older, but still in good condition.

Road deflection is a major cause for reduced mileage on asphalt concrete pavements [3-5]. All pavement types deflect to a certain degree, however, ACC pavements deflect considerably more than PCC pavements. Deflections for cold ACC pavements have been measured at 0.06 inches (1.5 mm), while deflections for PCC pavements are on the order of 0.03 inches (0.8 mm) [3-8]. Reports indicate that hot ACC pavements can deflect up to 1 inch (25 mm), but supporting data such as pavement temperature and conditions are not available [3-8].

PAVEMENT DAMAGE DUE TO VEHICLE WEIGHT

Pavement damage is influenced mainly by vehicle weight, and to a lesser extent, by tire pressure and configuration [3-9]. Heavy trucks cause asphalt pavements to rut [3-4] as shown in Figure 8. Both PCC and ACC pavements deteriorate from repeated heavy truck use. A measure of the damage that vehicles cause to roads is the “equivalent single axle load” (ESAL). This is a measure of the number of single axle trucks that would cause the same amount of wear as the mix of automobiles and trucks using the road during the same period of time.

Figure 8. Extreme case of rutting on ACC pavement. (S-56601)

Pavements are designed to withstand a particular number of ESALs before replacement or resurfacing. Calculations to determine the ESALs are complex and depend on pavement material, thickness, and other variables. Typical average daily ESALs on the rural interstate system in 1988 was 5,100 for trucks with 5 or more axles and 5,500 for all vehicles. Because semi-tractor trailer trucks account for approximately 15 percent of vehicle-miles on the rural interstate system [3-2], this illustrates large heavy trucks cause a majority of the damage to the pavements. Pavement wear in the U.S. costs approximately 2 billion dollars per year to state DOTs which maintain and rehabilitate roads. Also, as previously mentioned, deteriorated pavements increase vehicle costs and costs to society due to increased travel times, lost revenues, and vehicle damage.

A 1982 FHWA study reviewing user costs for the nation's roads was conducted to determine if users are "paying their fair share" of roadway damage. The study indicated that small automobiles paid for 70 percent of the damage they caused, while large automobiles and pickups paid for 120 percent of the damage they caused [3-10]. Small trucks paid for 130 to 170 percent of the damage they caused, while the largest trucks paid for 50 percent of the damage they caused. Overall, passenger vehicles paid for 115 percent of the damage, while trucks paid for 85 percent of the damage. A similar review in 1994 by the Government Accounting Office (GAO) recommended that the FHWA conduct an updated formal cost allocation study and that Congress examine a "national weight-distance user fee" [3-11].

Another study which compared pavement damage to user fees also concluded that heavy trucks do not pay for the damage that they cause. On the basis of the 1986 American Association of State Highway and Transportation Officials (AASHTO) Design Manual equations for pavement design and user taxes, a heavy truck should pay over 400 times more than what is currently paid in taxes for the damage caused to pavements as compared to the damage caused and the fees paid by an automobile [3-12].

Vehicles pay for the damage they cause through fuel taxes, excise taxes, use taxes, and tire taxes. The federal government collected over $18.5 billion in those types of user fees in fiscal year 1993 [3-11].

FUTURE TRUCK LOADING

Today, a majority of the heavy weight trucks are 5-axle combination trucks. Allowable gross vehicle weight limits are up to 80,000 pounds (36,300 kilograms). In 1986, the National Cooperative Highway Research Program (NCHRP) proposed reducing the weight per axle by introducing "Turner trucks" [3-4]. These trucks are multiple axle tandem trailer trucks used to haul freight long distances. The proposed trucks would reduce pavement wear approximately 40 percent by spreading the vehicle weight over more axles. It would follow that reduced axle weight would also lead to improved fuel economy on ACC, compared to PCC pavements.

CHAPTER 4

INCLUSION OF WASTE AND RECYCLED MATERIALS IN PAVEMENTS

Each year billions of tons of waste are generated and landfilled. Byproducts and waste materials from industrial processes are also being landfilled in record levels. As available landfill space in the United States decreases due to tightened standards imposed by the Environmental Protection Agency (EPA) and the general public's opposition to new landfills, the cost of waste disposal is rapidly increasing. To minimize the amount of materials destined for landfilling, efforts to recycle usable materials are increasing. Household, industrial, and construction wastes are increasingly being recycled into useful products. Wastes are being utilized as inexpensive fill material in ACC and PCC pavements, and as fuel and/or raw feed for production of the asphaltic binder and portland cement. Wastes are also being used in PCC as a partial replacement for portland cement [4-1].

CONSTITUENT MATERIALS

ACC and PCC are similar in the fact that they are made up of an aggregate and a binder. In ACC, the aggregate is usually rock and the binder is the asphaltic cement. The aggregate in PCC is also usually rock and the binder is portland cement. Both types of concrete use high aggregate contents ranging from 75 to 95 percent. Generally, the desired aggregate for use in both types of concrete is a strong stable fill material, and rock is utilized mostly because it is readily available and inexpensive. Extracting aggregate from solid rock, processing it into useful aggregate, and hauling the aggregate to the job site are the most expensive costs associated with using rock. In certain locations, it can be more cost effective to use an alternate fill material as a partial replacement to the rock aggregate. Increased performance or improved engineering properties are additional reasons for partial replacement of rock aggregate with a fill material. The only general rule for a fill material is that it must not negatively influence the concrete performance as determined by its physical properties.

