Foreword by Series Editor: Targeting Causes Rather Than Treating Symptoms

Pavements are the most ubiquitous imprints left by humans upon the natural landscape; the extent of coverage, as described by Bruce K. Ferguson and his contributing authors Gregg A. Coyle, Ronald Sawhill, and Kim Sorvig in the present book, is truly shocking. A large body of literature that links impervious surfaces to a wide variety of environmental problems exists. Indeed, this relationship is so established that one can truncate the old adage and, regardless of inferred intentions, simply state that the road to Hell is paved...Period.

Not far from where I live in the Alewife Brook watershed of Cambridge, Massachusetts (described as the case study in my book *Facilitating Watershed Management: Fostering Awareness and Stewardship*) is a region whose premier characteristic is that it is a sea of pavement. Indeed, it is actually possible to walk for a kilometer linking up one sprawling parking lot with another, several of which are of a size large enough to accommodate the landing of a jet airplane! It comes as no surprise that the nearby stream is the most flood-prone and nonpoint source polluted river in the eastern part of the State. In contrast, only twenty kilometers away, near the waters of Walden Pond, which have been empowered by many environmentalists around the world with near-sacred status (see my edited volume *Profitably Soaked: Thoreau's Engagement With Water*), lies one of the nation's first successful porous pavement parking lots (see page 64 and 124–125 in the present book). I well remember the day, following the 2000 Harvard conference, which gave rise to the first book in this series (*Handbook of Water Sensitive Planning and Design*), when Bruce Ferguson held the interest of a group of hydrologists with his demonstration of pouring water onto and *into* the asphalt there.

The present book, the sixth in the series by CRC Press — Integrative Studies in Water Management and Land Development — is the long-awaited and eagerly sought comprehensive review of porous pavements. The seamless fusion of landscape architecture, structural engineering, and hydrology are a perfect fit to the aspirations of this series of books. Herein we learn from Ferguson and his colleagues not only of the role of porous pavements in reducing the "feast or famine" nature of urban stream hydrology (in terms of there being either too much or too little water due to rapid runoff and lack of groundwater replenishment), but also of the role that such surfaces play in promoting well-watered and healthy trees, microclimatic thermal regulation, quieter and safer streets, and also in creating beauty in our (sub)urban landscapes.

The breadth of study, exhaustive research, wealth of technical detail, illustrative nd informative case studies, great photographs and clear figures, and diversity of eferences and web-pages cited, will ensure that this book will become the standard eference manual for practitioners. The detailed examination of the various porous avement typologies, each given its own chapter, in which strengths and limitations, naintenance issues, and application suggestions are honestly and straightforwardly resented, will mean that what Ferguson describes at the start of the book as "the ontroversial and technically challenging field of porous pavements" may not be uite so in the years to come. There is much to learn from these pages, which proide a clarion call for the imaginative use of porous technologies to mimic natural andscape functionality and thus alleviate many of the environmental stresses that lague our developed watersheds. Such an approach that specifically targets the auses of environmental dysfunction rather than only dealing with the symptoms of he disease will go far toward promoting healthy watersheds.

And finally, this book makes the point that when consideration is given to related nfrastructure costs needed to alleviate watershed disturbance, porous pavements nay often be the less expensive option in the long run. One final example, again rom the Boston area, illustrates how attention to issues of groundwater infiltration ould have saved thousands of dollars. Many older cities that developed as a result f filling in their wetlands and coastal areas may look forward with apprehension to what Boston is now having to address. There, some of the historic buildings, nchored as in Amsterdam and elsewhere, to massive cribs of wooden timbers buried leep within the formerly moist ground, are now showing signs of instability. This is lue to the increase in the extent of impervious coverage that has prevented the infiltration of water needed to preserve the structural integrity of the crib anchors. Engineers are now examining expensive methods of artificially injecting water into he ground to saturate the building foundations. How much simpler it would have een to have either left more open space free of impervious coverage or to have to sed any of the diversity of porous pavement options that Ferguson and his coleagues advance in these pages.

Robert L. France
Harvard University

Preface

Of all the structures built by human beings, pavements are the most ubiquitous. They occupy twice the area of buildings. And of all the physical features of contemporary cities they are the most influential. They dominate the quality of urban environments. In urban watersheds impervious pavements produce two thirds of the excess runoff. They are responsible for essentially all the hydrocarbon pollutants. They produce two thirds of the groundwater decline and the resulting local water shortages. They produce two thirds of the temperature increase in the urban "heat island". They determine whether urban trees extend their roots and live, or die.

The polluted quality of urban runoff, the overflowing of combined sewer systems, the diminishment of water supplies, the wasteful consumption of urban energy, and the decline and death of the "urban forest" force our attention on the reclamation of paved areas for the benefit of the biophysical environment and the human beings who live with it.

Porous pavements are those that have built-in networks of void spaces where water and air pass through. Although some porous paving materials are nearly indistinguishable from nonporous materials in construction and superficial appearance, their environmental effects are qualitatively different. They cause air, water and heat to enter different parts of the environment, there to undergo qualitatively different processes of storage, treatment, and flow.

Porous pavements can allow the oils from cars and trucks to biodegrade safely, the rainwater to infiltrate the soil, the heat of the sun to dissipate, the groundwater to be replenished, the roots of trees to breathe, and the streams to flow in dry summers. A large part of the solution to urban environmental problems is under our feet. By paying appropriate attention to the everyday materials on which we walk and drive, we can replenish renewable resources, restore regenerative processes, and produce a cleaner, healthier, safer, more sustainable world in which to live. Porous pavements are potentially the most important development in urban watersheds since the invention of the automobile.

But in most parts of North America porous pavements are outside the ordinary conventions of urban design and construction. Many people are curious about porous pavements, and many are skeptical.

PURPOSE AND NEED

This book's purpose is to give responsible professionals the information they need to put porous pavement materials into appropriate, informed, beneficial, and successful use. With factual knowledge of experience in the field and theoretical understanding of underlying mechanisms, individual designers can evaluate one kind of pavement material against another, participate in responsible professional debates, and competently and correctly adapt porous pavements to site-specific conditions.

This book is addressed to landscape architects, building architects, urban designers, civil engineers, urban foresters, construction contractors, construction product nanufacturers, city planners, environmental policy-makers, and all others professionally concerned with urban construction and the urban environment. It supplenents basic training in site design, site drainage, construction materials, and iorticulture with the special concepts of porous pavements and their implications for he urban environment. This is a reference for practitioners who need to update and expand their applied skills, and a textbook for university classes in site construction, vatershed protection, and sustainable development.

Previous guides to porous pavements have been published as the technology developed in the last 30 years. For porous asphalt several books emerged when the U.S. Environmental Protection Agency was supporting research (Thelen et al., 1972; Thelen and Howe, 1978; Diniz, 1979). For porous concrete the Florida Concrete and Products Association published fine guidelines based on its seminal experience (FCPA, no date; Wingerter and Paine, 1989; Paine, 1990). For paving blocks and grids, product licensng and manufacturing groups beginning with Uni-Group USA admirably invested in esearch and published the results (Rollings and Rollings, 1992 and 1999), and their work is now joined by a fine summary manual from the Interlocking Concrete Pavement Institute (Smith, 2001). This book leans gratefully on those earlier works. However each previous guide focused on an individual type of material without defining the field as a whole, and some of the early works are now out of date.

Professionals who have to design sites creatively and cost-effectively to meet ombinations of criteria need an overview of the available materials. They need information that will allow them to choose and apply materials to meet site-specific onditions and objectives, and examples of how the materials have fared in a variety f settings. They need lines of thought for evaluating the feasibility and appropriteness of alternative pavement applications on specific sites.

This book fills the void in the compilation of porous pavement information. It is he first that has inventoried the range of available materials, arranged them to contrast their applications in different types of settings, and related them to the context f the general site environment. It defines and organizes the field for the first time.

The research for this book consumed seven years, during which I interviewed 70 experienced researchers, designers, and suppliers, read 800 technical articles nd reports, and personally surveyed 270 installations of all kinds of porous pavements in all parts of North America. Near the beginning, Tom Richman of Catalyst n San Francisco clarified the image of a work that would be immediately usable by ractitioners. In conceiving it and pursuing its completion I have been inspired as sual by the examples of Albert B. Ferguson and Louise E. Ferguson of the motivaon and discipline to work intensely and joyfully for the good of the community, and y the example of Ian L. McHarg of moral will to seek new and better ways specifcally in environmental design.

