3. MITIGATION ALTERNATIVES - COOLING OUR COMMUNITIES

Research on the effects of urban heat islands is progressing at a time of immense public concern about air quality and human health issues. Specifically, the urbanization of the natural landscape through the replacement of vegetation with roads, bridges, houses, and commercial buildings has dramatically altered the temperature profile of cities. In fact, even within a city, different areas have different temperatures, depending on specific surroundings, type of exposed surface, and ground cover.

It is evident that urban heat islands have major effects on the surface energy balance, heating/cooling costs, and quality of urban life. While many of the factors which influence the formation of urban heat islands, including climate, topography, and weather patterns, can not be changed or altered, it is apparent that efficient and cost-effective ways of mitigating heat islands exist. There are two heat island factors, attributable to human activities, which can be readily controlled: the amount of vegetation and the color of surfaces.(3) Increasing vegetative cover through strategic landscaping around buildings and throughout cities can absorb solar radiation, provide shade, and control wind flow benefits. Changing dark colored surfaces to light colored ones would more effectively reflect, rather than absorb, solar energy and emit stored heat energy at a higher rate, thus reducing the cooling energy loads and ground level air temperatures influenced by these surfaces.

In general, it is observed that parks and areas with significant amounts of vegetation are cooler than neighborhoods full of paved surfaces and buildings. These differences may seem obvious, but they illustrate the fact that the climate in cities is greatly affected by human activities and the creation of the urban landscape.

The synergistic effect of reduced vegetation and significant amounts of dark colored surfaces can cause an increase in the afternoon summer air temperature on a typical city an average about 5°F higher than the surrounding rural area. For example, researchers have found that peak urban utility loads in five U.S. cities, including Los Angeles, CA; Washington, D.C.; Phoenix, AZ; Tucson, AZ; and Colorado Springs, CO increase by 1-2% for each 1°F rise in daily maximum temperature above a threshold of 60- 70°F. Thus, the additional air conditioning use caused by this increase in urban air temperatures is responsible for 5-10% of urban peak electric demand.(3) However, researchers also estimate that if 100 million urban tree spaces in this country were filled (three trees for one-half of the single family homes in this country), and if light colored surfacing programs were implemented, late afternoon air temperatures on a hot summer day could be reduced by 5 to 10° F.(3) Of course, specific results would vary depending upon location, but the combined strategy of increasing vegetative cover and using light color materials could reduce electricity usage by as much as 50 billion kilowatt hours per year (2 percent of annual electricity use in the United States).(3,4)

In addition to reducing temperature and energy demand, increasing vegetative cover and lightening the color of our urban paved and roofed surfaces provide many other physical, functional, and psychological benefits to urban dwellers. For example, they beautify urban areas, mask noise, reduce air pollution, lower smog levels, enhance community relations, and provide valuable habitat for wildlife.(3)

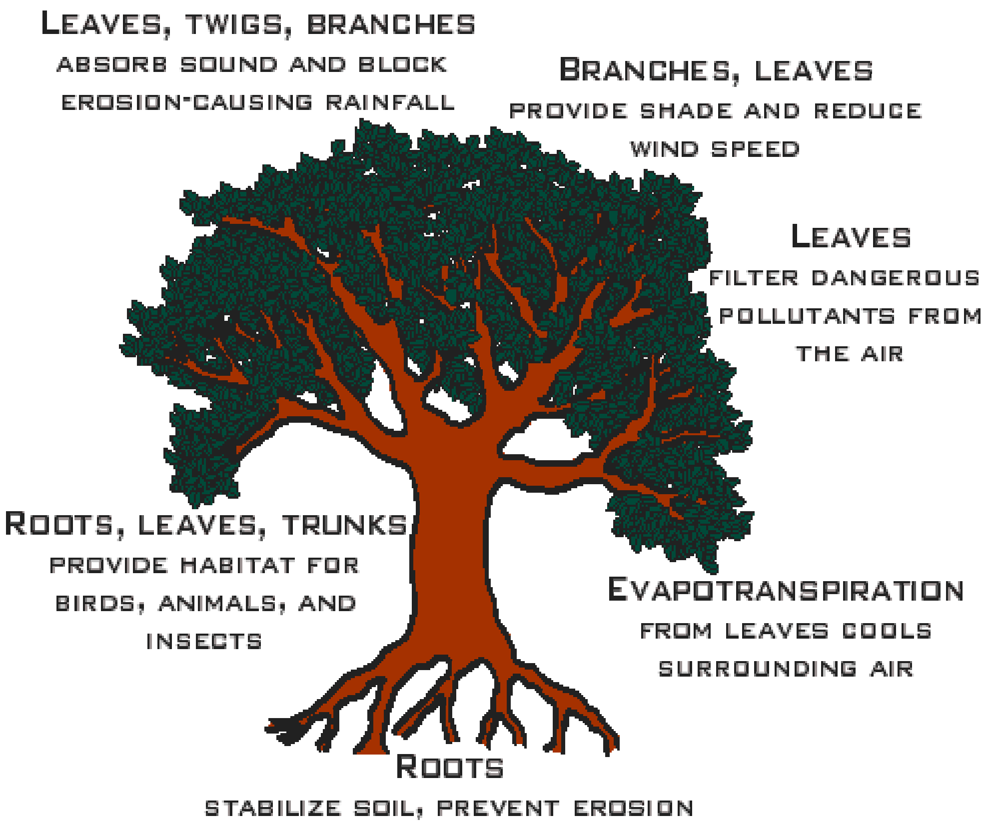
The concepts of strategic landscaping and light colored surfaces are not difficult to understand, but implementation of programs at the community level, or region wide, will require considerable education, public participation, planning, cooperation, policymaking, commitment of resources, and community support. The Cool Communities Program is an action oriented, energy reduction program of American Forests and the Department of Energy (DOE), with cooperative federal support also provided by the U.S. Environmental Protection Agency (USEPA) and the U.S. Department of Agriculture (USDA) Forest Service. This initiative mobilizes government agencies, businesses, and citizens to create positive, measurable change in energy consumption and the urban environment, through use of strategic landscaping and light colored surfacing, and attempts to increase public awareness of these issues.(24)

Unfortunately, wholesale implementation of these strategies is unlikely to occur and once in play, they will show gradual results over time rather than immediate results. A shift from the use of dark color roofing and paving materials to lighter colored alternatives is certain to encounter more resistance. The reasons for this are related to aesthetic sensibilities, preferences based upon habit and experience, availability of alternatives, lack of knowledge about alternatives, perceptions about cost, and uncertainty about true environmental benefits. This chapter provides both an overview of different mitigation strategies and points out some of the existing market barriers to implementation.

3.1 VEGETATION

The replacement of the natural land cover with anthropogenic surfaces alters the thermal, moisture, and visual properties of an urban climate in both direct and indirect ways. Direct benefits, which are generally related to individual buildings, include primarily cover from the solar radiation and protection from the wind; however, trees can also provide filtration of air pollutants, shielding from noise pollution, and stabilization of soil against erosion. Indirectly, vegetation cools buildings by reducing the temperature of the air surrounding them via evapotranspiration, a process by which a plant releases water vapor into the air. The cumulative effect of many trees and plants is the cooling of the air in a large area.(3) Another benefit of trees and vegetation, of particular interest and importance in cities, is their phytoremediation potential with respect to the clean up pollutants in contaminated soil, air and water.(25) In addition, vegetation can greatly increase the aesthetic value of property and ecological quality of an area by providing an important habitat for birds, animals, and insects. The beneficial functions of trees, in particular, are illustrated in *Figure 14*.(4)

Figure 14: Beneficial Functions of Trees



Source: http://eetd.lbl.gov/heatisland/ (4)

Increasing vegetation is fairly simple and relatively inexpensive in the short term, but these are also long term considerations related to the time and money needed for maintenance. Unfortunately, in the last several decades, more and more trees have been removed from urban environments due to construction and development. Today, only one tree is planted in our cities for every four removed.(3) Thus, as vegetation disappears, temperatures began to rise.

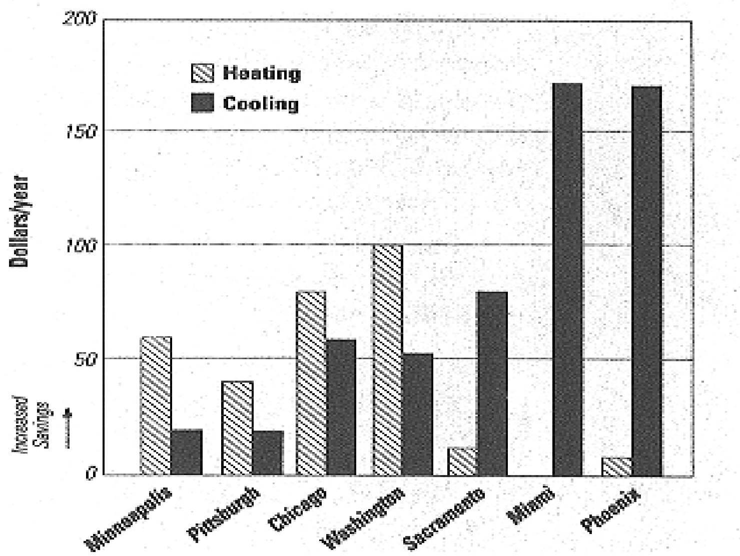
3.3.1 Effects

Direct Effects

Vegetative cover, specifically trees and shrubs, can be directly beneficial to buildings all year round. In the summer months, trees can serve as a barrier against incoming solar radiation, which in turn prevents structures and surfaces from heating up beyond the ambient air temperature. In fact, researchers have found that tree shade does a better job cooling a building and its interior than blinds, plastic coatings, or reflective coatings on glass.(3) Field measurements have shown that through shading, trees and shrubs strategically planted next to buildings can reduce summer air conditioning costs typically by 15 to 35 percent, and by as much as 50 percent or more depending upon specific situations.(3) In addition, simply shading the air conditioner by using shrubs or a vine covered trellis can save up to 10 percent in annual cooling energy costs.(4) In the winter, trees and shrubs can act as a barrier shielding a building from cold winter winds. However, because they also generate shade, trees and shrubs may also be a liability. This is because vegetation can block the warming rays of the sun, particularly those from the south, thus, actually increasing the heating energy consumption in the winter.