WASTE AND RECYCLED MATERIALS IN PORTLAND CEMENT AND PCC

Many waste materials have found their way into portland cement and PCC. Most of the waste materials in PCC are utilized in the final product as a fill material or as a material which improves the engineering properties of the concrete. Some examples of these materials are fly ash, silica fume, ground granulated blast-furnace slag (GGBFS), porcelain, and clay masonry. In some cases, engineering properties of the concrete can be maintained or increased by the partial replacement of the portland cement with an alternate material [4-1]. In this case, the material is no longer a fill material; it is a binder. Examples of this are the use of pozzolans such as fly ash, silica fume, or GGBFS in PCC.

Other materials such as vehicle tires, organic solvents, medical waste, carpet remnants, treated particulate emissions, and many others have been utilized in the production of portland cement either as a fuel or as an alternate raw material. In 1992, twelve U.S. cement plants reported using wastes as primary fuel and 36 reported using wastes as an alternative or supplementary fuel [4-2].

Although many materials have been successfully utilized in PCC, the focus of the following sections will be on (1) the use of fly ash in PCC, and (2) vehicle tires in the production of portland cement.

Fly Ash

Composition. Fly ash is a waste material produced by burning coal to generate electric power. Of the approximately 70 million tons (63.5 million metric tons) of fly ash produced in the U.S. in 1984, about 7 million tons (6.4 million metric tons) were used in PCC [4-3]. ASTM C 618 classifies fly ashes into two classes depending on their chemistry. Class "F" fly ash, which has pozzolanic properties, is produced from burning anthracite or bituminous coal. Class "C" fly ash has some cementitious as well as pozzolanic properties, and is produced from burning lignite or subbituminous coal. The major difference between the two classes is that Class "C" fly ash has a lower requirement for the major oxides of silica, alumina, and ferrite, and also has a higher free lime content. Class "C" fly ash is much more abundant than Class "F" fly ash. Factors such as glass content, fineness, and silica and alumina content affect the quality of the fly ash. Fly ash generally has a lower rate of strength development than the portland cement it replaces. Fly ashes with a high glass content have greater pozzolanic activity. Fineness also plays an important role in the pozzolanic activity of the fly ash. Increased fineness allows more fly ash particles to react more quickly which in turn increases the rate of strength development. High silica and alumina contents also increase the rate of strength gain.

EPA Mandate. Fly ash is a waste product. Using fly ash as a partial replacement for cement in PCC reduces the energy required to produce cementitious material in a given quantity of concrete. For example, summing all of the energy to produce, extract, and transport materials in concrete, a mix with fly ash as a partial replacement for cement will have less consumed energy. Therefore, the use of fly ash in concrete increases the "capacity" of cement plants [4-3]; more concrete can be made for a given cement plant capacity. Also, landfill space that would otherwise be occupied by the fly ash is freed. Based on these benefits, in 1980 the EPA proposed that the federal government mandate fly ash content be maximized in federally funded concrete projects. Because of variability in fly ash chemistry and lack of data on long-term properties, the guideline issued in 1983 basically encouraged the use of fly ash in concrete, but did not dictate a minimum addition.

The EPA's new guidelines for federal procurement mandate the use of fly ash or GGBFS in concrete. The new guidelines, effective May 1, 1996, require the purchase of materials with recycled content for all federal procurements greater than $10,000, including federal grants to states. Previous guidelines recommended but did not mandate the use of recycled products. New guidelines do not set a required minimum content, but do refer to existing specifications. There are exceptions to the new rule. Recycled materials are not required when: (1) the materials are not readily available, (2) the materials are too costly; or (3) the materials are not appropriate for the specific application [4-4].

Performance. The benefits of fly ash in concrete are substantial. The use of fly ash as a partial replacement for cement can increase or decrease the durability and sulfate resistance and decreases the leachability, porosity, and permeability of the concrete. In mass concreting, the use of fly ash reduces the overall heat generation of the concrete. On a pound for pound basis, fly ash generates 25 to 50 percent as much heat as cement [4-5]. Fly ash also hydrates more slowly than cement. This moderates the peak temperature within recently placed concrete and decreases the potential for thermal cracking. With respect to alkali-silica reactivity (ASR), an appropriate fly ash can greatly reduce expansion and subsequent deterioration associated with ASR-affected PCC [4-6].

Scrap Tires

Availability and Energy. Utilizing scrap tires as a fuel in the manufacture of portland cement reduces the cost and energy required to produce portland cement. As of 1990, there were approximately 2 to 3 billion tires stockpiled around the United States (Fig. 9). Nearly one quarter of a billion tires are discarded each year, an equivalent of one tire per person in the U.S. per year [4-7]. Discarded tires are an environmental problem because they are slow to decompose, are often a breeding ground for insects and animals, and are a serious fire hazard.