RRANGEMENT AND CONTENT

his book begins with broad basics to establish a foundation for all porous pavement aterials and applications. The first five chapters introduce the types of materials and arrangements and the roles they play in the urban environment, and outline the principles of pavement structure, hydrology, and rooting space.

Each of the remaining nine chapters is dedicated to one of the families of porous pavement materials (those families being defined and distinguished here for the first time): porous aggregate, porous turf, plastic geocells, open-jointed blocks, open-celled grids, porous concrete, porous asphalt, "soft" pavement materials, and decks. Each chapter outlines the nature of the material, the organization of the industry that supplies it, and its distinctive installation methods, performance levels, and appropriate applications.

This book emphasizes practice and experience in North America. North America has been a leader in some kinds of porous pavements, for example porous concrete, plastic geocells, the early development of porous asphalt, and now in this book the recognition of unbound aggregate as a valid and purposeful porous paving material; for the benefit of workers in all regions of the world this book reviews North American experience with those materials. In some other kinds of porous pavements, notably those of blocks and grids and recent developments in porous asphalt, North America has been behind countries in Europe and elsewhere; for the benefit of North American practitioners this book reviews the nature and availability of those materials and the growing experience with them.

This book is lengthy because it confronts practitioners' numerous, challenging, technical questions about porous pavement. As this book introduces the controversial field of porous pavements to the world for the first time, it is valid that those questions be asked, and necessary that they be answered.

This book emphasizes factual data from observed experience. Factual on-the-ground experience supercedes any degree of speculative theory. In the controversial and technically challenging field of porous pavements, factual evidence must be visible and accessible. Numerous case studies of specific materials in specific settings illustrate some features that are models for emulation, and others that are failures from which we can learn to do better in the future. Where the facts are simply not known, this book calls for further research. In addition this book cites numerous references because such references are the trail of recorded knowledge; they support specific statements and show where to go for further information. They lead readers to ongoing sources where they can update product information and obtain applicable industrial standards firsthand.

ADDITIONAL SOURCES OF INFORMATION

Site construction books such as those cited at the end of this preface give additional general background in pavement construction. The sources listed in Table P.1 provide updates on the general fields of urban construction and its use in environmental protection.

Specific paving products mentioned in this book were identified through searches on the web, exhibits at professional conferences, membership lists of industrial associations, and articles and advertisements in professional magazines. Practitioners must know what is available for their use. However, listing of proprietary products is for information only; it does not imply any recommendation or endorsement.

TABLE P.1

Examples of Sources of General Information on Sustainable and Environmentally Restorative Construction

Name	Contact Information
Environmental Building News	www.buildinggreen.com
Environmental Design + Construction	www.edcmag.com
GreenClips	www.greenclips.com
Low Impact Development Center	www.lowimpactdevelopment.org
American Recycler	www.americanrecycler.com
Rocky Mountain Institute	www.rmi.org
Smart Communities Network	www.sustainable.doe.gov
Southface Institute	www.southface.org
Sustainable Communities Network	www.sustainable.org
U.S. Green Building Council	www.usgbc.org
Green Builder	www.greenbuilder.com/sourcebook

TABLE P.2

Examples of Multi-industry Information Sources for Updating and Expanding Lists of Specific Porous Paving Materials

Name	Contact Information
CAD Details	www.caddetails.com
Erosion Control	www.forester.net/ec.html
LA Info Online	www.la-info.com
Landscape Architecture	www.asla.org/nonmembers/lam.cfm
Landscape Catalog	www.landscapecatalog.com
Landscape Online	www.landscapeonline.com
Material Connexion Library	www.materialconnexion.com
Stormwater	www.stormh2o.com
Sweets	www.sweets.com

Additional products and companies surely exist, or could exist in the future. Lists can be updated and enlarged at any time by re-searching the same types of sources, including the magazines and multi-industry "catalog" web sites listed in Table P.2. Industry-specific information sources are given in specific chapters of this book.

ROLES OF PRACTITIONERS

Every site-specific project presents a unique combination of conditions and objec- ives. Where porous pavements are used, they must be used right. Practitioners must apply porous pavements with the same degree of knowledge, selectivity, care, and ngenuity they would bring to any other aspect of any development project. Although pavements are mundane things, professionals must become accustomed to paying ttention to them in ways they may never have done before.

No statement in this book constitutes a recommendation for any specific site. The information in this book is intended to be used by design professionals competent to evaluate its significance and limitations and who will accept the responsibility for its proper application. With knowledge and care, responsible designers can adapt pavement materials and configurations to satisfy specific performance criteria, write appropriate and precise specifications, compare one type of material with another, objectively evaluate the causes of failure when it occurs, and select and adapt new types of materials where they are appropriate.

This book does not advocate replacing one rigidly conventional technology with another, or provide fixed recommendations to be followed blindly into all project sites. Instead it advocates a complete "toolbox" from which designers can choose selectively and appropriately in their everyday work. No type of pavement, porous or nonporous, should be smeared thoughtlessly everywhere. Porous pavements do not, by themselves, solve all urban environmental problems. But pavements are so ubiquitous, and the potential effects of making them porous are so fundamental, that anyone who does not acquire the ability to use porous pavements is not working with a complete professional toolbox.

Every year the U.S. paves or repaves a quarter of a million acres of land. Today we are able to answer many of the technical questions that have in the past inhibited the adoption of porous pavements. It is time now for porous pavements to take their place alongside other paving materials as alternatives that practitioners can draw on selectively and knowledgeably in their everyday work.

The potential for porous pavements has built up like an overbalanced snowbank leaning over a mountain ridge and ready to fall. They say that, when a snowbank is like that, you can start an avalanche with a clap of your hands: the small sound makes the whole mountainside quiver and come tumbling down. Perhaps, for porous pavements, this book will be a clapping of hands.

References

Croney, David, and Paul Croney (1998). *Design and Performance of Road Pavements*, 3rd ed., New York: McGraw-Hill.

Diniz, Elvidio V. (1980). *Porous Pavement, Phase 1 — Design and Operational Criteria*, EPA-600/2-80-135, Cincinnati: U.S. Environmental Protection Agency, Municipal Environmental Research Laboratory.

Florida Concrete and Products Association (no date). *Construction of Portland Cement Pervious Pavement*, Orlando: Florida Concrete and Products Association.

Harris, Charles W., and Nicholas T. Dines (Eds.) (1998). *Time-Saver Standards for Landscape Architecture: Design and Construction Data*, 2nd ed., New York: McGraw-Hill.

Hopper, Len (editor in chief) (in press). *Landscape Architectural Graphic Standards*, Hoboken, New Jersey: John Wiley and Sons.

Keating, Janis (2001). Porous Pavement, *Stormwater* 2, 30–37.

Landphair, Harlow C., and Fred Klatt (1998). *Landscape Architecture Construction*, 3rd ed., New York: Prentice-Hall.

Nichols, David B. (1992). Paving, in *Materials*, Vol. 4 of *Handbook of Landscape Architectural Construction*, pp. 69–138, Scott S. Weinberg and Gregg A. Coyle, Eds., Washington: Landscape Architecture Foundation.

1 Why Make Pavements Porous?

CONTENTS

Wherever pavements are built, porous pavements can improve the environment in vital ways. A pavement is any treatment or covering of the earth surface that bears traffic. A porous pavement is one with porosity and permeability high enough to significantly influence hydrology, rooting habitat, and other environmental effects. "Dense" pavements are those that are not porous. This chapter introduces the magnitude of pavements and the types of effects that porous pavements can achieve for water, air, living things, and human welfare, alone or in partnership with other aspects of urban design and construction.

THE MAGNITUDE OF PAVEMENTS IN AMERICA

Figure 1.1 shows the proportion of land covered by built structures in contemporary urban land-use districts. The dark portion of each column represents pavements; the white portion represents the roofs of buildings. The data are averages of measurements in the areas of Chesapeake Bay (Appendix D of Cappiella and Brown, 2001) and Puget Sound (Wells, 1994, p. 11).