When shading and wind shielding effects are considered together, trees are shown to reduce both heating and cooling energy use in warm and temperate climates. These results are illustrated in *Figure15*. This figure shows the results from a computer simulation that looked at the combined shading and wind shielding effects from a 30% increase in tree cover around a typical house built before 1973.(3)

Figure 15: Changes in the Expenditures of Energy – Wind Shielding and Shading Effects



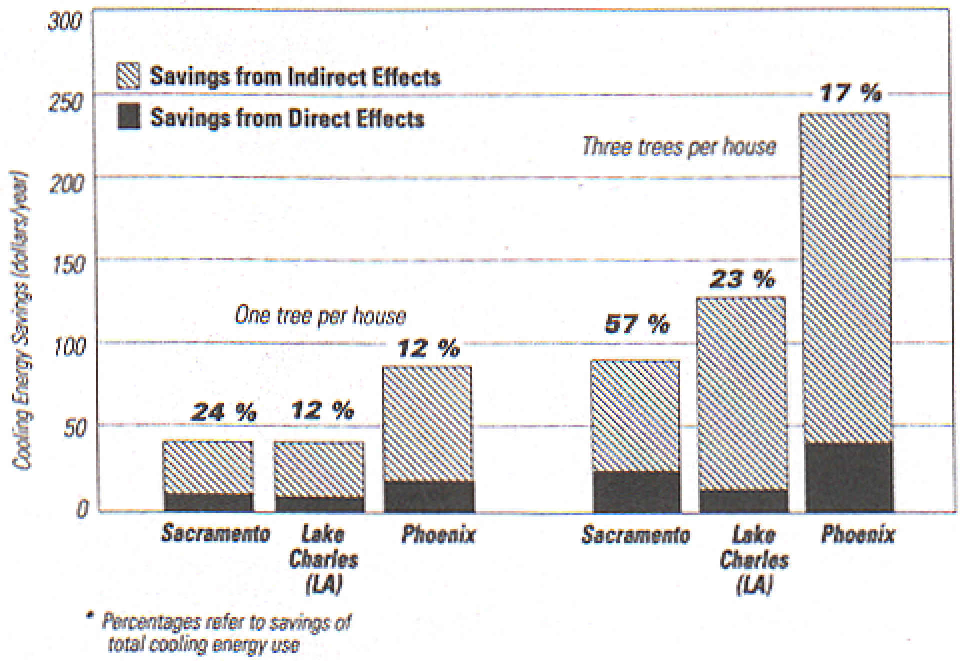
Source: Cooling Our Communities (3)

Indirect Effects

Vegetation has great potential to cool cities through a process known as evapotranspiration.(3,4) Evapotranspiration occurs when plants secrete, or transpire, water through pores in their leaves. The water draws heat as it evaporates, thus cooling the air surrounding the leaves in the process. Trees can transpire up to 100 gallons of water in a day. In a hot dry climate, this cooling effect equals that of five air conditioners running for 20 hours per day.(3) The cumulative effect of many trees and plants grouped together not only creates a pleasant green space within a community, but can act to cool surrounding areas.

The evapotranspirative properties of trees have the potential to produce greater indirect effects on temperature and energy consumption. For example, *Figure 16* shows a comparison of the relative savings attributable to indirect and direct effects of increasing vegetative cover around a typical, well insulated, new house.(3)

Figure 16: Estimated Cooling Energy Savings from Increased Vegetation



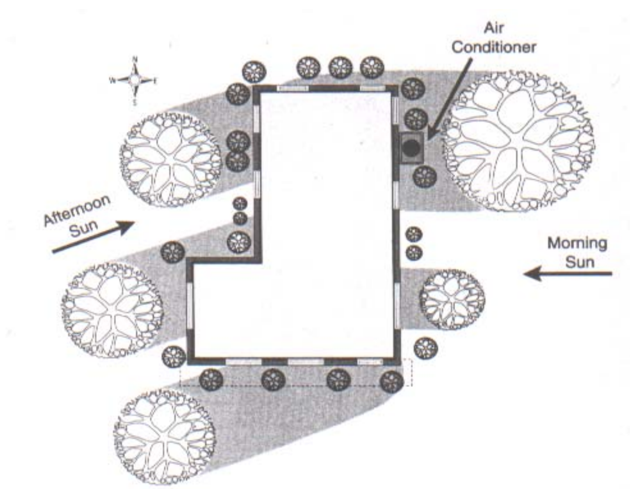
Source: Cooling Our Communities (3)

When the effects of evapotranspiration are combined with the effect of strategically placed shade, temperatures can drop by as much as 9°F in the immediate vicinity of the trees. Increasing vegetative cover by just 10 and 30 percent (about one and three properly placed trees per house, respectively) may reduce cooling energy by as much as 10 to 50 percent, depending on housing stock type, age, construction and other factors. Typically, older and more poorly insulated buildings, and those in hotter, drier regions, will have greater energy savings. As the number of trees increase, the relative contribution of the indirect effect, such as evapotranspiration and aesthetic benefits, grows in comparison to the direct effects, including protection from solar radiation, wind, and noise. However, these numbers generally apply only to trees located in optimal energy conserving locations in order to maximize their shading effects.(3,26)

3.1.2 Implementation Strategies

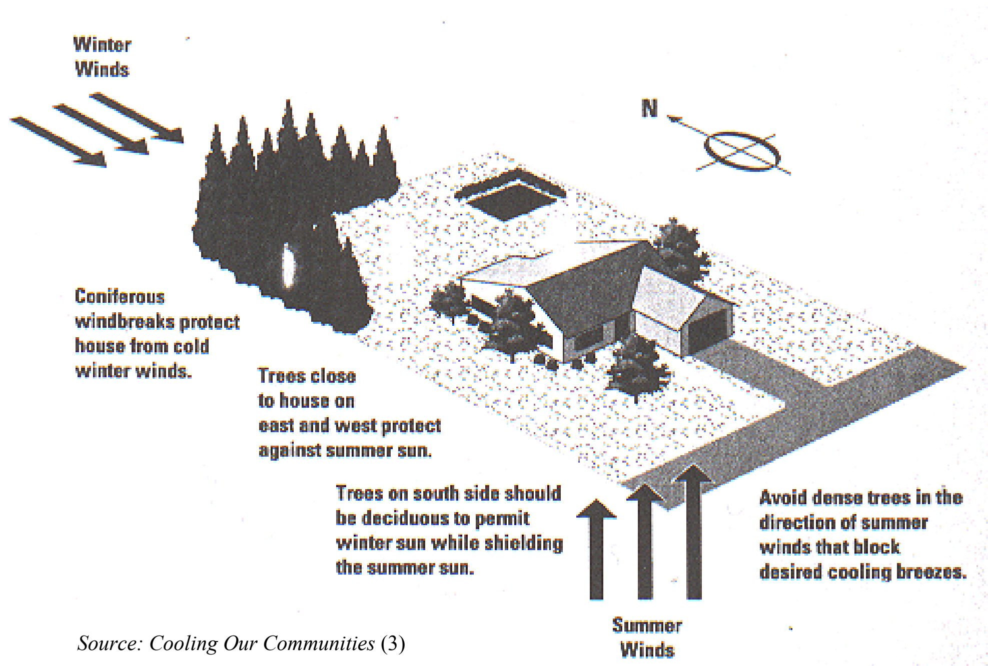
Planting trees and bushes will not only make a city greener, but can help reduce urban temperatures and energy consumption. However, randomly planting trees throughout a city isn't the best way to achieve optimal benefits, for the effectiveness of vegetation depends on its particular type, density, shape, dimensions, and placement. *Figure 17* and *18* illustrate the strategic planting of vegetation around a building.(3)

Figure 17: Sample Residential Landscape



Source: Cooling Our Communities (3)

Figure 18: Strategic Planting Diagram



Source: Cooling Our Communities (3)

In the summer, proper placement can ensure that trees shade the areas most critical in lowering internal temperatures and shade them at the most critical time of the day. For example, trees should be placed to shade the east, west and south sides of a building in order to block late morning, afternoon, and early evening sun. For a home monitored in Sacramento, California, researchers found that this reduced cooling energy use by as much as 30%.(4) Studies in Chicago have shown that shade from a street tree located to the west of a typical brick residence can reduce the annual use of air conditioning energy by 2-7% (138-205 kWh) and peak cooling demand by 2-6% (0.16-0.6 kW).(3) Street trees that shade the east side of buildings can produce similar cooling savings, but have a negligible effect on peak cooling demand and can slightly increase winter heating costs. Shade from street trees to the south, on the other hand, actually increase heating costs more than they decrease cooling costs. (26) As a result, deciduous trees, which drop their foliage in the fall, maximize the beneficial effects of shading because their broad leaves protect a building from detrimental summer radiation, while allowing most of the desirable winter sunlight to shine through the bare limbs. Evergreen or coniferous vegetation can be positioned to reduce the influence of cold winter winds on the heating requirements, as long as these windbreaks do not impede winter sunlight. In South Dakota, for example, houses measured consumed 25 percent less fuel when located on the leeward sides of windbreaks than when exposed. When wind breaks were present on the north, west, and east sides, fuel consumption was reduced by 40 percent.(3)

Increasing the urban canopy of cities is not a faultless measure, for there are many potential problems associated with the addition of vegetative cover. First, increasing the amounts of trees and plants in an area may increase the demand of water needed for irrigation. Fortunately, preliminary analysis suggests that using trees to shade lawns can drastically reduce water needs in a community by saving that which would otherwise go to watering the lawn.(4) In addition, using shrubs or natural groundcover instead of grass or trees may reduce water usage even further.(3)

A second problem is linked to the fact that trees and vegetation emit volatile organic carbons (VOCs) that combine with oxides of nitrogen (NO_x) to form smog. However, different species emit different amounts of VOCs. For example, ash and maple are among the more VOC-free trees, emitting only about 1 VOC unit (defined as one microgram per hour per gram of dry leaf). Eucalyptus trees and weeping willows, on the other hand, are a problem for they emit 32 and 230 VOC units, respectively.(4)