One method of tire disposal is utilization of the tires as fuel to generate heat in cement kilns. Tires have approximately the same energy per pound as coal [-7, 4-8, 4-9]. On a pound basis, combustion of a tire releases approximately 15,000 Btu (15.8 megajoules), while coal releases 12,000 to 16,000 Btu (12.7 to 16.9 megajoules). Discarded tires have the potential energy to supply 0.09 percent of the U.S. energy needs [4-7].

Data on Tires as Fuel. As of 1992, eight cement plants across the U.S. were utilizing tires as a supplemental fuel and a few additional plants were experimenting with the idea [4-8]. By 1996, twenty-three cement plants across the U.S. were utilizing tires as a supplemental fuel [4-9]. A number of cement plants across the U.S. have extensive data on trial burns of scrap tires.

Extensive air and water quality testing and quality of life testing were performed during trial burns of 16 to 17 percent replacement of coal by shredded tires at a California cement plant [4-8]. Results of the testing revealed that emissions of RCRA metals and organic compounds actually decreased during burning of the coal/tire mixture. This was partially due to an increased energy content of the tires compared to coal. Although total carbon dioxide emissions were not measured, a decrease in formaldehyde, carbon monoxide (CO), and NO_X emissions contributed to an overall drop in measured emissions Emissions of benzene, dioxin, and total PAH's slightly increased during the burning of the coal/tire mixture; however, these compounds account for only a small portion of the total emissions. An estimation of the total maximum multipathway carcinogen risk showed that burning coal alone accounts for 4.9 excess cancer cases over a lifetime per 1 million exposed people, compared to a value of 3.7 for burning the coal/tire mixture [4-8]. As a baseline comparison, the EPA's acceptable risk is 1 to 100 excess cancer cases over a lifetime per 1 million exposed people.

Figure 9. Small stockpile of scrap tires. (S-59920)

WASTE AND RECYCLED MATERIALS IN ASPHALT CONCRETE

Many waste materials have also found their way into ACC. Most of the waste materials are used as inert fill materials, however, some materials can be used as asphalt cement replacements. Some examples of fill materials are tire rubber, fly ash, crushed glass, asphalt roofing shingles, slag, porcelain, contaminated soils, and clay masonry [4-10 through 4-12]. Materials such as finely ground tire rubber, roofing shingles, and polymer wastes can be used for asphaltic cement replacement.

Although materials such as clay masonry, slag, porcelain, and roofing shingles have been used in asphalt concrete pavements, their use is not widespread. Testing conducted in Europe showed that when ACC pavements were constructed with broken brick as aggregate, the asphalt cement content had to be increased from 4-5 to 6-7 percent, drastically increasing the cost of the mix [4-12]. Fatigue tests also carried out on this same material showed that a 6-3/4 inch (170 mm) thick pavement performed equally to a 4 inch (100 mm) thick conventional ACC pavement.

Porcelain

Porcelain also has had limited use in ACC. Initially, crushed porcelain was used as a base material, and later it was incorporated into the ACC pavements. Much of the initial use of porcelain in the early l990s was due to California's encouragement of replacing older toilets with newer water-conserving toilets [4-11]. Since the initial projects in California, the use of crushed porcelain has been sporadic.

Roof Shingles

Each year, 6 to 7 million tons (5.4 to 6.4 million metric tons) of asphalt roof shingles are discarded in the U.S. An additional 1 million tons (0.9 million metric tons) are discarded as waste material from shingle manufacturers [4-10]. Waste shingles in ACC usually replace a portion of the fine aggregate and asphalt cement. Shingles are typically recycled at rates approaching 10 percent of the total ACC. At greater than 10 percent replacement, plant modifications are required [4-10].

Disney World in Florida utilized recycled asphalt shingles in some parking lots at rates of 4 to 10 percent replacement. Shingles were shredded to minus 1/2 inch (13 mm) for complete melting and uniform dispersion within the ACC. The overall cost of the ACC pavement was reduced by $2.80 per ton ($3.09 per metric ton), however, information on costs of the materials, shredding, and transportation were not available [4-10].

Slag and Fly Ash

Slag and fly ash from coal burning power plants are also used in ACC pavements and as base material [4-13]. Slag, used as a fill material, improves skid resistance when used in the wearing course [4-10, 4-14], and may also reduce aggregate stripping and overall wear. Slag from some sources is unacceptable. Steel mill slags with high concentrations of soft lime particles have been associated with map cracking of ACC pavements [4-10]. Fly ash is used as a fill material in ACC [4-3], and because of its fineness, may also act as an asphalt extender [4-10].