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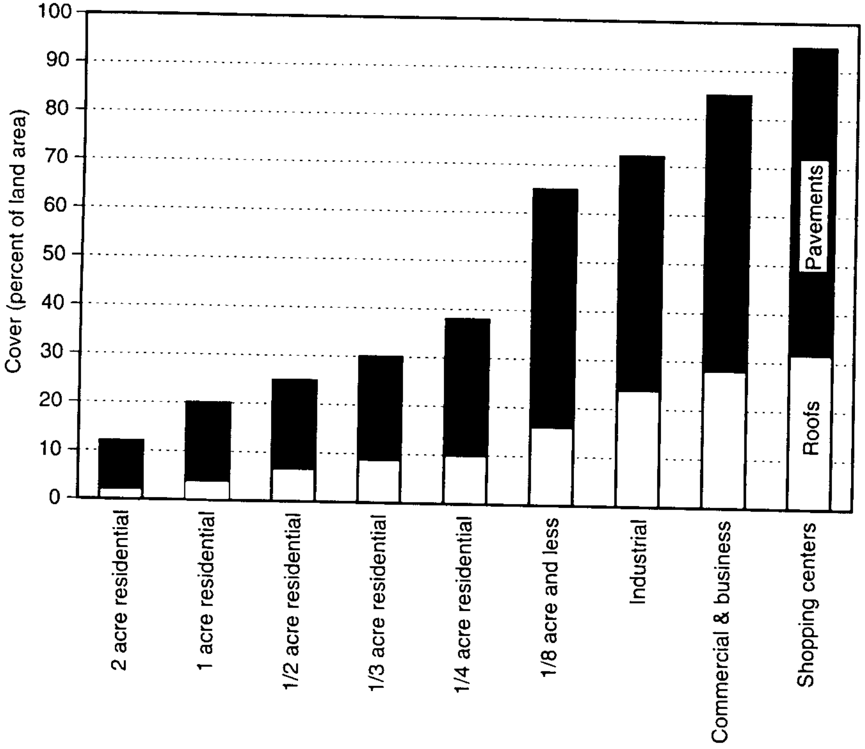

IGURE 1.1 Built cover in contemporary urban land uses (total built cover from Arnold and ibbons [1996]; distribution of pavements and roofs from an average of data in Appendix D f Cappiella and Brown [2001] and Wells [1994, p. 11]).

The left side of the chart shows dispersed, large-lot residential areas covering 12 ercent or more of the land with built construction. Progressing toward the right of he chart, one finds increasingly intense residential, industrial, and commercial land ses producing a correspondingly greater built cover. Shopping centers are in a class y themselves, routinely covering more than 90 percent of the land with built strucures. Pavements occupy 65 to 70 percent of the built cover. In intensely built-up reas, pavements cover more than half of all the land.

Figure 1.2 analyzes built cover by comparing the areas of building roofs and ree categories of pavements. The height of each column represents the proportion f built cover occupied by each type of structure. The roof areas of buildings have hite columns; the pavements have dark columns. The three charts show data for ngle-family residential, multifamily residential, and commercial land uses. In all ree charts, the white columns for building roofs show that buildings occupy about ne third of the built cover; pavements occupy the other two thirds.

In single-family residential districts the area of street pavements is large because ng streets are necessary to connect the dispersed dwellings. Local streets occupy 69 rcent of all road mileage in the U.S. (derived from data in Table No. 1019 of the .S. Census Bureau, no date). The parking is residential driveways. In single-family districts the driveways, local streets, and pedestrian sidewalks all have low traffic loads, so they are all eligible for consideration as porous pavement materials without structural conflicts.

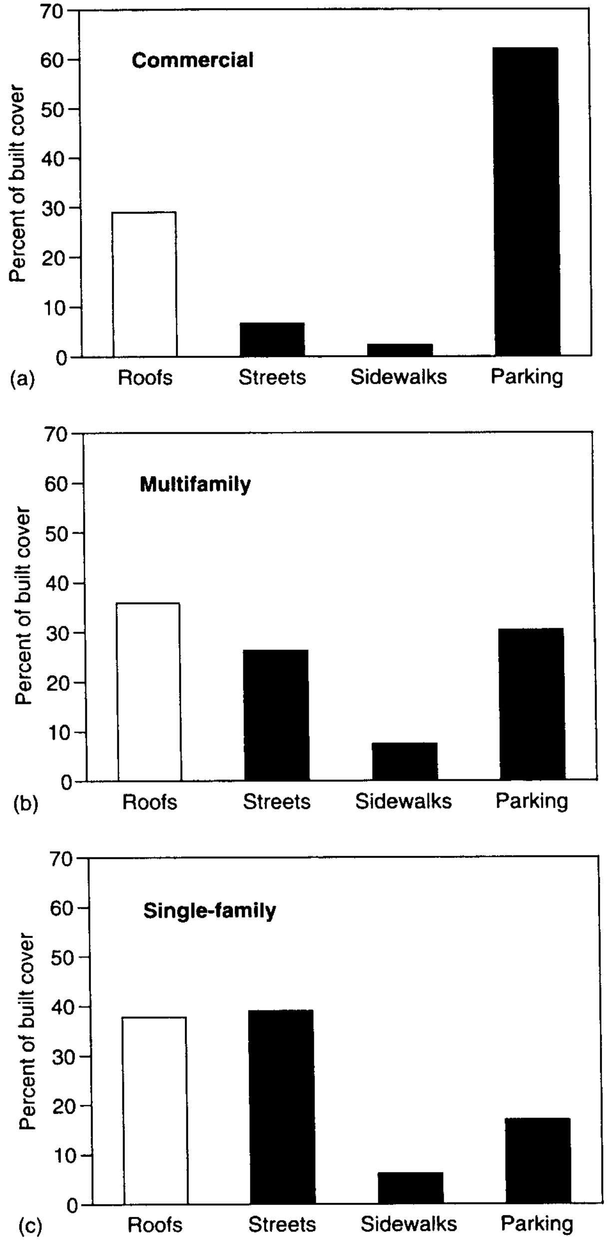

FIGURE 1.2 Types of built cover in three land uses (average of data from Wells [1994, p. 11] and Appendix D of Cappiella and Brown [2001]).

In multifamily residential districts the areas of both streets and on-site parking are substantial. The sidewalks and most of the parking lots in such districts have low traffic loads, so they are eligible for consideration as porous pavement materials. The traffic load in the streets could vary from place to place.

In commercial districts on-site parking lots dominate the built cover. Although public highways in commercial districts are wide, they occupy a small area compared with nearby parking lots. Large portions of parking lots have low or moderate traffic loads, including most of the parking stalls and all the outer, less-used portions of parking lots. The low- and moderate-traffic areas are eligible for selective porous pavement construction.

In summary, these figures show that it is possible to select porous pavement materials for approximately half of the built cover in most urban land uses.

In a large region such as a county with diverse interacting land uses, the total amount of pavement depends on the number of people living and working there. Figure 1.3 shows built cover in relation to population density. The total height of the curve represents the total built cover in a region. The dark portion represents the area of pavements; the white portion represents building roofs. These regional values are lower than most of those for individual urban land uses because they average in a region's parks and undeveloped lands along with built-up urban districts. With increasing population density the amount of built cover increases as the intensity of streets, buildings, and parking lots increases to support the people.

Figure 1.4 shows the regional amounts of pavement and roofs per person. This curve goes in the direction opposite from that for coverage of the land: as population density increases, the amount of built cover per person declines. This is because at high densities people live and work in multistory buildings that are close together and require fewer connecting streets, and the population uses public transportation and parking garages that require less pavement space for the storage of cars.

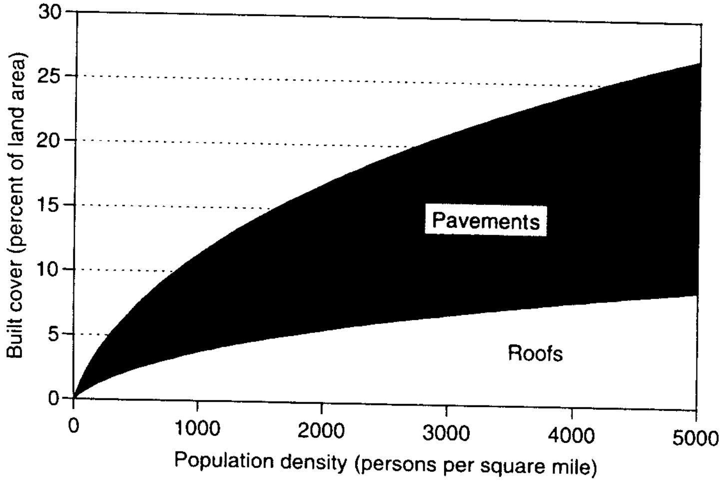

FIGURE 1.3 Built cover per land area in large areas such as counties (based on the equation for "medium" total built cover in Stankowski [1972] and pavements = 2/3 of total).

The amount of pavement in America is rapidly increasing as urban and suburban areas expand with the growing population. In recent years the U.S. population has been growing at a rate of 3.27 million persons per year (derived from data for 1990 and 2000 in *American Factfinder*, http://factfinder.census.gov). Using an arbitrary value of 0.05 acres of pavement per person from Figure 1.4, one can conclude that the country's paved area is growing at a rate of approximately 250 square miles per year.