Another problem is associated with the amount of solid waste generated in a community. Specifically, the problem of the disposal of potentially large amounts of leaves, twigs, branches, and other debris from vegetation in landfills. Fortunately, there are many alternative options available for this type of disposal. For example, leaves can be used for compost, whereas branches and trunks can be used for firewood or chipped for mulch. Clearly, any community embarking on a large-scale tree-planting program must also consider the merits of community-wide composting and yard waste recycling programs.(3)

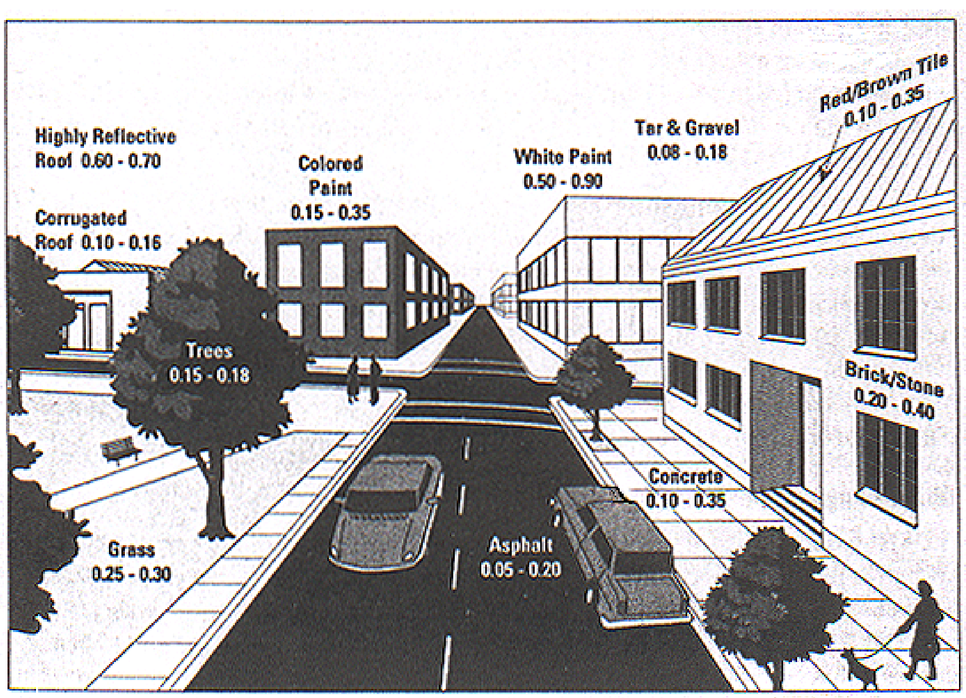
Depending on the region, and including these other factors, the combined benefits of urban tree planting will often be greater than the costs incurred. Unfortunately, achieving this potential is often conditioned upon receiving the necessary local, state, and federal support. Although many communities in this country already have tree-planting programs and ordinances in effect, starting an effective and comprehensive program requires extensive research, material development, technology transfer, education, public participation, implementation guidelines, and community outreach movements.(3)

3.2 LIGHT COLORED SURFACES

Our built urban environments contains innumerable surfaces, including building roofs and walls, streets, freeways, parking lots, driveways, school yards, and playgrounds. Typically, when these surfaces are dark, they absorb the solar energy of the sun and heat up and when they are light, they reflect the sun's rays and stay cooler. Thus, the color of a city's urban surface acutely effects the climate and temperature within that area.

The measure of a surface's reflectivity is called albedo. Albedo is measured on a scale of 0 to 1. A surface with a relatively high albedo, 0.75 or greater, is generally light in color and reflects most of the sun's rays. A surface a low albedo, 0.25 or less, is usually dark in color and will absorb most of the incoming solar energy. *Figure 19* shows the albedos for some common surfaces found in urban areas.

Figure 19: Surface Albedo Values



Source: Cool Communities (3)

3.2.1 Effects

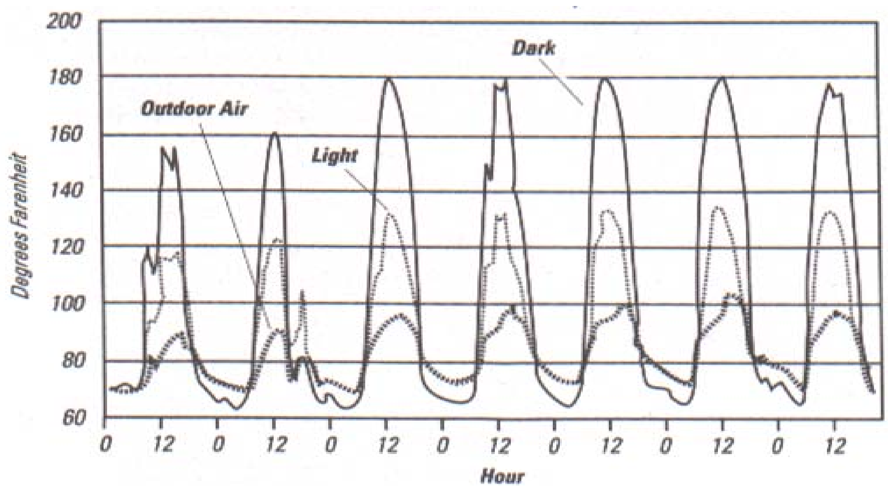
Like vegetation, reductions in temperatures and energy use from albedo modifications accrue to both individual buildings and entire neighborhoods. At the building scale, cool roofs reduce air conditioning loads. For example, numerous experiments on individual buildings in California (4) and Florida (27) show that painting the roof white reduces the air conditioning load between 40 and 70%, depending on the building type, climate zone, thickness of insulation, and angle and orientation of roof. At the community scale, collectively increasing the albedo of urban surfaces can help mitigate the urban heat island effect by lowering area temperatures and reducing total energy use.

Unfortunately, few field measurements exist that document the reductions in temperature or energy use resulting from altering the albedo of surfaces in houses and communities. This is because very few albedo modification programs have been initiated in the U.S. or abroad. However, preliminary analysis and computer simulations of neighborhoods suggest that changing roof, wall, and street colors by increasing surface albedos could significantly reduce air temperatures, decrease cooling energy use, and increase air quality, while keeping cost and potential risks low, for changes can be incorporated into normal maintenance cycles.(3,28,29)

Through these simulations, researchers estimate that albedo changes could reduce a city's air temperature by as much as 4-5°F in hot sunny climates with many dark surfaces.(3,30) This, in turn, could produce total simulated energy savings approaching 50 percent during average periods of cooling demand and 30 percent during peak hours.(3) In addition, simulations of the cooling achieved by increasing the albedo of roads and roofs in the LA Basin, indicated a 4°F cooling by noon resulting in a reduction in population weighted smog exceedances of 10-12%.(30)

Figure 20 illustrates the daily effects of color on surface temperature. For low albedo surfaces, the difference between the surface and ambient air temperature may be as high as 85°F, while for high albedo surfaces, the difference is only about 30-40°F.

Figure 20: Effects of Surface Color on Temperature



Source: *Cooling* ***Our Communities*** (3)

3.2.2 Implementation Strategies

The practice of using light colored surfaces in building is not a new concept. In tropical and sub-tropical regions, such as the Mediterranean and North Africa, for example, surfaces have been white washed for centuries to keep albedos and reflectivity high and temperatures low.(3) Unfortunately, this practice is too commonly overlooked by architects and developers of today with the low cost and widespread use of air conditioning.

Because no urban community in the United States or abroad has yet initiated a formal program of albedo modification, there is little practical experience with respect to successful implementation practices, potential drawbacks, or conflicts with other urban issues. However, one way to begin programs for light-colored surfacing strategies is through public education. Providing information on the albedo of building materials and the related energy savings may help inspire consumers to develop ordinances and implement these measures. Municipalities can pass ordinances that specify the use of light-colored paving materials in road building and renovations or zone for light colored building materials in commercial areas. Likewise, offering financial incentives could motivate architects and developers to design and build light colored, energy efficient buildings and communities.(3)

3.2.3 Roofs

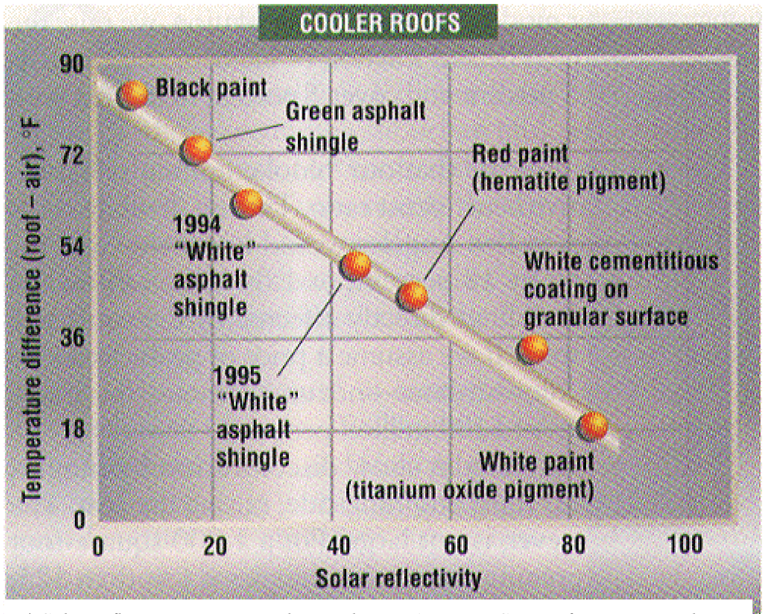
Summer Benefit

Numerous studies have shown that dark materials absorb more heat from the sun. When these dark materials are used on the surfaces of roofs, their temperature increases the heating of the air around them contributing to the heat island effect. In addition, a portion of the radiative heat energy collected by the roof may be transferred to the inside of a building. In the summertime, this unwanted heat energy generates conditions that often lead to more air conditioning and higher utility bills.