Recycled Glass

Approximately 12.6 million tons (11.3 million metric tons) of glass are discarded each year. Recycled glass is sometimes used as a partial aggregate replacement in ACC pavements. This practice is referred to as “glasphalt.” Typically the glass is used at a rate of 5 to 15 percent [4-10, 4-15] replacement for the fill material; however, successful replacement of 25 percent has been reported [4-15]. The maximum size fraction of the glass is typically around 3/8 inch (10 mm). Costs of glasphalt vary depending on the price of the glass, hauling, crushing, and normal ACC prices. Some cities such as New York City and Los Angeles crush the glass in their sanitation departments and avoid the disposal costs by using the glass at city-owned asphalt plants. This allowed the city of New York to place approximately 450 thousand tons (408 thousand metric tons) of glasphalt in 1992. In New York City, the use of 10 percent replacement of glass saves the city approximately $1 per ton ($1 per metric ton) [4-15]. Glasphalt is utilized in NYC because the cost of using the glass is much cheaper than landfilling the glass and purchasing aggregate for use in ACC pavements [4-10,4-45]. The use of recycled glass is not always as attractive elsewhere. The city of Baltimore recently stopped using glasphalt when it realized the cost of glasphalt was $5 to $10 more per ton ($5.50 to $11 more per metric ton) than conventional ACC.

Glasphalt does have advantages as well as disadvantages when compared to conventional ACC. Glasphalt can have a highly reflective surface, which can cause a “slight glare” during bright sunlight and a “sparkle,” due to automobile headlights or moonlight [4-15]. Government agencies do not agree whether the “slight glare” or “sparkle” are advantages or disadvantages. A glare during daylight could be a driving hazard, whereas a sparkle at night could increase driver visibility. Although no studies on the reflective properties of glasphalt could be found, glasphalt may outperform conventional ACC by having reduced temperatures from solar effects. This could make glasphalt a useful surface to combat the “urban heat island effect” as previously discussed

Early projects involving glasphalt had difficulty with a loss of skid resistance and stripping of the glass [4-10, 4-15]. This has been overcome by minimizing the glass content and maximum size fraction. The addition of 1 percent lime has minimized stripping.

Due to concerns, some government agencies do not use glasphalt in roads with high-speed traffic, parking lots for recreational areas, or in residential streets [4-15]. Concerns have also arisen about the potential to recycle glasphalt, but no studies could be found on this subject.

Scrap Tires

Since the passage of Section 1038(d) of the Intermodal Surface Transportation Efficiency Act (ISTEA) and beginning in January 1994, federally funded ACC paving projects require the use of shredded scrap rubber tires (crumb rubber) in the ACC mix. By 1997, approximately 20 percent of the federally funded ACC paving projects must use 20 pounds of ground rubber per ton (10 kilograms per metric ton) of asphalt [4-7, 4-10, 4-16]. The ISTEA mandate will consume approximately 70 million tires per year. The rubber may be used as a replacement for fill material or binder. Subsection 1038(b) of the ISTEA mandate requires the FHWA and EPA to adequately address these issues [4-7]. Limited information is currently available addressing human health issues, environmental effects, recyclability, and engineering properties of the rubber modified ACC pavements [4-10, 4-16].

The use of rubber in ACC pavements is not a new concept. Rubber modified ACC (RMAC) pavements have been used for the last 30 years [4-7, 4-17, 4-18]. Numerous reports have been published on all issues related to rubber in ACC pavements, with many new research reports currently being published. Most states now have some experience with rubber modified ACC pavements.

Performance of RMAC pavements seems to be varied, with some states reporting poor results and other states reporting excellent results. A NCHRP report concludes that based on current information, further studies need to be performed. The mixed results of the RMAC pavements were concluded to be a combination of the lack of experience with the new materials, poor design, project location, and field conditions [4-7].

Some environmental concerns have been addressed and results indicate the potential to leach inorganic substances as well as organic substances. One study by the Minnesota Pollution Control Agency designed to address the extreme “worst case” conditions found that RCRA metals concentrations were below hazardous levels, and that limits of chronic toxicity for PAHs were exceeded in all cases [4-7]. Water samples collected at one of two roadway sites exceeded recommended allowable limits for four metals. Water samples from the second site exceeded the recommended allowable limits for PAHs. A joint study by the EPA and FHWA compared pavements containing RMAC and conventional ACC pavements and concluded that there is not a substantial increase in the hazards to humans or the environment [4-7].

Cost of crumb rubber (shredded tires) is also an issue. 20 pounds of crumb rubber per ton (10 kilograms per metric ton) of ACC amounts to roughly 2 tires. Transportation and grinding costs for tires are expensive. One study estimated an increased cost of $15 per ton ($16.67 per metric ton) for including 2.5 to 6 tires per ton of ACC [4-17].

CHAPTER 5

THE POTENTIAL TO RECYCLE PAVEMENTS

Recycling of ACC and PCC pavements is an environmentally sound practice which is occurring more frequently. Using recycled pavement materials in new pavements saves money and resources, and minimizes damage to the environment by not having to mine and haul as much virgin material to construction sites. Environmental damage is also minimized through decreased materials in landfills and possibly through less trucking.

Recycled PCC and ACC pavements are commonly used in various phases of reconstruction as clean fill, sub-base material, base material, and aggregate in new ACC and PCC pavements. Various examples of recycling pavements are well documented in the literature [4-12, 5-1 through 5-14]. Examples of recycled ACC in PCC pavements and PCC in new ACC pavements can also be found in the 4-12, 5-1, 5-2, 5-14].