PAVEMENTS IN ALTERNATIVE PATTERNS OF NEW DEVELOPMENT

When one is planning the future development of a site or a region, the opposite directions of the curves in Figures 1.3 and 1.4 present opposing choices between dispersed, low-density development and concentrated, high-density development. Table 1.1 shows that the choices present contrary arrays of pavement per acre and per person. The same type of choice applies both within an individual development site and

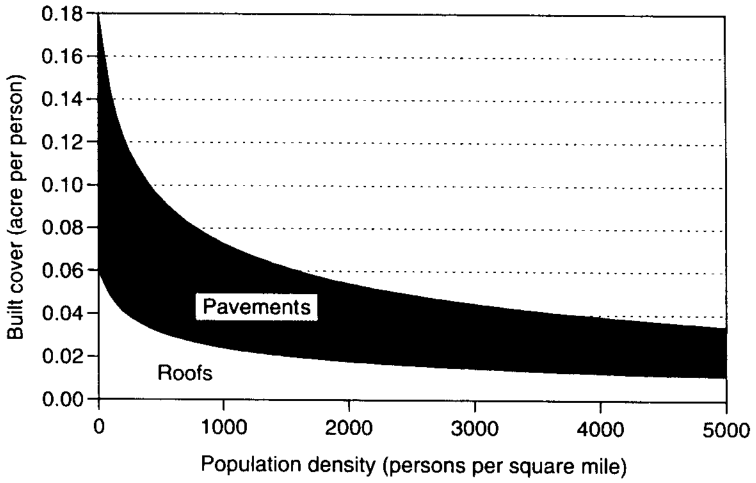

FIGURE 1.4 Built cover per person in large areas such as counties (based on the equation for "medium" total built cover in Stankowski [1972] and pavements = 2/3 of total).

TABLE 1.1
Implications of Choices in Urban Land-Use Pattern in a Site or Region

	Concentrated, High-Density Development	Dispersed, Low-Density Development
Local concentration of pavement where development is built	High	Low
Total quantity of pavement to serve a given population	Low	High

Summarized from Center for Watershed Protection, 1998; University of Georgia School of Environmental Design, 1997; Richman and Associates, 1997.

across an urbanizing region. For application in a given specific locale, each development pattern has a combination of advantages and disadvantages (Center for Watershed Protection, 1998; University of Georgia School of Environmental Design, 1997; Richman and Associates, 1997). The selection of each is likely to depend on site-specific conditions.

In dispersed development including large-lot single-family residences, the quantity of pavement is high for a given number of residents because the area paved for automobiles to connect to their dispersed buildings is large. However, the effect is diffuse, and its intensity at any one location is low.

On the other hand, dense development concentrates a given unit of development on only a portion of the available land. It generates high local concentrations of vehicles and people. But it uses a relatively small amount of pavement to support a given unit of development while leaving other areas pristine. Within an individual development site, a concentrated layout features a "clustering" of dwellings on small lots with correspondingly short streets and driveways. On a regional scale, concentrated development is done with compact mixtures of land uses where everyday needs can be met within small distances, nonautomotive transportation, and high residential and commercial densities. The total and per capita pavement areas are low. The total runoff and pollution from a site or a region as a whole are lower than they would be with dispersed development. A densely developed area that absorbs a given population growth is in effect a sacrificial area to preserve the quality of pristine lands elsewhere.

Within any given land-use pattern, the dimensions of necessary pavements can be minimized within the functional requirements of site-specific traffic and land use. In commercial districts the required amount of parking is that needed for actual utilization by a specific land use in a specific location; some jurisdictions could reduce their requirement by 30 percent (Albanese and Matlack, 1999; Willson, 1995). In residential districts the required street width is that needed for actual utilization by traffic and on-street parking; some municipalities could reduce their pavement widths by one third. Half the residential driveway pavements could be eliminated by reducing the driveways to separate wheel treads, as shown in Figure 1.5.

WHERE NOT TO MAKE PAVEMENTS POROUS

On certain special sites, pavements should remain dense and impervious for the sake of resource conservation and environmental protection.

On some sites the surface runoff from dense pavements is a resource that can be "harvested" into special swales or cisterns and used for irrigation or other productive purposes. Harvesting reduces the amount of freshwater to be imported from municipal supplies. However, the expense of collecting, storing, and perhaps treating the harvested water is worth the benefit only in certain limited climatic and site circumstances. Harvesting can be done only where the surface is correctly pitched toward a point of collection or use. The potential uses of the water tend to be limited to those that are tolerant of low water quality unless a treatment system is added.

On many old industrial "brownfield" sites, dense pavements prevent rainwater from percolating through old toxic deposits in the soil. This protects aquifers and streams by preventing the leaching of pollutants out into the environment.

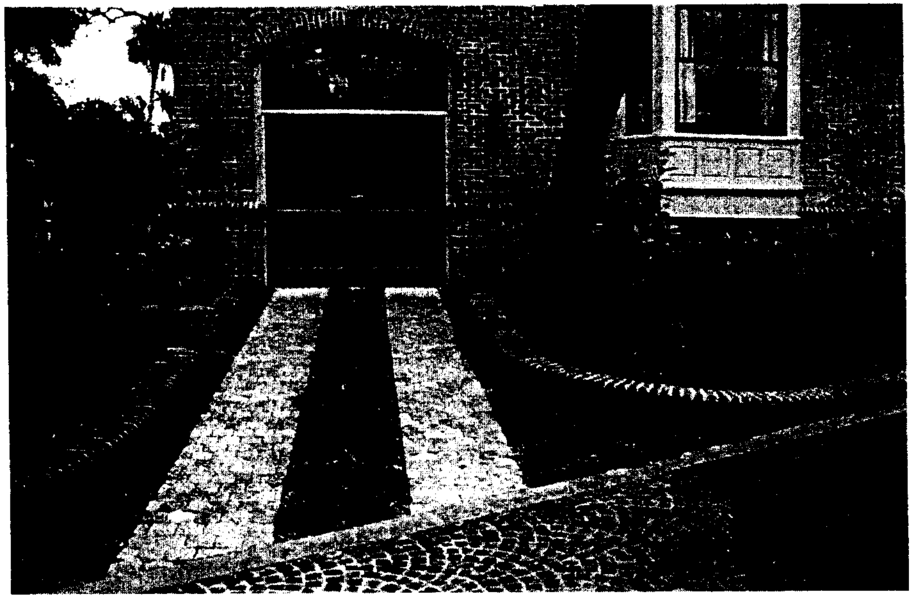

FIGURE 1.5 A residential driveway reduced to two wheel tracks.

In portions of many sites the necessary provisions for porous pavements that will be described in Chapter 2 cannot easily be met. The site layout directs clogging sediment onto the pavement surface, or the slope is excessively steep, or the traffic loading is too great. In these areas porous pavements may not be feasible.

Apart from these exceptions, in all land uses, in all patterns of development, on all types of sites, large areas of pavements are eligible for construction with porous paving materials. The environmental effects they promise are geographically widespread and functionally multifaceted.

THE PROMISE OF CLEAN WATER

The scene in Figure 1.6 exemplifies the problem that urban watersheds present when they are developed with impervious structures. It shows a culvert in the densely built-up Nine Mile Run watershed in Pittsburgh discharging water during a rainstorm. Before the storm these surfaces, like those in any built-up area, had been accumulating pollutants deposited from the atmosphere, dripped from vehicles, leached from metal gutters, and defecated by animals. When the first rain fell, the watershed's impervious pavements and roofs turned essentially all of the pollutants into surface runoff that flushed the pollutants into the stream. As the rain continued, even though the culvert was big enough to walk through, it flowed nearly full. Growing volumes of runoff eroded stream banks, destroying habitats and producing further sediment pollution. Bed materials shifted; banks sloughed in; biota were flushed out of the chute-like channel. In Pittsburgh and other old cities the floods got into sanitary sewers, adding overflows of raw sewage to the stream flow.

FIGURE 1.6 Discharge during a storm from the main Nine Mile Run culvert in Pittsburgh, Pennsylvania (photo courtesy of STUDIO for Creative Inquiry, Carnegie-Mellon University).

FIGURE 1.7 Discharge from the Nine Mile Run culvert after rainfall has stopped (photo courtesy of STUDIO for Creative Inquiry, Carnegie-Mellon University).