There is a sizable body of measured data, primarily collected for the residential sectors of California and Florida, documenting energy-saving effects of light colored roofs.(4,27,31,32, 33,34) This measured data, along with extensive computer simulations, clearly demonstrate that increasing the albedo of roofs can be effective in reducing temperatures and energy use for individual buildings and communities. In addition, studies have suggested that lighter roofs incur no additional cost, other than the incremental cost associated with the high-albedo material, if color changes are incorporated into routine re-roofing and re-surfacing schedules.(31)

Solar reflectivity is used to measure how much radiative heat energy materials collect in the sun. *Figure 21* shows the solar reflectivity of different roofing materials as a function of their individual temperature differences with the surrounding ambient air.(4)

Figure 21[*]



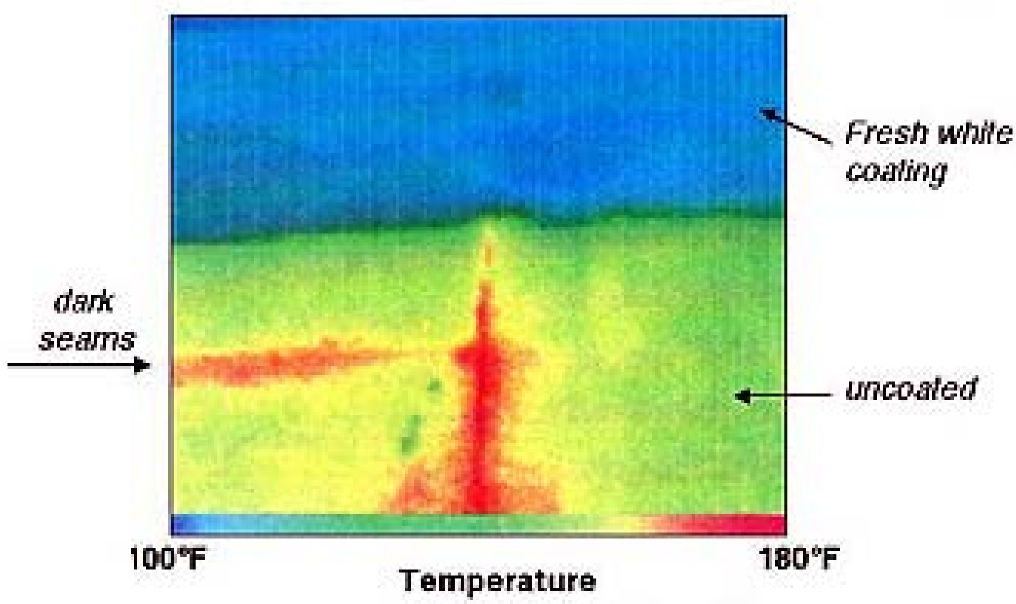
** Solar reflectivity is measured according to American Society for Testing and Materials (ASTM) E903*
Source: http://eetd.lbl.gov/heatisland/ (4)

The extremes of white and black paint define the solar reflectance index (SRI). In general, the temperature difference rises as solar reflectivity decreases. Thus, darker colored shingles significantly raise the roofed surface temperature. Traditional roofing materials have a SRI of between 5% (brown shingles) and 20% (green shingles). Red-painted tiles are cooler than white asphalt because the seemingly darker surface actually reflects infrared better. White shingles with SRI's around 35% were popular in the 1960s, but they lost favor because they became dirty easily and the labor costs of maintaining the high albedo of a roof coating would exceed the cost of conserved energy. Manufacturers have recently developed clean, "self-washing" white shingles with even higher SRIs up to 62%. The current trend is to make roofing materials more reflective so that the sun's radiant energy is reflected back into space instead of absorbed. Roofing with materials whose SRI rating is 50% or higher will keep a buildings and cities cooler and reduce energy bills.(4)

In addition to high solar reflectance, a high infrared emittance and good convective heat transfer is also desirable because roof surface temperature is greatly influenced by the various heat flows at the outside surface. Infrared emittance is a measure of the ability of a surface to emit its energy in the form of heat radiation. Thus, a high infrared emittance would help facilitate the discharge of stored heat energy from the roofing material. Likewise, materials with good convective heat transfer properties would assist in the transfer of heat away from the roof by the surrounding air.(4)

The infrared image of a roof painted with a light reflective coating shows a dramatic reduction in roof temperature between the low and high albedo sections. This phenomenon is depicted in *Figure 22*.

Figure 22: Infrared Roof Image

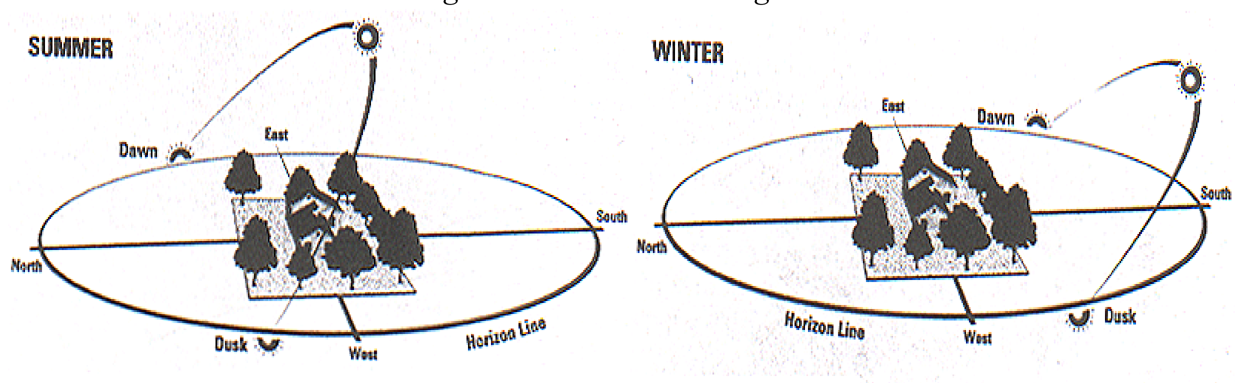


Source: http://eetd.lbl.gov/heatisland/ (4)

Winter Penalty

The same steps that make buildings easier to cool in the summer also can make them more difficult and expensive to heat in winter. However, in hot climates, the summertime benefit greatly outweighs the wintertime penalty. This is because the sun is high overhead in the summer, and shines mainly on the roof of a building. In winter the low sun shines primarily on the building side walls and through the windows. *Figure 23* illustrates the solar path diagram for the summer and winter sun.(3)

Figure 23: Solar Path Diagram



Source: Cooling Our Communities (3)

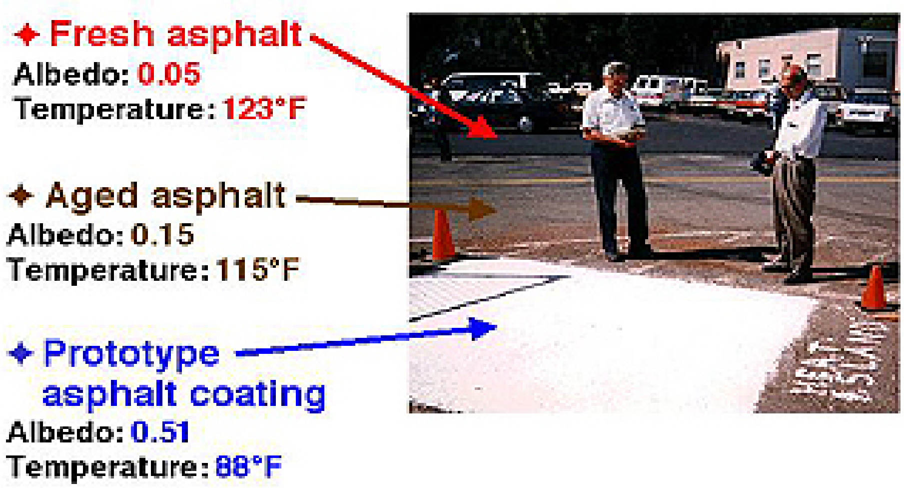
In a climate like that of San Fernando Valley, CA, a homeowner would save about $40 over a season of air conditioning use if the roof were white rather than green. On the other hand, the winter heating bill for the white roofed home would be only $10 more than the green roofed home. This produces a net savings of $30.(4) In the U.S., white roofs also retain their energy advantage surprisingly far north. This is due to the fact that the length of the day is approximately halved in the winter, the sun is relatively low so that it shines on only half the roof area compared to summer, and the skies are about three times cloudier in winter than summer.(4) The combination of these three factors combined illustrate the greatly reduced potential of solar absorption by a roof during the winter. Thus, because so little winter sunlight ever makes it to the roof at all, the color of the roof has an insignificant winter penalty.

3.2.4 Pavement

Another contributor to the heat island effect is pavement. It has been well documented that dark materials absorb more heat from the sun. In fact, dark, low albedo surfaces in the sun can become up to 55°F hotter than corresponding light, high albedo surfaces, as seen previously in *Figure 20* (page 52).(4) Thus, roadways and parking lots paved with dark materials absorb immense amounts of solar energy, heat the air around them, and contribute greatly to the heat island effect.

Today, there are many new paving materials being developed that can reflect more sunlight so that they absorb less solar radiation and stay cooler. *Figure 24* demonstrates how one such prototypical material compared to new and aged asphalt during a study conducted by the Lawrence Berkeley National Laboratory (LBNL) in collaboration with Reed and Graham, Co. of San Jose, California.(4) In general, it was found that for a increase in albedo of 0.1, the pavement temperature decreases by about 8°F.

Figure 24: Comparison of Pavement Albedos and Temperatures



Prior to embarking on a large-scale heat island mitigation program that promotes the use of high albedo pavement materials, it is necessary to rigorously consider all of the costs and benefits of each pavement alternative. Life cycle analysis is a technique utilized for the comparative evaluation of the overall effects of alternative methods.

Life Cycle Analysis

Methodology

A life cycle analysis provides an entire life assessment of a product, process, or activity encompassing: extracting and processing raw materials; manufacturing; transportation; distribution; use; re-use; maintenance; recycling; and final disposal. There are two different methods of life cycle analysis currently being utilized in industry: life cycle cost analysis (LCCA) and life cycle assessment (LCA).