RECYCLING PORTLAND CEMENT CONCRETE PAVEMENT

Recycling of PCC was first used on a large scale in the reconstruction of Europe after World War II [5—12]. Although recycling was very successful in Europe, it was not used in the U.S. until 1972. Some of the first projects considered for recycling were repair and replacement of the U.S. interstate system. However, in most cases the interstate was completely new construction, thus recycled material was not available. As repair and replacement needs of the interstate system became a concern, recycling of the old pavements was considered.

Iowa, in 1976, was one of the first states to experiment with recycling of PCC pavement [5-12]. Recycling was considered because of the need for large amounts of aggregates which were not locally available. The pavement selected for recycling was a 50-year old PCC pavement with an ACC overlay. During reconstruction, the ACC overlay was easily removed and discarded. The underlying PCC pavement was then shattered, removed, and recycled. The results of this project proved successful in more ways than initially realized. Money was saved by recycling the PCC pavement into aggregate instead of hauling in new aggregate, thus minimizing potentially extensive damage to haul roads, conserving landfill space, and saving energy.

Since the Iowa project, great success has been achieved by recycling on many projects (Figs. 10 and 11). Pavements showing signs of freeze/thaw damage have been successfully recycled into new pavements that do not show any signs of freeze/thaw damage after many years of use [5-10, 5-11]. Wyoming has reported successful recycling of alkali silica reactivity (ASR) damaged pavements [5-10, 5-12]. Recent research shows that recycling of PCC during any stage of ASR can produce a PCC which is free of the damaging effects of ASR [5-15]. Pavements contaminated with chlorides from road salts are generally recycled into base material or as aggregate for unreinforced pavement. This is because high chloride concentrations have been shown to cause corrosion of reinforcing steel.

Life cycle analyses performed by Wyoming on recycled PCC show a distinct advantage over large-scale patching or sealing and overlaying with ACC [5-6]. The analyses show that recycling of PCC pavements is superior to overlaying because no rutting occurs, clearance problems beneath bridges do not develop, subgrade problems can be cost-effectively fixed, less aggregate is required, and fewer traffic interruptions occur over the life of the roadway. Advantages of recycling compared to patching are less traffic interruptions, greater overall life of the pavement, and cost-effectiveness.

Figure 10. Removal of PCC for recycling. (S-42534)

Figure 11. PCC stockpile for recycling. (S-42546)

RECYCLING OF ASPHALT CONCRETE PAVEMENT

The first reported recycling of ACC pavements in the U.S. was in 1915 [5-16]. Since then, recycling of ACC pavements has become a widely accepted practice [5-5] (Figs. 12 and 13). As of 1993, 41 of 50 states use recycled ACC pavements in all facets of reconstruction from the pavement to the base to the subgrade to fill materials [5-16]. Reasons for recycling existing ACC pavements are similar to those for recycling PCC pavements. One report indicates recycling of ACC saves as much as 15 percent of cost and energy requirements [5-3]. This savings comes from minimizing the need for new aggregate, and in some cases eliminates the need for new asphaltic cement binder. In most cases, however, the asphaltic cement binder is degraded and needs to be either partially or fully replaced 4-12, 5-3, 5-5, 5-17]. Air pollution is also minimized due to less hauling of new aggregates and landfill space is conserved through recycling. Life cycle analyses also show recycling of ACC pavement advantageous to overlaying with ACC pavements because of the reduced virgin materials needed for paving, decreased hauling, cost effectiveness of sub-base repairs, and increased lifetime.

Four methods of recycling ACC pavements are well documented in the literature [4-12, 5-7]. The first and most common method is “hot in-plant regeneration” and involves removing the old asphalt pavement either through scarification or bulk removal and crushing [4-12]. The removed pavement, called RAP (reclaimed asphalt pavement), is then heated and mixed with additional asphalt cement. Paving operations are then similar to conventional asphalt paving. Initially this method had problems with air pollution; however, simple modifications to asphalt batch plants minimized this problem [5-3].

“Hot in-place regeneration,” sometimes referred to as “surface regeneration’” is a completely mobile process of rejuvenating ACC pavements. Although this method is not commonly used, its use will probably increase in the future. This method of “repaving” is broken down into four different categories, designated as reshaping, regripping, repaving, and remixing [5-7]. Although each method is too complex to describe in detail in this paper, an overview will be provided. The reshaping method uses heat to soften the ACC so that it can be rerolled to smooth the surface of the road. It is mainly used to eliminate problems of rutting. Regripping is very similar, except minimal amounts of new material are added to fill deep ruts and holes. During regripping, the pavement surface may also be coated with a thin layer of new material. The process of repaving is similar to regripping, except new asphalt is placed on the surface instead of as an optional coating. The process of remixing involves heating the asphalt, removing the surface through milling, heating and mixing with new ACC or asphaltic cement, and repaving. Typically, physical properties of surface-regenerated ACC pavements are very similar to that of conventional ACC. Studies have shown a 50 to 65 percent savings in using “hot in-place regeneration” over conventional ACC paving. Materials savings of 50 percent can also be achieved [5-7].