Figure 1.7 shows the discharge from the same culvert when the rain stopped. Little flow remained in the stream because there was no water left in the watershed: it was all flushed out during the storm. Groundwater levels were low. Fish were gasping for oxygen in the shallow, warm, sluggish water. Some cities were left with local water shortages.

Impervious pavements and roofs such as those in the Nine Mile Run watershed are collection pans that propel runoff and pollutants into streams without conservation or treatment. The large area that pavements cover, and the automobiles that use them, make impervious pavements the most significant generators of urban runoff and pollutants (Arnold and Gibbons, 1996). The water that dense pavements spoil and discard would, if it were conserved, be capable of supporting the future population growth of millions of people (Otto et al., 2002).

Too often the response has been to construct detention basins like the one shown in Figure 1.8, which illustrates the culvert bringing pulses of surface runoff from the

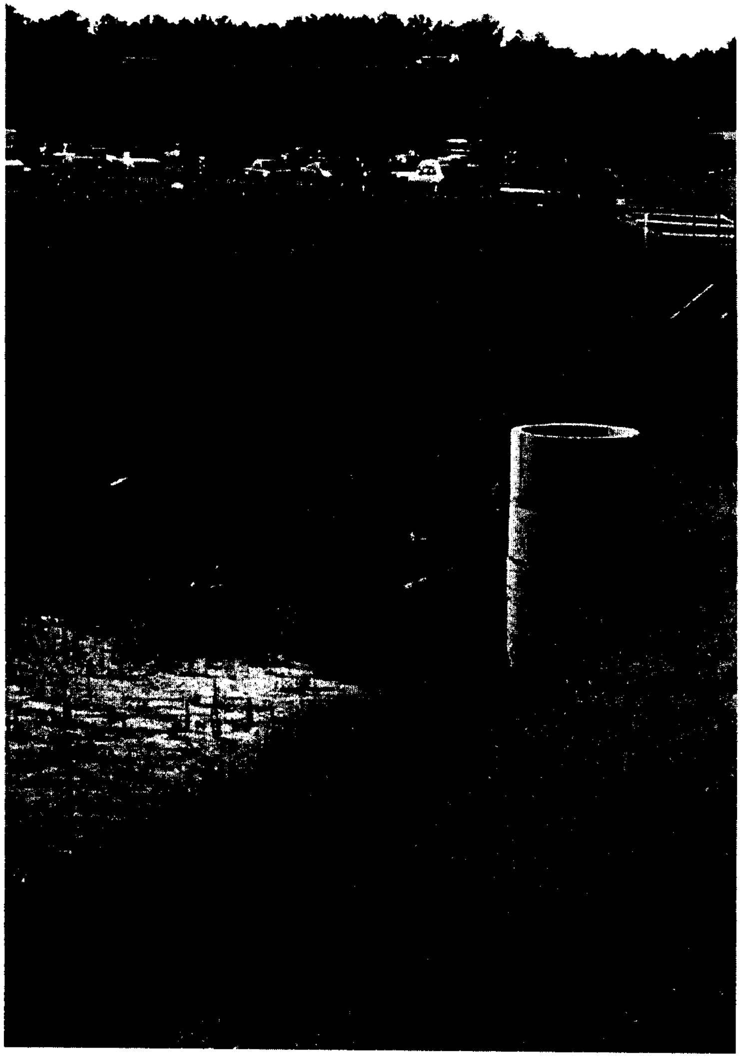

FIGURE 1.8 Detention basin in the corner of a commercial site.

shopping center's impervious roofs and pavements into a reservoir. The basin stores the runoff briefly so that it discharges slower and slightly later than it would otherwise. All single-purpose stormwater basins like this one cost money to construct. The land dedicated to them is lost to the local economy and the life of urban residents. Detention basins have failed to prevent downstream flooding and erosion, and have never done anything for water quality, ground water replenishment, or urban water supplies (Ferguson, 1998, p. 164). Paradoxically, we have specified impermeable pavements that flush away runoff, then paid for detention basins to counteract the pavements' runoff and pollution, and then paid again to import water supplies to replace the naturally occurring rainwater we have spoiled and thrown away.

Figure 1.9 shows how porous pavements can protect urban watersheds and aquifers before off-pavement stormwater basins are necessary. Some water has been poured on the surface of a porous concrete parking lot. The circular stain indicates that the water has gone down through the pavement's pores, and not across the surface. A porous pavement infiltrates and treats rainwater where it falls. Its pore space stores water like a detention basin. Almost every porous pavement reduces runoff and restores infiltration during small, frequent, numerous storms; some reduce runoff also during rare large storms when downstream flooding would be a severe concern. Infiltrating water recharges aquifers and sustains stream base flow. The pores house a microecosystem that filters and biodegrades the pollutants that occurs generically on residential, commercial, and office pavements; the underlying soil ecosystem is a backup treatment system that assures high treatment levels. Spreading out stormwater infiltration and treatment systems over a development site with porous pavements makes full use of the land's ability to infiltrate, treat, and store subsurface water. Porous pavements cure the diseases of urban watersheds and aquifers at the source, reducing or eliminating symptoms to be treated downstream.

Figure 1.10 contrasts the hydrologic effects of porous and dense pavements. In newly developing areas porous pavements protect the pristine resources of watersheds and aquifers. In old cities, renovating old pavements with porous paving materials compensates for the inadequacy of old combined sewer systems. Wherever paving must be done, porous pavement materials bring rainwater back into contact with the underlying soil. By controlling the fate of precipitation where it falls, they unify stormwater management and the fulfillment of practical urban needs efficiently in single structures.

THE PROMISE OF LONG-LIVED TREES

In the U.S., over half a million trees are planted every year in densely built-up urban settings (Arnold, 1993, p. 121). The scene in Figure 1.11 exemplifies the problem that trees present where they are surrounded by impervious pavements. Trees that could live for 100 years or more, when planted in narrow pits surrounded by dense pavement, are found to be dead or dying only seven years after planting (Moll, 1989). Almost all are diminutive in size for trees of their age (Grabosky and Gilman, 2004; Quigley 2004). In the background of the figure are trees planted at the same time outside the pavement; they have grown into large, healthy trees while those in the pavement have failed.

FIGURE 1.9 Infiltration into the surface of the porous concrete parking lot at the Florida Aquarium in Tampa, Florida.

Where an "urban forest" lives, it replaces carbon dioxide in the air with oxygen and improves air quality by removing sulfur dioxide, nitrogen dioxide, carbon monoxide, ozone, and particulate matter (American Forests, 1999; Nowak et al., 2002; Robinette, 1972; Urban, 2000). Trees cool the air by shading and transpiring; the cooling may further reduce the air pollution from parked vehicles in parking lots (Scott et al., 1999; Greg McPherson, personal communication, 2003). Trees reduce glare, and attenuate noise. They house natural birds and insects. To a city they add color and gentle movement, and symbolize the presence of nature. Their arrangements frame vistas, screen objectionable views, and define spatial units in "outdoor architecture" (Arnold, 1993). They enhance worker productivity, reduce stress, attract

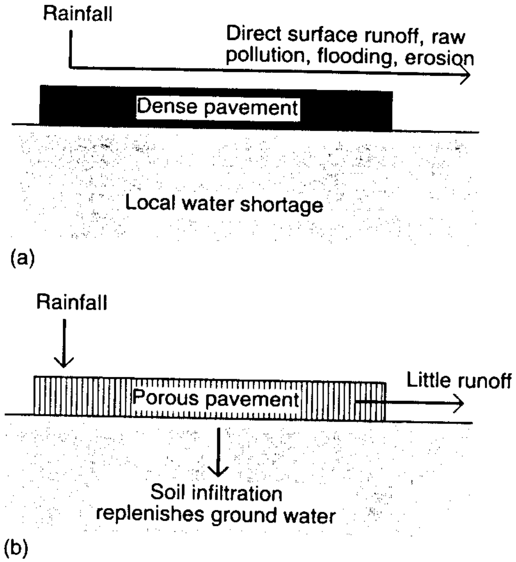

FIGURE 1.10 Contrasting hydrologic effects of dense (impervious) and fully permeable porous pavements.

customers to commercial districts, and add economic value to property (Wolf, 2003). The benefits for which trees are planted are fully achieved only when trees grow to full size and live long lives. American Forests' *City Green* software evaluates the effects of tree cover in individual urban developments and districts. Updates on the environmental effects of urban trees are available from the U.S. Department of Agriculture's Center for Urban Forest Research (http://cufr.ucdavis.edu).