Traditional methods, such as those often used in the analysis of alternative pavement designs (35), employ LCCA as the accepted way of comparing products or services. In this procedure, the comparison of competing products is based solely on total lifetime cost and performance. Increased concern over improving the sustainability of industrial operations has introduced the need to consider resource depletion, human health effects, and environmental impact in product selection, yet this is not routinely done in LCCA. Thus, LCA offers a structured way of introducing these considerations into the decision making processes and examining alternatives, such as selection of a building material or choice of a manufacturing process.(36) Life cycle assessment is a way of compiling and examining the inputs and outputs of the energy, resource, and environmental impacts directly associated with a product or service system through every step of its life. The associated overall impacts can then be determined and weighed in order to identify possible system issues, analyze tradeoffs, assist in more detailed research, and set the stage for improvements.

In general, a life cycle assessment can be utilized internally or externally by an organization in the material selection for infrastructure design. The potential uses of LCA internally include: environmental strategy development; product process design, improvement, and optimization; identification of opportunities for environmental improvement; environmental auditing and waste minimization. Subsequently, the external applications of LCA for an organization encompass: comparison of competing products or services; advocacy of products or services; establishment of government policy; eco-labeling; and public education and communication.(36)

In order for legitimate claims to be made about how one product compares to another, the LCA and subsequent comparison must be based on analyses conducted using a uniform set of rules. A complete life cycle assessment study can be generalized into four phases: project characterization, inventory analysis, impact assessment, and improvement assessment.(36,37)

Phases

At the beginning of a product LCA, the scope and purpose of the current assessment must be specified. This is important because different parties have different underlying values and principles, which will lead to diverse formulations of environmental issues and impact how LCA results are used and interpreted. Thus, as a guide, the use and application of an LCA, in addition to the principles and goals of the study, should be clearly stated in the scope of an LCA study.(37) Furthermore, the LCA process must make provisions for a critical review of the findings. The degree to which a critical review is required, and how it should be done, depends on the purpose of the LCA. For example, if the LCA is to be used for comparative claims that are made public, an in depth review is essential in order to ensure the validity of the scientific and technical methods used, the quality of the data in relation to the goal, the validity of the LCA conclusions relative to the limitations identified in the study, and the transparency and consistency of the study. (36)

The second phase of a LCA begins with the construction of a process flow chart, listing all mechanisms involved in each life cycle phase and specifying system boundaries. The product or service being inventoried is described as a system that performs a defined function. The system is separated from its surrounding environment by a system boundary across which there is an inflow of materials and energy and an outflow of products and emissions. Thus, after the process diagram is complete, all relevant inputs and outputs from a product or service are compiled and quantified for each stage in the life cycle.

The value and credibility of any LCA depends upon the quality of its data that must be maintained throughout a life cycle assessment if the user is to have any confidence in its results. Data quality is defined as the degree of confidence in individual input data, in the data set as a whole, and ultimately in decisions based on the LCA study using such data as input. Unfortunately data quality is influenced by many factors and varies enormously. The major issues of concern include the collection method, data source, representativeness, amount, age, consistency, and reproducibility of the data, level of aggregation, and completeness of coverage.(36,38) Poor quality data limits the external uses of an LCA. For example, it may be impossible to compare two competing products if the data for one of the products is not sufficiently representative or accurate.(36) Specifically, this issue is often associated with the acquisition of emissions and other environmental data, from the individual industries involved in a product’s life cycle, for a great deal of this type of information is not a matter of public record and is thus not easily accessible to an outsider.(39)

In the third phase, an evaluation is done on the magnitude and significance of the potential impacts associated with those inputs and outputs. These outcomes, which usually consist of a list of emissions to water, air, solid waste and use of raw materials, are translated into a normalized functional unit used to illustrate their respective contributions to relevant issues of concern. This allows a LCA to focus on relative comparisons of whole systems with respect to resource use, human health effect, and environmental impact in relation to the defined functional unit. As a result, life cycle assessment does not represent measuring or predicting actual impacts, predicting potential impacts (in the sense of possible future impacts), estimating risks, or assessing safety.(37)

Instead, in the final stage, the results are used as indicators that enable a better understanding of the environmental impact of the product during its life cycle, set priorities in the design process, and focus attention on the issues that offer the best opportunity for improvement. Of course, in this interpretation phase, it must be ascertained that, for comparative studies, equivalent assumptions have been made and all uncertainties identified.(37)

In some ideal cases an LCA will show a clear single dominant impact that can be easily addressed; however, impacts are usually spread over the different phases of the life cycle and over different environmental effects. Thus, in order to make explicit comparisons, the true and meaningful differences among the results of the category indicators must be identified. This can be accomplished through the utilization of a number of further analytical techniques. Some specific techniques are gravity analysis, sensitivity analysis, and error or uncertainty analysis. Gravity analysis allows the specification of which processes or life-cycle stages are the major contributors to the LCA results. Sensitivity analysis evaluates the effects that the ranges in data, methodological assumptions, reference values, etc., have on model outcomes. This can help interpret which of these factors may most influence the results. Finally, error or uncertainty analysis evaluates the natural variability of error in the data and methods, and allows one to assess if measured system parameters are significantly different from zero and each another. These techniques and the information they provide may help identify areas for additional analysis and interpretation and explain the significance of the LCA results.(37)

The assessment and comparison of an entire system or a network of industrial operations over a product's life cycle is difficult due to the complexity and disparity of study systems, for example, differences in unit operations among alternative systems. It becomes even more difficult as one then attempts to relate the elaborate systems to a diverse range of even more complex environmental issues. The LCA system wide approach is a necessary contribution to this assessment of an entire system; however, in order to simplify the LCA process, a number of assumptions, value choices, and subjective judgments are required during the analysis. As a result, a certain amount of discontinuity and inconsistency within the LCA inventory data quality, methods, and results are inevitable.(37) This is not to say that life cycle assessment methodology is valueless or lacks credibility. In fact, LCA is a very useful design tool if the methodology and assumptions used in the assessment are clearly stated and caution is exercised in the interpretation of results.

Concrete and Asphalt Pavement

Currently, the primary components in highway design are cost of construction, economy of maintenance, durability, and safety.(40) However, increased concern over improving the overall sustainability of a design has introduced the need to also consider resource depletion potential, human health effects, and environmental impact of a design. Life cycle assessment offers a way of compiling and examining the inputs and outputs of a design through every step of its life

In this section, a comparison of concrete and asphalt pavement will be examined and discussed. The research reported, which is based upon the LCA technique, was conducted by Wilfred H. Roudebush, Ph.D. with the sponsorship of the Portland Cement Association (PCA Project Index No. 94-04) through a subcontract with Construction Technology Laboratories, Inc. The Portland Cement Concrete LCA project followed the guidelines proposed by the Society of Environmental Toxicology and Chemistry (SETAC). These guidelines parallel the draft standards proposed by the International Organization for Standardization (ISO) in the 14040 series, 'Environmental Management - Life Cycle Assessment - Principles and Framework' and other ISO draft documents.

Project Characterization

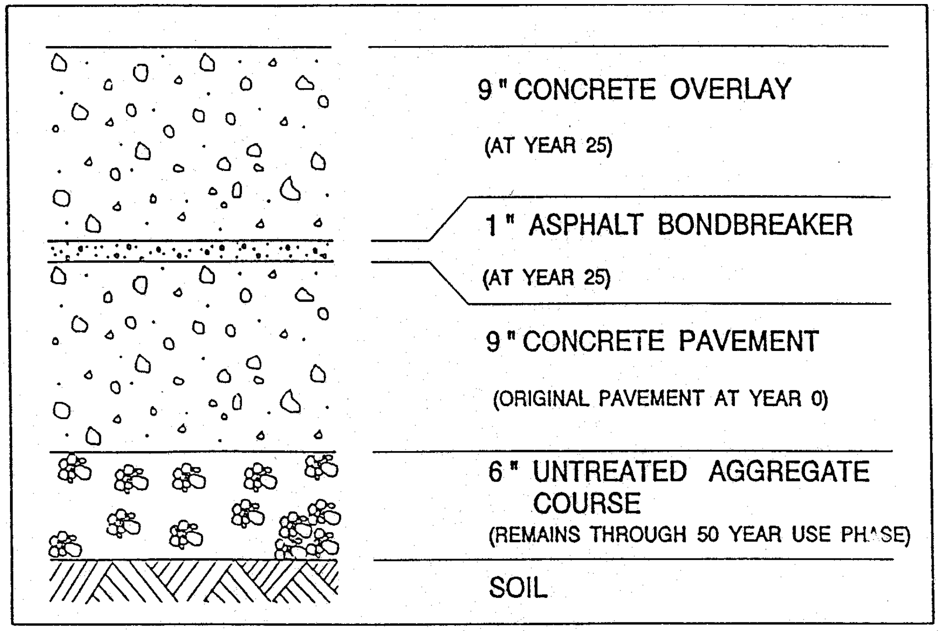
One of the first steps in conducting an LCA is to determine and designate the scope of the project, including the comparable subsystems of the alternatives being considered. These subsystem designations already exist for many alternatives related to highways and can be found in Standard Specifications for Construction of Roads and Bridges on Federal Highway Projects (FP-92).(41) The concrete highway system used in this assessment included United States Department of Transportation (USDOT) divisions 301-Untreated Aggregate Courses and 501-Portland Cement Concrete Pavement. The asphalt highway system employed included USDOT divisions 301-Untreated Aggregate Courses and 401-Hot Asphalt Concrete Pavement.(42)

The PCA project compares a kilometer of portland cement concrete and asphalt concrete pavements for a 50 year design life. The pavement dimensions for both highway pavement system alternatives were 24 feet wide and are American Association of State Highway and Transportation Officials (AASHTO) equivalent designs according to the American Concrete Pavement Association.