“Cold in-plant regeneration,’ is similar to “hot in-plant regeneration;” however, the heat is replaced by softening and rejuvenating agents. This type of recycling produces asphalt suitable for base and subbase materials. Cold in-place regeneration is a combination between cold in-plant recycling and hot in-place recycling. Limited information on this method suggests highly variable surface properties and the potential for serious rutting due to early traffic [5-7].

Recycling of ACC and PCC pavements is advantageous compared to the use of virgin materials. Reduction in costs occurs through (1) the elimination of extraction and long hauls of new aggregate and (2) the elimination or minimization of waste materials. This also allows for less energy to be consumed and less air pollution from trucks used for mining and hauling. An added benefit is that less landfill space is used because materials are recycled instead of discarded. Although specific data could not be found, recycling of ACC pavements appears to be much more common and widespread than recycling of PCC pavements.

Figure 12. Loosening of ACC pavement before removal. (S-39363)

Figure 13. Removal of ACC pavement for recycling. (S-38441)

CHAPTER 6

COSTS DURING CONSTRUCTION, MAINTENANCE, AND RECONSTRUCTION

Pavement type is often selected based on the lowest initial cost, or regional and jurisdictional preference. The placement or construction of PCC pavements generally has a higher initial cost than ACC pavement for a given application. Yet, PCC pavement generally has a longer useful service life and less maintenance costs during its life. Experience by the individual state DOTs and the FHWA show that service life for a typical ACC pavement ranges from 6 to 20 years while a PCC pavement typically lasts 13 to 30 years. Many reports exist of pavements exceeding their design life [6-1]. Recent literature is also filled with life cycle cost analyses showing that PCC pavements cost less than an equivalent ACC pavement for the same lifetime [6-1, 6-2, 6-3, 6-4, 6-5, 6-6]. These studies typically assume ideal conditions for both pavements.

COST COMPARISONS

Costs during construction are highly variable due to different construction methods, design criteria, different materials, experience of construction crews, and a large number of other factors. Each job differs in the amount of materials that may be recycled and hauling distances for virgin materials. Due to these uncertainties, it is difficult to provide estimated costs for a "typical" construction project. Because of hauling distances, size of the job, and design criteria, PCC or ACC pavements advantages may be equal or in favor of one or the other. The literature is filled with examples where ACC and PCC pavements are compared. Unfortunately, a number of authors appear to be biased either toward the use of PCC or towards the use of ACC.

LIFE CYCLE COST ANALYSIS

A life cycle cost analysis considers the pavement's initial cost, maintenance, and reconstruction costs during a specified lifetime. The analysis generally calculates the total cost based on the present value of the projected costs. Proposed federal legislation will mandate life cycle cost analyses be performed prior to construction projects greater than $25 million [6-7]. Awarding paving contracts based on life cycle analyses was previously tried. Due to legal battles, this idea was dropped in 1982 [6-4]. Many assumptions are needed for this type of analysis such as pavement deterioration rate, traffic loading, projected inflation rates, cost of capital, and projected maintenance schedules and costs.

LIFE CYCLE COST UNCERTAINTIES

Uncertainties in life cycle cost analyses include estimates of pavement wear and their effect on future costs [6-8]. Pavement performance and maintenance costs are not well known and are highly variable [6-4]. Estimates of costs and quantities can easily be misinterpreted or misrepresented. Some examples are (1) estimating that the price of fuel will exceed or keep pace with inflation, which rarely occurs in the U.S. and (2) use of a discount that favors a particular outcome, such as a low rate to justify high initial costs (or vice versa).

ENVIRONMENTAL LIFE CYCLE ASSESSMENT

As global warming and depletion of the ozone layer become more of a national concern, materials manufacturers are seeking ways to market their products as environmentally friendly or "green." A preferred and equitable procedure to compare competing materials such as PCC and ACC pavements is to perform an environmental life cycle assessment. The analysis would include the environmental effects to obtain, produce, transport, and place constituent materials; and effects of maintenance, replacement, and disposal. These environmental aspects include impacts of resources depleted, air emissions, water emissions, solid wastes, and energy consumption.

Methodology

The environmental life cycle assessment methodology is in its infancy, but it is receiving national attention as a method to sustain the earth's environment and compare alternatives. The analysis procedure is extraordinarily complex because of the large amount of data required.

An inventory analysis, the first step, lists the resources and energy used, and emissions and wastes. Many organizations including the Canadian Standards Association [6-9, 6-10] and the EPA [6-11] use a SETAC (The Chemical Engineering Institution) Technical Format. However, the results of the inventory do not include environmental impacts and generally are unsuitable for comparing competing materials. Suitable methodologies for the impact and comparison stages are not yet defined.