Tree survival and growth require a large rooting zone with free exchange of air, water, and nutrients. The zone is ordinarily within 24 to 36 inches of the surface. Tree roots grow by tentatively exploring in all directions with numerous slender absorbing roots and extending in the directions where they find oxygen and moisture most abundant (MacDonald et al., 1993).

Tree-planting pits only a few feet wide surrounded by impervious pavements and compacted soil provide too little volume of aerated, penetrable soil for roots to grow as trees require. Roots that do penetrate beyond the pit into the soil below an impervious pavement quickly exhaust the soil's air because there is no exchange with the atmosphere; in anoxic conditions the roots fail to function and die. As a tree's root system fills the pit's rooting space to capacity, the growth of the crown slows and the tree becomes small in stature for its age. But as the crown continues to grow slowly, it becomes large in proportion to the confined root system that supplies water to it. With a small rooting volume supplying water to the leaves and branches, the tree becomes drought-stressed and increasingly susceptible to disease and insect infestations. Confined root space ultimately limits the size and lifetime of the tree (Watson and Himelick, 1997, pp. 10, 43–44).

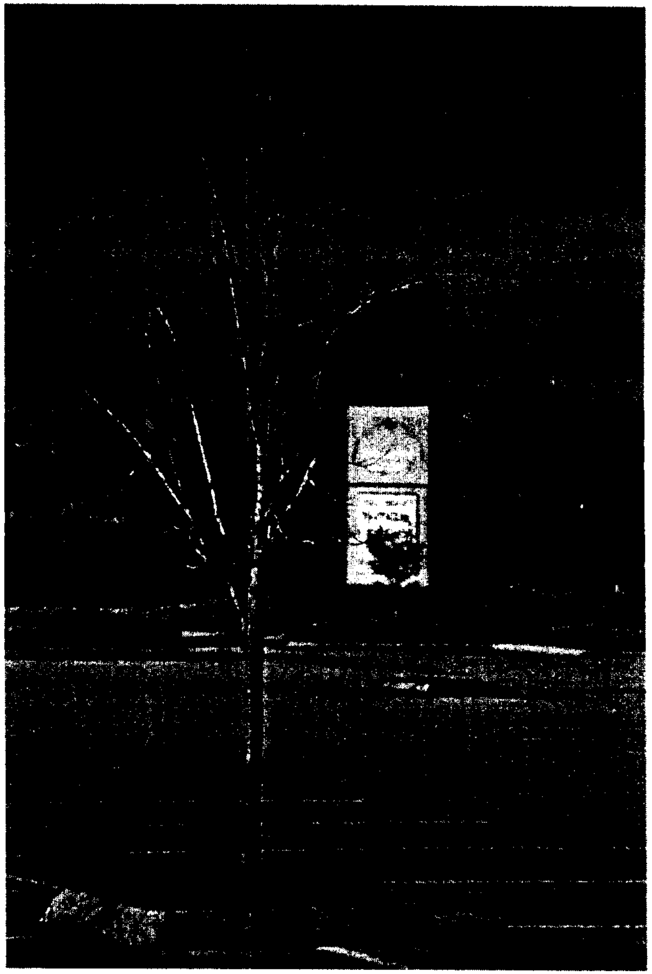

FIGURE 1.11 Dwarfed, declining, and dead sugar maples planted in a densely paved parking lot, seven years after planting.

For a tree in a root space that is only marginally constricted, frequent watering may for a time compensate for the soil's small native moisture reservoir (Watson and Himelick, 1997, pp. 12). Selection of tree species relatively adapted to constricted and compacted soil can further assist tree health and longevity within the ultimate constraint of rooting space. References such as those of Arnold (1993), Dirr (1998), Hightshoe (1988), Trowbridge and Bassuk (2004), Wyman (1965), Watson and Himelick (1997, p. 19–26), and Zion (1968) evaluate numerous tree species for tolerance to conditions such as these, as well as for the heat and air pollution that are likely to be present in urban districts.

To aerate the soil, a layer of porous aggregate has sometimes been placed under a dense paved surface; if the aggregate is exposed to the air at intervals, then air might move laterally from the uncovered spots to areas under the pavement. Networks of perforated pipes are intended similarly to distribute air into the soil zone (Arnold, 1993, pp. 128–130). But these systems are crutches added to overcome the natural barrier of dense surface pavement.

A porous pavement is a complete and vital way to allow air and water into rooting media in densely built-up areas. It allows the exchange of air and moisture through the pavement surface similar to that in a healthy natural soil surface. The soil's moisture regime fluctuates like that in natural soils, with rapid wetting during rain or snowmelt, followed by evapotranspirative drying and re-aeration, while the continuous exchange of air with the atmosphere maintains high soil oxygen levels.

Under a porous pavement, it is possible today to construct load-bearing rooting media made of open-graded aggregate in which the networks of pore spaces are partly filled with soil for root growth and are partly open for the exchange of water and air (Watson and Himelick, 1997, p. 44). "Structural soils" like those that will be described in Chapter 5 combine stone aggregate for the structural support of load-bearing pavements and porous aerated soil for tree roots. Beneath a porous surface and a porous structural-soil base, the subgrade soil is an additional reservoir of potential rooting media. For all subsurface rooting media, porous pavement surfacing is essential for the continuous exchange of air and water.

Trees have thrived where they have been given viable rooting zones under porous pavement surfaces, growing to the full size for which they were intended. Figure 1.12 shows healthy trees rooted in a heavily used park called The Commons in the Metrotech Business Improvement District in downtown Brooklyn, New York. The surface pavement is porous aggregate through which air and water penetrate. Below the surface aggregate layer is a structural soil combining porous aggregate and soil. The structural soil extends under the entire paved surface, making a large rooting zone for the trees while supporting the load of thousands of pedestrians per day. Porous pavements transform the "urban wasteland" into a thriving habitat for people and trees together.

FIGURE 1.12 Large, healthy honey locust trees rooted in "structural soil" beneath a porous aggregate pavement in the Metrotech Business Improvement District in Brooklyn, New York, 14 years after installation.

THE PROMISE OF COOL CITIES

Built-up areas in the U.S. are typically 2 to 8°F higher than the surrounding countryside (Akbari et al., 1992, p. 16). Figure 1.13 shows an example at Woodfield Mall, a shopping center in Schaumburg, Illinois, on a cold, clear, windless evening in 1972 (Norwine, 1973). The large multistory building is surrounded by a dense asphalt parking lot big enough to hold 10,000 cars. In 1972 the mall was newly built; the area around the mall was still mostly farmland, only beginning its transition to a suburban commercial district. The contours of temperature show that the built-up area is 2 to 4°F warmer than the unpaved surroundings. The maximum temperature is near the center where both the pavement and the building contribute to the temperature effect. The effect is called the urban "heat-island" because on a map like that of Woodfield Mall, the built-up area appears as an island of warmth; on larger maps entire cities appear as islands in a sea of cooler rural temperatures.

The heat-island effect is greatest in the late afternoon and evening, and particularly in clear, calm weather. Over 90 percent of the increase in temperature is due to urban construction materials that absorb and store solar heat without evapotranspirative cooling; only the remaining 1 to 10 percent comes from the active emissions of vehicles, buildings, and factories (Rosenfeld et al., 1997). A solid structure

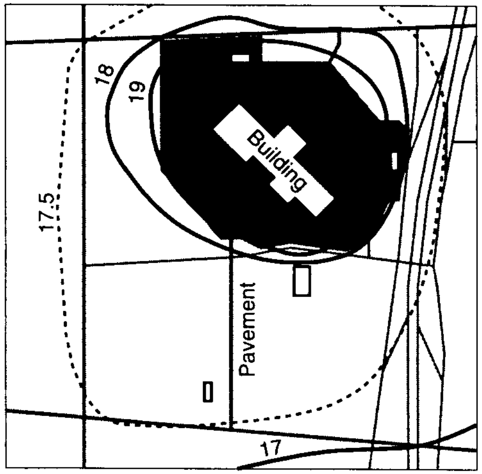

FIGURE 1.13 Contour map of temperature (°F) in the area of Woodfield Mall, Schaumburg, Illinois, on the evening of March 9, 1972 (after Norwine, 1973).

absorbs solar heat and conducts it into the depth of the material, making the structure into a thermal "storage battery." Late in the day, when the sun's heat is not so intense, solid construction materials re-emit their stored heat to the air, raising the urban air temperature even after the sun has set (Asaeda et al., 1996). Pavements contribute at least as much as buildings to heat-island formation because pavements have high thermal inertia at the ground surface (Goward, 1981).