The concrete highway pavement system consisted of a 9 inch thick portland cement concrete layer on a 6 inch untreated aggregate base course. After 25 years, the pavement system is resurfaced with a 1 inch asphalt concrete bond breaker and a 9 inch portland cement concrete overlay. The components of the concrete highway pavement system are given in *Figure 25*. The original concrete pavement, asphalt bondbreaker, and concrete overlay were demolished and removed at the end of year 50. The untreated aggregate base course remained after demolition of the pavement. Sequencing of subsystem components during the use phase is graphically given in *Figure 26*.

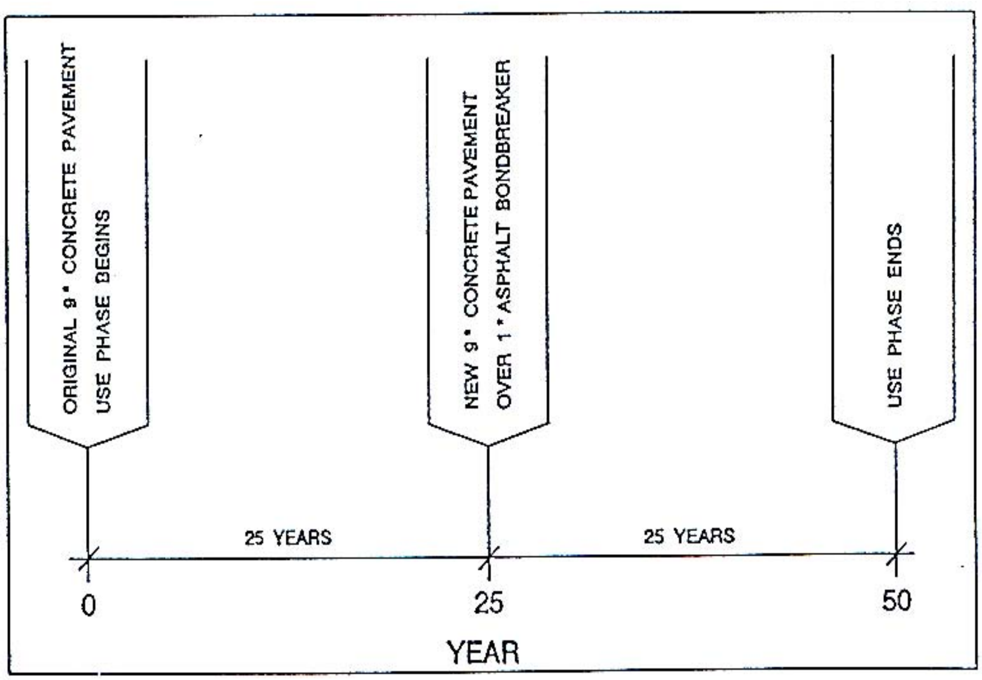
The asphalt highway pavement system consisted of a 5 inch thick asphalt concrete pavement on a 14 inch untreated aggregate base course. At the end of year 14, the pavement is resurfaced with a 5 inch asphalt concrete overlay. Both the original pavement system and the overlay are removed and reconstructed after 25 years. At the end of year 39, the pavement is resurfaced with a 5 inch asphalt concrete overlay. The reconstructed asphalt concrete pavement and overlay are demolished and removed at the end of year 50. The untreated aggregate base course remained after pavement demolition. The components of the asphalt highway pavement system are given in *Figure 27*, and the sequencing of subsystem components during the phase is graphically given in *Figure 28.*

Figure 25: Concrete Highway Pavement System Components



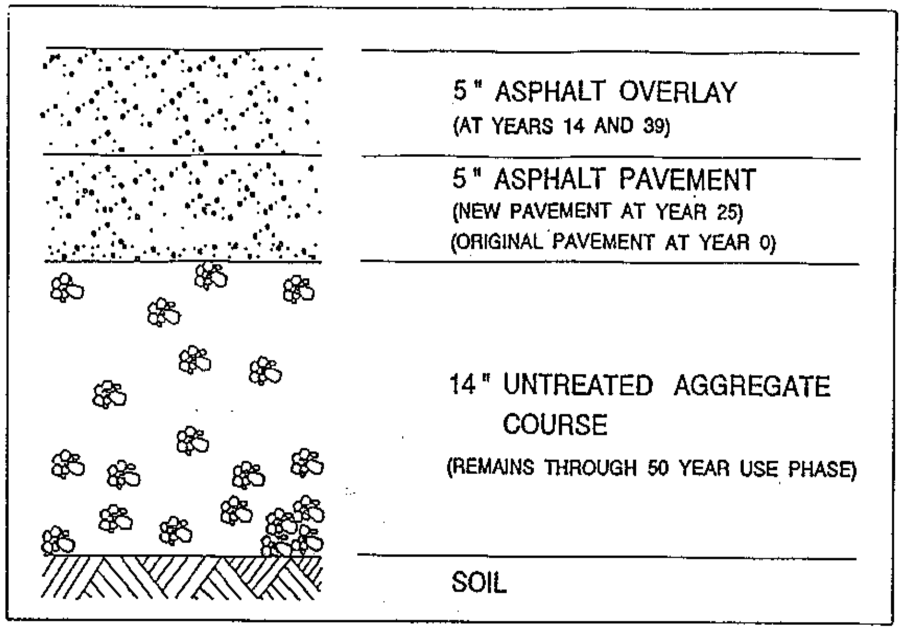
Source: Roudebush, W.H., 1996 (42)

Figure 26: Concrete Highway Pavement Subsystem Component Sequencing



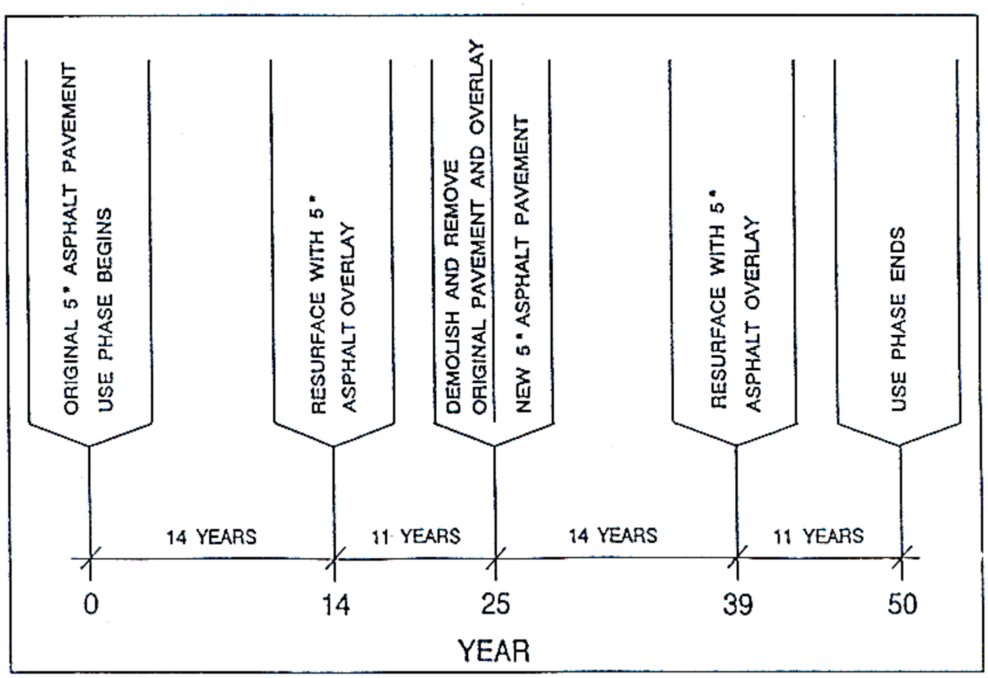
Source: Roudebush, W.H., 1996 (42)

Figure 27: Asphalt Highway Pavement System Components



Source: Roudebush, W.H., 1996 (42)

Figure 28: Asphalt Highway Pavement Subsystem Component Sequencing



Source: Roudebush, W.H., 1996 (42)

The assessment period is subdivided into 10 life cycle phases through which the alternative pavement materials, components, and systems proceed. These phases are described in *Table 5*.(42) It should be noted that life cycle phases A through C are not generally included in LCCA, and thus, at present time do not influence the selection process. These phases comprise the material transformity phase, which incorporate all the factors that go into processing and transforming a raw material into the material utilized in a design.

Table 5: Life Cycle Phases

Phase	Description
(A) Natural Resource Formation	• production and consumption of various environmental system (ecosystems, geology systems, etc.) which include minerals, which are formed by earth processes over millions of years and biomass, resulting from living organism net production occurring over shorter periods of time
(B) Natural Resource Exploration and Extraction	• renewable environmental inputs in the form of land used during extraction and storage of extracted natural resources • reclamation of land, after natural resource extraction • transportation of natural resources for material production
(C) Material Production	• conversion of natural resources into materials used in pavement component production
(D) Design	• inclusion of five sub-phases, according to the American Institute of Architects (1987): 1) schematic design 2) design development 3) construction documents 4) bidding and negotiations 5) construction administration
(E) Component Production	• production, storage, as needed before use, and transportation of components to the site for construction • conducted by manufacturing facilities specializing in various alternative components
(F) Construction	• construction of initial concrete and asphalt pavements • work done during the guarantee and warranty periods of the construction contract • dependent upon such factors as type of construction, techniques of construction, time of construction, quality of materials, components and subsystems, and workmanship
(G) Use	• operation, maintenance, alteration, repair, replacement, financing, tax elements, insurance, and any other activities related to the pavement system from substantial completion of construction to the time of demolition, including periods of nonuse or abandonment • affected by quality of materials, decisions on utilization of recycled materials, components, subsystems, and phase duration.
(H) Demolition	• demolition and removal the materials, components, and subsystems of a pavement system • sensitive to decisions on reuse and recycling of materials, components, and systems during this phase
(I) Natural Resource Recycling	• reduces the demand for raw materials that are made by the environment during natural resource formation (Phase A), natural resource exploration and extraction (Phase B), material production (Phase C), and component production (Phase E) requirements of future systems • reduces the need for disposal and landfill land use

(J) Disposal	• evaluation of demolition debris placement, compaction, and landfill containment • estimate of landfill closure and landfill postclosure which include groundwater monitoring, final cover, contour grading, surface water diversion, gas mitigation control, re-vegetation, and security/monitoring systems.