The advantage of an environmental life cycle analysis is the ability to include all costs to society and depletion of the earth's resources. An environmental life cycle analysis includes the embodied energy required to make PCC or ACC. This includes the energy required to extract resources, produce and transport the constituent materials, and place the materials. Results of the embodied energy comparisons for PCC and ACC pavements depend on the assumptions made such as [6-12, 6-13, 6-14]:

1. Whether asphalt binder is a waste material from the petroleum cracking process and therefore should have no energy associated with it.
2. Whether to include the lost value of fuel in the asphalt binder.
3. Whether PCC pavements require a sub-base (crushed stone, lime stabilized soil, etc.).

Embodied energy studies are a relic of the 1970s and 80s and are no longer performed in isolation from an environmental life cycle assessment.

Energy and Emissions during Production

An environmental life cycle assessment includes the impact of energy and emissions during the production of asphalt and portland cement. Data on energy and emissions during the cracking of petroleum to produce asphalt were not readily available. However, asphalt should be assigned its fair share of the total emissions and energy from the refining process that also produces fuels and chemicals.

Portland cement content in PCC pavements is generally on the order of 15 to 20 percent [6-15]. Thus, there are 2,000 pounds of cement in approximately 3-1/2 cubic yards of concrete (340 kilograms in 1 cubic meter). During production of cement, approximately 1 pound (0.45 kilograms) of carbon dioxide is liberated for every pound (0.45 kilogram) of cement produced [6-16]. Approximately half of this amount comes from the fuel used to produce the cement, and the other half is liberated from the chemical reactions of the raw materials used to produce the cement [6-17], mainly calcination of limestone (heating of limestone to liberate all of the carbon dioxide)

Approximately 75 million tons of cement are produced each year in the U.S. [6-18]. This results in approximately 80 million tons (73 million metric tons) of carbon dioxide released into the atmosphere. Approximately 15 million metric tons (14 million metric tons) of cement are produced each year in Canada, releasing an equal amount of carbon dioxide. This results in 0.7 percent of all carbon dioxide emissions in Canada [6-16[. In Great Britain, 1.2 percent of all carbon dioxide emissions result from cement production [6-15].

Carbon dioxide production varies greatly between cement plants and depends on the cement manufacturing process, fuel type, production rate, and raw materials. Industry average carbon dioxide generation rates are available for the three major cement process types in the U.S. and Canada. The percent of carbon dioxide for calcination of limestone compared to the total carbon dioxide generated in wet, dry, and precalciner/preheater process types, respectively, is 55, 60, and 70 percent [6-19]. A majority of cement manufacturing processes are either dry or preheater/precalciner type processes. Typically, new cement manufacturing facilities are precalciner type processes.

Reconstruction of Roads

Another benefit of an environmental life cycle assessment is consideration of the secondary effects associated with reconstruction. These include the effects of traffic jams and slowed vehicle times due to a reduction in available lanes or roadways during reconstruction. Effects include additional pollutants and energy consumption due to longer travel times for vehicles and loss in labor revenue for commercial vehicles. Quantifiable data could not be found on the specific “down time” associated with construction and maintenance operations during the life of PCC and ACC pavements. However, costs and wasted time associated with congestion due to reconstruction are enormous. In fact, numerous acknowledgments of this problem have been made [6-14, 6-20], yet little effort is evident that highway departments are working to alleviate this significant waste of energy and resources.

SUMMARY AND CONCLUSIONS

This report summarizes a literature survey and investigation of six specific areas for which the environmental impact of portland cement concrete (PCC) and asphalt cement concrete (ACC) paving are compared. The following summary and conclusions are presented.

1. **Effect of the pavement color on the microclimate.** Materials with high albedo remain cooler when subjected to solar radiation and therefore have the potential to reduce heat island effects and the potential for smog in warm climates. Studies show the temperatures of conventional portland cement concrete (PCC) pavement are less than those of asphalt cement concrete (ACC) pavement. Albedo for PCC and ACC pavement surfaces vary depending on the age, wear, surface texture, and composition. Values range from 0.1 to 0.4 for PCC and 0.05 to 0.2 for ACC. The differences in albedo between the two pavement types are greater for new pavement than for weathered pavement.
2. **Artificial lighting requirements of the pavements at night.** The nighttime fatality rate, adjusted for the proportional number of vehicles, is triple the daytime rate and is attributed to reduced driver visibility. Artificial lighting of pavements can reduce the fatality rate but is costly. More lights are needed per mile to achieve the same illumination for ACC pavement as for PCC pavement. This is primarily due to ACC reflecting light specularly and PCC reflecting light diffusely. One study showed 31 percent savings in initial, energy, and maintenance costs for lighting PCC versus ACC pavement.
3. **The effect of pavements on vehicle fuel consumption.** Fuel consumption of trucks is greater on ACC than PCC pavement, and increases with truck weight per axle. Reported mileage increases on PCC versus ACC pavement range from 5 to 25 percent. Significant energy savings are possible on PCC pavement because the average combination (heavy) truck consumes 10,695 gallons (40,485 liters) of fuel and travels an average of 5.6 miles per gallon (2.4 kilometers per liter).
4. **Inclusion of waste materials in pavements.** Wastes are being utilized as inexpensive fill material in ACC and PCC pavements, and as fuel and or raw feed for production of the asphaltic binder and portland cement. Wastes are also being used in PCC as a partial replacement for portland cement. Materials used as fill in PCC include fly ash, plastic fibers, silica fume, ground granulated blast furnace slag (GGBFS), porcelain, and clay masonry. Materials used as a partial replacement of portland cement include pozzolans such as fly ash or GGBFS. Other materials such as vehicle tires, organic solvents, medical waste, carpet remnants, treated particulate emissions, and many others have been utilized in the production of portland cement either as a fuel or as an alternate raw material. In 1992, twelve U.S. cement plants reported using wastes as primary fuel and 36 reported using wastes as an alternative or supplementary fuel. Some examples of fill materials in ACC are tire rubber, fly ash, crushed glass, asphalt roofing shingles, slag, porcelain, contaminated soils, and clay masonry. Materials such as finely ground tire rubber, roofing shingles, and polymer wastes can be used for asphaltic cement replacement.
5. **The potential to recycle pavement at the end of its useful life.** Recycled PCC and ACC pavements are commonly used in various phases of reconstruction as clean fill, sub-base material, base material, and aggregate in new ACC and