Excess heat has a combination of advantages and disadvantages for cities. In many cities in temperate parts of the U.S., the heat island reduces the demand for winter heating by about 8 percent, as indicated by the decrease in "heating degree days," a measure of the climatic requirement for heating (Akbari et al., 1992, pp. 16–17; Landsberg, 1981, pp. 119–121). In cities with winter temperatures that hover near freezing, warmer temperatures reduce the frequency of snowfall and the necessity of snow removal.

However, in the same cities during the summer, the heat-island increases the climatic demand for air conditioning by about 12 percent (Landsberg, 1981, p. 120). The greater energy consumption needed in cities for cooling than for heating is magnified by air-conditioning technology, which requires more energy to produce a given amount of cooling than to produce an equivalent amount of heating. Three to eight percent of today's urban electric demand is used to compensate for the heat-island effect alone. Americans spend about one billion dollars per year for that extra energy (Akbari et al., 1992, p. 16). With more energy being used, power-plant generators run faster, polluting the atmosphere with increased carbon dioxide emissions.

Higher urban temperature aggravates air pollution in the city itself. Heat accelerates chemical reactions in the atmosphere that transform emissions from cars and smokestacks into ozone, an irritating gas that is the main ingredient of smog. For a 5°F increase in temperature, the number of ozone-polluted days increases by 10 percent (Akbari et al., 1992, p. 21; Rosenfeld et al., 1997).

City heat also produces a kind of water pollution. The runoff that drains off hot urban surfaces is correspondingly warm, raising the temperatures of nearby streams compared with those where the water has passed through cool porous soil. Figure 1.14 shows this effect in watersheds in Maryland. As stream temperature rises, the water's capacity to hold dissolved oxygen to support aquatic life declines.

For people outdoors, excessively high urban temperatures are associated with decreased comfort and are implicated in heat-related health problems including some deaths of persons with heart conditions (Huang, 1996; Landsberg, 1969, pp. 59–60).

The heat-island effect has a subtle influence on rainfall that could be considered either an advantage or a disadvantage. During summer thunderstorm conditions, city heat enhances convective rainfall downwind of city centers. Seasonal rainfall increases of 9 to 17 percent are possible (Changnon and Westcott, 2002; Changnon et al., 1991; Huff and Changnon, 1973; Landsberg, 1970).

Limiting the amount of pavement to serve a given unit of urban development would limit the opportunity for the heat-island effect to occur. Choices in patterns of development that influence the amount of pavement were discussed earlier in this chapter. Consideration of the heat-island effect complicates the choice of development pattern because a dense conurbation with canyon-like complexes of buildings and streets tends to absorb and store more solar energy than does an isolated complex like Woodfield Mall as it existed in 1972 (Goward, 1981).

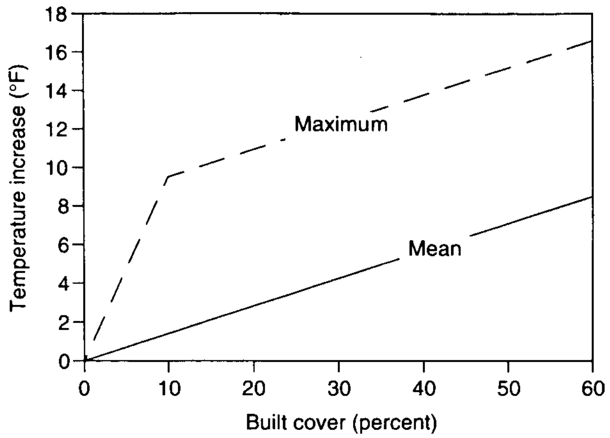

FIGURE 1.14 Increase in urban stream temperature over background temperature of rural streams, in the Maryland Piedmont (after Schueler, 1994).

For a given amount of construction, the use of light-colored construction materials may reduce the buildup of urban heat (Rosenfeld et al., 1997). Light-colored materials such as concrete absorb less solar heat than do dark-colored materials such as asphalt.

Shading by canopy trees is a powerful and certain way to limit the heat-island effect (Akbari et al., 1992, p. 21). Tree canopies intercept solar heat before it enters any "storage battery" on the ground and actively cool themselves with evapotranspiration. As described earlier in this chapter, in densely built-up places porous pavements are a prerequisite for the growing of large, long-lived shade trees for this purpose.

Porous "grass pavements" actively cool the ground surface with their natural evapotranspiration. This was demonstrated in Japan, where Asaeda and Ca (2000) monitored the surface temperature of grass on a warm sunny day in August. At noon, the grass surface was 18°F cooler than a nearby dense asphalt surface; at 6:00 pm it was still 14° cooler; at midnight it was 9° cooler. The grass was cooler even at depths of several feet below the surface. Porous pavements with grass components — whether grass alone or grass reinforced by geocells or concrete grids — are eligible for selective use in areas with infrequent traffic. The eligible areas are small and scattered, but together all the fragments can add up to a significant portion of an urban district. In some areas the maintenance of living grass would be inhibited by a requirement of water for irrigation.

In Asaeda and Ca's study, the 42 percent porosity of the soil in which the grass was growing may have added a small insulating effect, suppressing the material's storage battery effect. However, the cooling effect of the grass was due mostly or entirely to evapotranspiration of water; in the same study, a nonliving porous pavement material did not have the same cooling effect. The researchers simultaneously monitored a concrete block's surface with 30 percent porosity, and found its surface temperature to be essentially identical to that of dense asphalt all day long.

The thermal similarity of porous concrete and dense asphalt was a surprising result of the Japanese study because of the concrete's light color and high porosity.

Porous materials have less thermal conductivity and thermal capacity than corresponding dense materials (ASHRAE, 1993, pp. 22.6–22.9; Malhotra, 1976, p. Table 13; CRC Press, 2000, pp. 12–204; Geiger, 1965, pp. 29, 145–146; Livet, 1994, cited in Huber, 2000, p. 24), so they ought to conduct daytime heat downward and hold it in an internal storage battery less effectively than dense materials. Perhaps on the clear sunny day of the Japanese study, when radiation was the dominant means of heat transfer, the dark-colored asphalt was able to radiate its accumulated heat outward at a rate proportional to its absorption of incoming solar radiation, ending up with the same net temperature as that of the concrete. In these conditions the insulating effect of porous concrete's air-filled pores might have had no significance. Or perhaps the advection (movement of air) through the pores of a porous material counteracts its low thermal conductivity and capacity: in one day a sandy soil can "breathe" through its surface a volume of air equal to a column 70 feet high, transferring heat between surface and subsurface (Geiger, 1965, p. 27).

Slightly different results were observed in Ontario (James and Thompson, 1996), where during clear days the surface of a porous pavement of open-jointed concrete blocks with aggregate joint fill was cooler than that of a nearby dense asphalt pavement, and at night it was warmer; on average the temperature was the same. The researchers attributed the difference in temperature between the materials to the difference in color (albedo). Daytime rain cooled the dense asphalt surface markedly, but had little influence on the porous concrete–aggregate surface.

Research comparing corresponding porous and nonporous pavement materials, for example, porous concrete and dense concrete, is called for. Research to confirm the Japanese result and extend it into other types of weather conditions is needed. Table 1.2 lists examples of web sites where information on urban heat islands may be updated in the future.

THE PROMISE OF QUIET STREETS

Traffic noise is objectionable where residential areas adjoin highways and busy streets. Most people consider traffic noise problematic within 100 or 200 feet of moderately traveled roads and 500 feet of heavily trafficked freeways (United States Federal Highway Administration, 1980). The noise of a moving vehicle originates in the engine exhaust, the flexing of rolling tires, the rumbling of tires that pass over a rough pavement surface, and the splashing of tires on a wet surface. Engine exhaust noise is reduced by vehicular provisions such as mufflers; the other noise factors depend at least partly on the pavement.

TABLE 1.2

Agencies That May Update Information on Urban Heat Islands

Agency	Contact Information
National Aeronautics and Space Administration	http://science.msfc.nasa.gov/; at that address use the "Search" command to find "heat island"
Lawrence Berkeley Laboratory	http://Eetd.LBL.gov/HeatIsland/

The bel (B) is a unit for expressing the intensity of sound energy (Webster, 2000). In application the units are recorded in decibels (dB); one decibel is one tenth of a bel. A decibel compares the intensity of a sound to that of a reference sound on a logarithmic scale (Truax, 1999). The internationally agreed-upon reference is the threshold of human hearing, which is assigned a value of 0 dB. One decibel is approximately equal to the smallest difference in sound energy detectable by the human ear. The scale extends to the loudest sound the human ear can tolerate without pain at about 120 to 140 dB.