Source: Roudebush, W.H., 1996. (42)

Inventory Analysis

The methodology utilized in this life cycle assessment comparison of cement and asphalt pavement is referred to as environmental value engineering (EVE). Using this methodology, which is based on a system developed by Dr. Howard E. Odum, University of Florida, Gainesville, environmental impacts of different system alternatives can be compared using one system of normalized units denoted as *emergy*.

Emergy is defined as all the available energy that was used directly and indirectly in the making of a product, including the environmental impacts related to inputs of environment, fuel energy, goods, and services. However, energy of one kind is not equivalent to energy of another kind and accumulates from one phase to the next. Thus, in order to sum up all the available energies used, they must expressed in terms of one common quantity, *emergy*. This resultant *emergy* has units of solar emjoules (sej), which are related to the amount of solar energy required to generate the inputs.(43)

The inputs of environment, fuel energy, goods, and services that occurred for each of the various subsystem components during each life cycle phase of the pavement alternatives, were first accounted for in raw data units (i.e.: grams, joules, dollars). This input information was obtained from companies, individuals, and documents related to specific life cycle phases.(42) In general, the input information collected consisted of primary data, from operating companies. If primary data were not available, secondary data were used.

This would include information from equipment vendors, public sources and commercial databases, and estimates from similar operations.(36)

From this energy information, an *emergy* input table was constructed for each pavement alternative system and each life cycle phase using the appropriate emergy conversions. These conversion factors were obtained from research data of the *emergy* analysis and are based on the scientific methods of Dr. Howard T. Odum and his associates at the University of Florida, Gainesville, FL, and Dr. Wilfred H. Rotidebush at Bowling Green State University, Bowling Green, OH.(42) (See Appendix C)

The individual subsystem *emergy* input data were then complied for every source within each life cycle stage and aggregated into an overall *emergy* input data table for each pavement alternative. The tables of aggregated *emergy* input source data for the highway pavement systems, concrete (Alternative A) and asphalt (Alternative B), are given in *Table 6* and *Table 7*, respectively. Referring to these tables, the *emergy* input sources of environment, fuel energy, goods, and services are given in the *emergy* input source data columns, and life cycle phases are represented in the rows along the left side of the table. Phase *emergy* totals and the individual input *emergy* source proportions of the total phase *emergies*, supplied in the right column, are given below each input source at applicable life cycle phases. Total *emergy* for the highway pavement system alternative is given in the lower right hand corner of each aggregated *emergy* input source data table.(42) It should be noted that subsystems and life cycle phases had identical *emergy* inputs for both alternates and thus, were excluded from the assessment.

Table 6: Aggregated Emergy Input Source Data for Concrete Highway Pavement System (Alternative A)

Life Cycle Phase	*Emergy* Input Source Data (sej) (fraction of the total)				Total Phase *Emergy* (sej)
	Environment	Fuel Energy	Goods	Services	
A-C: Transformity	5.33e18 (0.8883)	3.15e17 (0.0525)	1.13e17 (0.0188)	2.45e17 (0.0408)	6.00e18 (0.5505)
D: Design	0	0	0	0	0
E: Component Production	0	0	0	0	0
F: Construction	2.63e13 (0.0004)	1.59e16 (0.2646)	2.60e15 (0.0433)	4.16e16 (0.6922)	6.01e16 (0.0055)
G: Use	3.99e18 (0.8400)	3.42e17 (0.0720)	1.22e17 (0.0257)	2.93e17 (0.0617)	4.75e18 (0.04358)
H: Demolition	2.62e13 (0.0003)	2.98e16 (0.3539)	1.04e16 (0.1235)	4.40e16 (0.5226)	8.42e16 (0.0077)
I: Recycling	0	0	0	0	0
J: Disposal	0	0	0	0	0
INPUT SUMS	**9.32e18**	**7.03e17**	**2.48e18**	**6.24e17**	
TOTAL CONCRETE PAVEMENT SYSTEM *EMERGY*					**1.09e19**

Source: Roudebush. W.H.. 1996 (42)

Table 7: Aggregated Emergy Input Source Data for Asphalt Highway Pavement System (Alternative B)

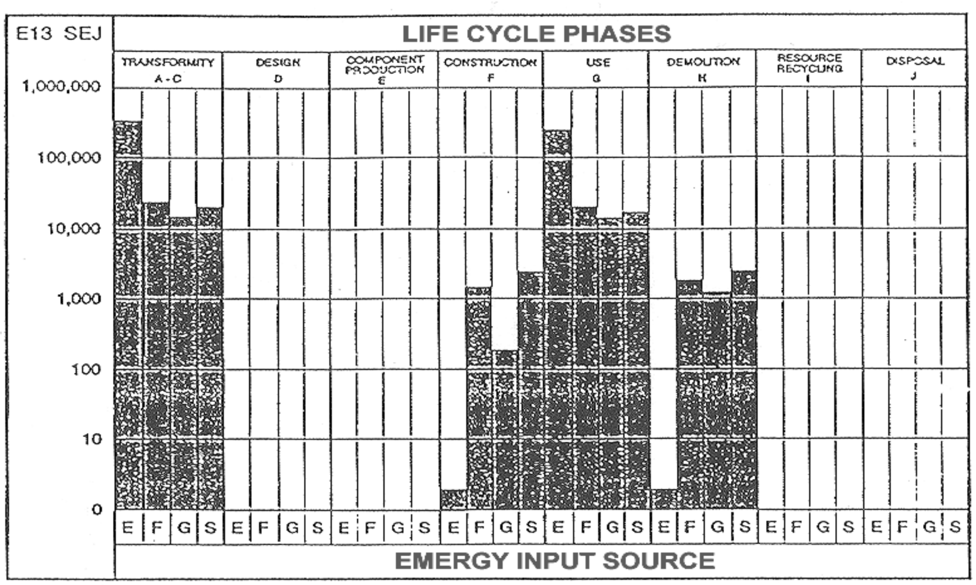
Life Cycle Phase	*Emergy* Input Source Data (sej) (fraction of the total)				Total Phase *Emergy* (sej)
	Environment	Fuel Energy	Goods	Services	
A-C: Transformity	6.40e18 (0.7232)	8.49e17 (0.0959)	8.01e17 (0.0905)	8.01e17 (0.0905)	8.85e18 (0.4255)
D: Design	0	0	0	0	0
E: Component Production	0	0	0	0	0
F: Construction	8.67e13 (0.0019)	2.34e16 (0.5189)	3.39e15 (0.0752)	1.82e16 (0.4036)	4.51e16 (0.0022)
G: Use	6.69e18 (0.5622)	1.84e18 (0.1546)	1.68e18 (0.1412)	1.69e18 (0.1420)	1.19e19 (0.5721)
H: Demolition	3.34e13 (0.0019)	9.57e15 (0.5500)	1.25e15 (0.0718)	6.54e15 (0.3759)	1.74e16 (0.0008)
I: Recycling	0	0	0	0	0
J: Disposal	0	0	0	0	0
INPUT SUMS	**1.31e19**	**2.72e18**	**2.49e18**	**2.52e18**	
TOTAL ASPHALT PAVEMENT SYSTEM *EMERGY*					**2.08e19**

Source: Roudebush. W.H.. 1996 (42)

From these aggregated data in *Tables 6 & 7*, the total *emergy* input ranking for each pavement alternative can be ascertained. For the concrete pavement system, the ranking from greatest to least is material transformity phases A-C, use phase G, demolition phase H, and construction phase F. For the asphalt pavement system, the ranking from greatest to least is use phase G, material transformity phase A-C, construction phase F, and demolition phase H.

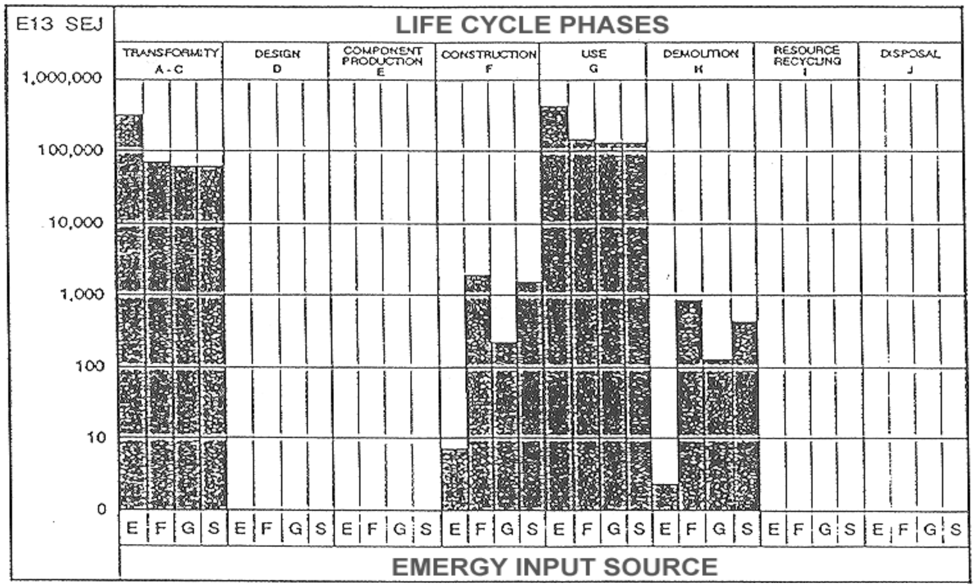
These data tables were then used to construct aggregated *emergy* input signatures that illustrate the total *emergies* from the input sources of the different pavement alternatives during each phase of the assessment life cycle. The aggregated phase *emergy* input signatures for the highway pavement systems, Alternative A and B, are given in *Figure 29* and *Figure 30*, respectively. Referring to these figures, the *emergy* input sources of environment (E), fuel energy (F), goods (G), and services (S) are given under each life cycle phase in columns and labeled along the bottom of the signature. The input source *emergy* values are represented along the left side of the figure with each horizontal quantity line representing an order of magnitude change. It should be noted again that subsystems and life cycle phases that had identical *emergy* inputs for both alternates were excluded from the assessment. (42)