PCC pavements. Some recycling methods for ACC pavement eliminate or reduce the need for new asphaltic cement binder. Recycling of ACC and PCC pavements is advantageous compared to the use of virgin materials. Cost reductions and environmental benefits occur through (1) the elimination of extraction and long hauls of new aggregate and (2) the elimination or minimization of waste materials. A study on recycled PCC shows a distinct advantage over large-scale patching or sealing and overlaying with ACC. The study shows that recycling of PCC pavements is superior to overlaying because no rutting occurs, clearance problems beneath bridges do not develop, subgrade problems can be cost-effectively fixed, less aggregate is required, and fewer traffic interruptions occur over the life of the roadway. Most of these advantages also exist when considering whether to recycle versus patch or seal and overlay ACC pavements.

6. **Costs during construction, maintenance, and reconstruction**.

6.1 The placement or construction of PCC pavements generally has a higher initial cost than ACC pavement for a given application. Yet, PCC pavement generally has a longer useful service life and less maintenance costs during its life. Life cycle cost analyses, as cited in the references, show that PCC pavements cost less than an equivalent ACC pavement for the same lifetime. Proposed federal legislation will mandate life cycle cost analyses be performed prior to construction projects of $25 million or more.

6.2 An equitable methodology to compare environmental effects of competing materials such as PCC and ACC pavements is to perform an environmental life cycle assessment. The analysis would include the environmental effects to obtain, produce, transport, and place constituent materials; and effects of maintenance, replacement, and disposal. The environmental aspects include impacts of resources depleted, air emissions, water emissions, solid wastes, and energy consumption. The environmental life cycle assessment methodology is in its infancy but is receiving national attention as a method to sustain the earth's environment and compare alternatives.

RECOMMENDATIONS

The following areas of research, action, or implementation would help promote portland cement concrete pavement as an "environmentally friendly" alternative. Each topic is identified as providing one of the following three alternatives: an overall advantage to PCC, a disadvantage to PCC, or not enough information is available to reach a recommendation.

1. **Effect of the pavement color on the microclimate.** More data are needed on the albedo of new and aged PCC and ACC. Additional data are required to verify weathered PCC has a greater albedo than weathered ACC. These data may show that PCC has an advantage compared to ACC in this area. Standard test methods and a method of rating the benefits of high albedo are required to implement incentive plans to encourage the use of high albedo surfaces. The thermal mass effects of PCC and ACC paving will make their solar property measurements and predicted maximum temperature calculations more complex than those for painted surfaces.
2. **Artificial lighting requirements of the pavements at night.** PCC has an advantage compared to ACC in this area. However, available lighting technology has changed substantially and become more energy efficient in the last ten years. An updated study on lighting requirements on PCC and ACC pavements would be useful. The reflectance of aged PCC and ACC should be verified to ascertain whether current design procedures are accurate for aged pavements. These two items could lessen the advantage of PCC compared to ACC.
3. **The effect of pavements on vehicle fuel consumption.** PCC has an advantage compared to ACC in this area. However, no study exists on fuel mileage as a function of pavement temperature. Such a study would be useful because the greater truck fuel mileage on PCC versus ACC pavement is due to greater pavement deflections on ACC pavement, and these deflections increase with temperature on ACC pavement.
4. **Inclusion of waste materials in pavements.** Further research is not recommended. PCC does not have a clear advantage compared to ACC in this area. Governmental regulations, the cost of landfill space, and marketing incentives will most likely drive the PCC and ACC industries to use more waste materials.
5. **The potential to recycle pavement at the end of its useful life.** Further research is not recommended. PCC does not have a clear advantage compared to ACC in this area. Governmental regulations, the cost of landfill space, and marketing incentives will most likely drive the PCC and ACC industries to utilize more recycled materials.
6. **Costs during construction, maintenance, and reconstruction.** Governmental regulations and construction industry trends should be monitored to ascertain the most cost-effective approach to compare the environmental effects of competing materials. Not enough information is available to clearly indicate whether PCC or ACC is more advantageous in this area.

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