Figure 29: Concrete Highway Pavement System Aggregated Emergy Input Signature



Source: Roudebush, W.H., 1996 (42)

Figure 30: Asphalt Highway Pavement System Aggregated Emergy Input Signature



Source: Roudebush, W.H., 1996 (42)

From the aggregated emergy input diagrams, portrayed in Figures 29 & 30, the ranking for the emergy inputs, across all of the phases, could be ascertained for each pavement alternative. For the concrete pavement system, the ranking from greatest to least is:

1. environment for phases A-C
2. environment for phase G
3. fuel energy for phase G
4. fuel energy for phases A-C
5. services for phase G
6. services for phases A-C
7. goods for phase G
8. goods for phases A-C
9. services for phase H
10. services for phase F
11. fuel energy phase H
12. fuel energy phase F
13. goods phase H
14. goods phase F
15. environment phase F
16. environment phase H

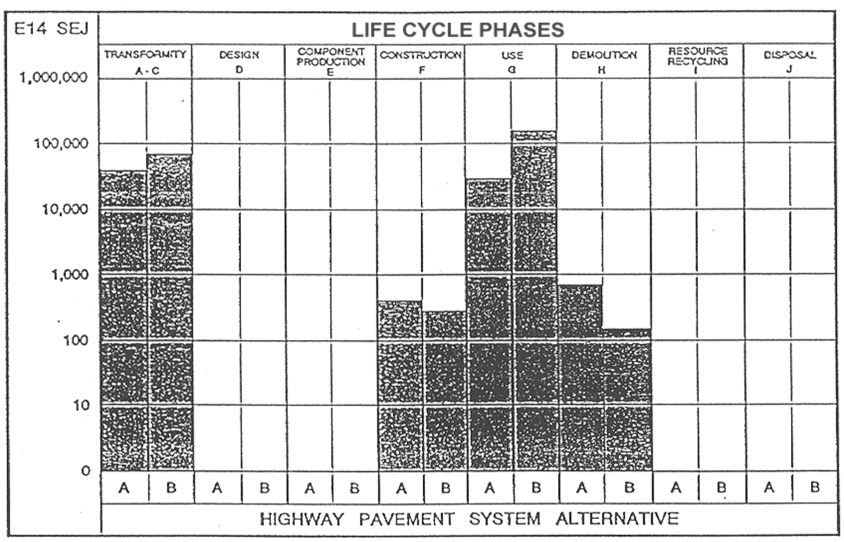
For the asphalt pavement system, the ranking from greatest to least is:

1. environment for phase G
2. environment for phases A-C
3. fuel energy for phase G
4. services for phases G
5. goods for phase G
6. fuel energy for phases A-C
7. goods for phase A-C
8. services for phases A-C
9. fuel energy for phase F
10. services for phase F
11. fuel energy phase H
12. services phase H
13. goods phase F
14. goods phase H
15. environment phase F
16. environment phase H

<u>*Impact Assessment*</u>

The primary purpose of the aggregated *emergy* input data tables and signatures is to compare the inputs of the different pavement alternatives and locate *emergy* concentrations within each assessment life cycle that should be a focus for potential reductions. Thus, a total *emergy* input signature, given in *Figure 31*, was constructed to provide a graphical representation of the *emergy* concentrations, presented in *Tables 6 & 7*, that occurred for all the systems of each pavement alternative, (A) concrete and (B) asphalt, during the life cycle phases. Referring to this figure, the values for the total input source *emergy* are specified for both alternatives within each life cycle phase and are represented along the left side of the figure with each horizontal quantity line representing an order of magnitude change. Once again subsystems and life cycle phases having identical *emergy* inputs for both alternates were excluded from the assessment.(42)

Figure 31: Total Phase Emergy Input Signature

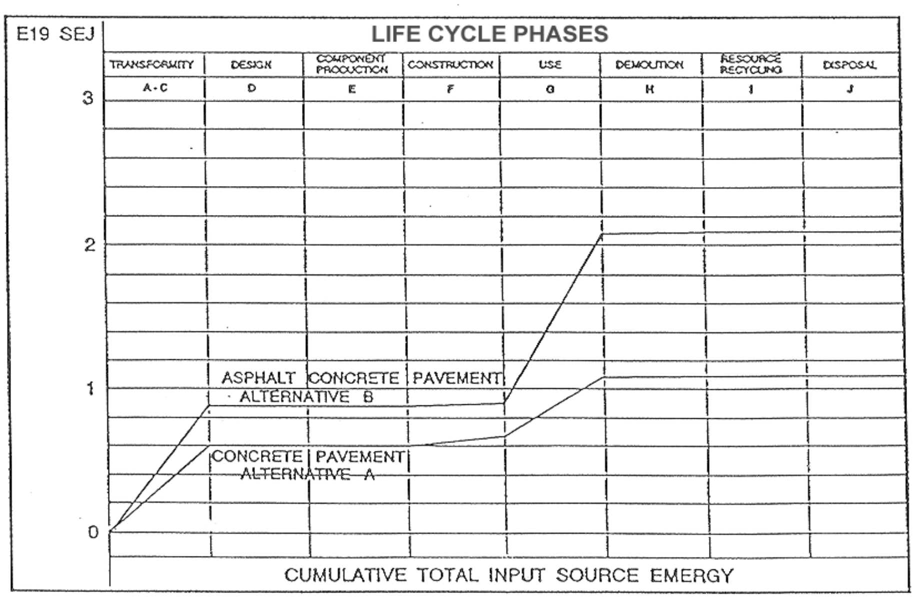


Source: Roudebush, W.H., 1996 (42)

A few comparative observations can be made based on data contained in *Tables 6 & 7* and illustrated in *Figure 31*. First, for the material transformity phases (A-C) and the use phase (G), alternative A required 32.2% and 60.1% **less** *emergy*, respectively, than alternative B. This is primarily due to the fact that the asphalt system uses a greater volume of material during construction, reconstruction, and resurfacing. Second, during the construction phase (F) and demolition phase (H), alternative A required 33.3% and 383.9% **more** *emergy*, respectively, than alternative B. However, the construction phase (F) and demolition phase (H) only account for approximately 1% of the total pavement system *emergy* of both pavement alternatives. Moreover, the environment *emergy* inputs of phases F and H specifically account for less than one percent of total inputs during these phases. As a result, in order to reduce total *emergy*, the inputs of fuel energy and services should be the focus. Finally, because the transformity phases (A-C) and the use phase (H) account for about 99% of the total system *emergy* in both alternatives, a reduction in any of the inputs would result in a reduction of the overall pavement system *emergy*.

Overall, alternative A used approximately 47.6% less system *emergy* overall, thus revealing concrete as the better alternative from this environmental LCA point of view. This is graphically presented in *Figure 32* using the total cumulative impact *emergy* of input sources for both pavement system alternatives.

Figure 32: Cumulative Total Input Source Emergy



Source: Roudebush, W.H., 1996 (42)

It should be note that the slopes of the cumulative *emergy* do not reflect true *emergy* intensity because the life cycle phases are not represented by actual periods of length.(42)

<u>*Improvement Assessment*</u>

Traditionally in life cycle analysis, an emphasis has been placed on the respective costs of different pavement alternative throughout their lifetimes. As a result, when concrete and asphalt systems are compared, the asphalt pavement alternative was usually selected because a concrete system is more expensive to construct and maintain.(35) However, increased concern over improving the sustainability of industrial operations has promoted the need to look at the fuller perspective. Thus, a new life cycle assessment strategy must be developed that accounts for items such as resource depletion, human health effects, and environmental impact in product selection.

Life cycle assessment, using environmental value engineering, employs a systems approach methodology to more accurately compare the input requirements and related environmental impacts of pavement alternatives.(42) As a result, when concrete and asphalt highway pavement systems are compared using this revised life cycle analysis approach, concrete proves to be superior. Unfortunately, the current market and technology barriers to shifting from the use of asphalt as a repair and resurfacing material to concrete or another alternative material are substantial in many areas for reasons often associated with material handling, ease of construction, and amortized cost. Moreover, it should be noted that these results only represent one particular approach. Thus, in order for a clearer overall perspective to be attained, additional life cycle assessment techniques must be established and refined.

In addition, other variable inputs related to the use of concrete and asphalt highway pavement system alternatives, such as pavement lighting and vehicle fuel consumption, should also be considered and included in future assessment for a more accurate comparison.(42) For example, preliminary studies have shown that lighting requirements for concrete pavement are approximately 30% less than for asphalt pavement (44), and trucks consume approximately 20% less fuel on concrete pavements than on asphalt concrete pavements (45).

4. CHICAGO AREA CASE STUDY

Through the manipulation of the ratios between the percentage of vegetative cover and high and low albedo surfaces, it may be possible to substantially reduce urban heat island effects. For example, research at the Lawrence Berkeley National Laboratory (LBNL) has examined these effects in simulations of the cooling achieved by increasing the albedo of roofs and roadways in the LA Basin. Researchers showed that a 4°F cooling was obtained by noon, which in turn resulted in a 10-12% population based reduction in smog exceedances.(46)

As shown previously in *Table 2* (page 16), Los Angeles is the only area in the extreme classification for ozone nonattainment. Chicago is among the cities classified as severe ozone nonattainment areas, which serves as the impetus for this study evaluating the estimated effects of cooling strategies to abate the urban heat island effect and ozone problem in Chicago.

In this chapter, the heat island and ozone exceedance distribution of the immediate Chicago area are located geographically. The relationship between temperature and ozone is examined in order to obtain an understanding of the regional features associated with the observed ozone exceedance distribution. Finally, an urban fabric analysis is conducted for the city of Chicago as an initial step in the investigation of how increased vegetative cover and the use of cooler roof and pavement materials may help decrease the effects of the urban heat island

4.1. TRENDS IN METROPOLITAN CHICAGO

4.1.1. Monitoring Stations

Ozone is generally monitored only between the months of April and October, the so-called ozone season. Several Chicago monitoring stations may collect data over a longer period