To the human ear, the subjective impression of loudness is modified by a sound's frequency or "pitch" (Truax, 1999). The ear perceives a sound with high pitch as having greater loudness than a sound of objectively similar intensity but lower pitch. For a measure that simulates the overall impression of loudness perceived by the ear, the objective sound intensity (dB) is weighted according to frequency, and assigned the symbol dBA. Figure 1.15 shows examples of dBA for some common sounds.

Other scales of noise have been developed to take additional variables into account, such as the Traffic Noise Index developed in Britain, which takes into account both the peak noise levels and the general ambient noise level over a 24-hour period. Another is the Community Noise Equivalent Level, developed in California, which weights noises according to social factors such as time of day (on the assumption that evening noises are most annoying), season, type of residential area where the noise is heard, and previous community experience with similar noises.

One way to reduce the traffic noise that reaches sensitive communities is the construction of noise barriers in the form of earth mounds or masonry walls. Properly constructed barriers can reduce noise by 10 to 15 dB. Because the decibel scale is logarithmic, a reduction of 10 dB amounts to cutting the loudness in half

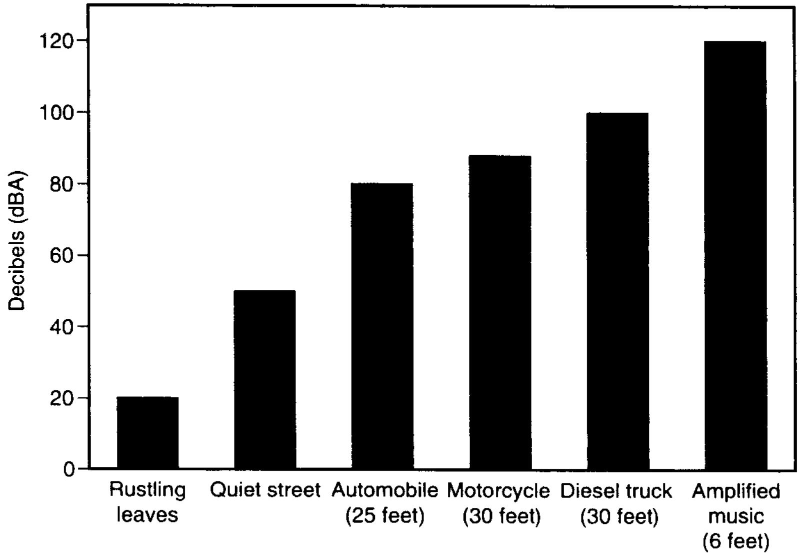

FIGURE 1.15 Typical average noise levels for some common sounds (data from Truax, 1999).

(United States Federal Highway Administration, 1980). However, walls and mounds require space and funds for construction and are appropriate and feasible only along certain stretches of freeways.

Porous pavements reduce traffic noise at the source, particularly the noise from tires. A porous surface both absorbs sound energy and allows some of the air around tires to be pressed into the voids, dissipating air pressure before any noise is generated. Noise reduction is particularly effective for high-frequency (high-pitched) sounds which are perceived relatively loudly. This means that the tire noise from a porous pavement is both lower in loudness and lower in pitch than that from a corresponding dense pavement. Recently installed porous asphalt reduces noise compared with dense asphalt by 3 dBA or more (Huber, 2000, pp. 6–7 and 9; Kuennen, 1996; Bendtsen and Larsen, 1999).

The intensity of traffic noise tends to rise in wet conditions because the tires force water noisily across the pavement surface (Shackel and Pearson, 1997). At these times porous pavements have an additional advantage over nonporous pavements because the surface of porous pavements is better drained in wet weather and any puddled water is squeezed through the pores as much as across the noisy surface.

THE PROMISE OF SAFE DRIVING

In wet weather, driving is difficult and dangerous where the pavement is slippery. The wheels separate from the pavement with hydroplaning, sheets of water obscure pavement markings, and moving vehicles throw up curtains of blinding mist.

Table 1.3 lists the types of street settings where pavement skid resistance is most important to safety, based on tests of skid resistance in places where accidents were reported in Britain. In the "most critical" category of sites are those urban streets where vehicles turn rapidly around sharp corners or need to stop suddenly as signals change and traffic backs up.

TABLE 1.3

Relative Importance of Skid Resistance to Driving Safety in Various Urban Settings

Category of Street	Examples
Most critical sites (pavement skid resistance is most critical)	Roundabouts (traffic circles)
	Streets with sharp bends (radius less than 500 feet)
	Steep gradients of greater than 5 percent, or longer than 300 feet
	Approaches to traffic signals
	Approaches to pedestrian crossings
Intermediate sites	Freeways and other roads designed for high speeds
	Urban streets with high traffic volume
	Other principal roads
Other sites (pavement skid resistance is of only ordinary importance)	Straight roads with low gradients
	Curves without intersections
	Streets with passenger-car traffic only

Sabey, 1968, cited in Croney and Croney, 1998, pp. 470–471 and 483.

The resistance of almost any pavement surface to skidding of vehicles comes mostly from the numerous small edges of aggregate particles in the pavement material (Croney and Croney, 1998, pp. 471–478). Both dense pavements and corresponding porous pavements possess that kind of friction when they are dry. However, in wet weather a film of water over a dense pavement's surface inhibits the firm contact of tires with the surface. A dense pavement can be particularly slippery in the first minutes of a rain event (Croney and Croney, 1998, pp. 474–475) because the lubricants that vehicles drop onto pavement surfaces in the days or weeks before the rain combine with water in a sheet of water and oil that simultaneously relaxes the tires' contact with the pavement and adds a layer of lubricant (the lubricants are the same petroleum products that show up as "first-flush" pollutants when surface runoff carries them into streams).

Porous pavements remove water and oil from the surface directly downward through their pores, preventing surface accumulation. The same pores are pressure-relief channels where any ponded water escapes from beneath vehicle tires, keeping the tires in contact with the surface (Diniz, 1980, p. 5). Figure 1.16 shows the resulting contrast in friction between porous and dense materials. When wet, the friction coefficient of dense asphalt collapses to only one fourth of its dry-weather value, while porous asphalt retains its dry-weather friction value.

In wet conditions porous pavements also improve driving visibility. With no layer of water over the pavement, vehicles do not kick up plumes of mist from their wheels. The pavement itself is more visible because of the absence of puddled water. At night, well-drained pavements produce little glare from vehicle lights.

For these reasons the state highway departments in Georgia, Oregon, and other states place porous asphalt overlays on their major highways. In wet weather the porous surfaces improve driving comfort and reduce accidents. In effect, by improving traffic flow, they increase the capacity of highways without the expense of widening the roads.

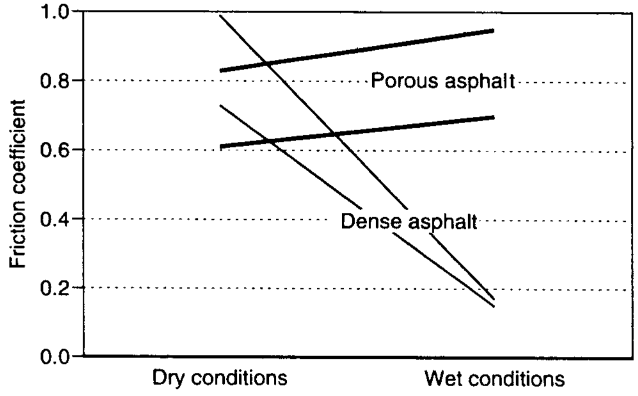

FIGURE 1.16 Friction coefficients of pavement surface materials (data from Diniz, 1980, p. 27).

THE PROMISE OF REDUCING COST

The selection of porous pavements in place of dense ones has directly reduced construction costs in some developments. In most regions of North America, porous aggregate used alone without binding or reinforcement is the least expensive of all paving materials, including conventional dense asphalt. Although the low-traffic places where aggregate can be used are individually small and isolated, they occur in pockets throughout urban districts, and together represent a large area of pavement. Where aggregate is used in place of other paving materials, the construction cost per square yard of pavement is immediately reduced.

Where other porous materials are used, they are more expensive, but they are still capable of reducing construction cost because they perform necessary stormwater functions that would otherwise have to be accomplished by additional pipes and reservoirs. Because porous pavements absorb, store, and treat water within the pavement structure, they reduce or eliminate the need for drainage inlets, storm drainage pipes, and stormwater detention areas. A porous pavement with little or no drainage structures is commonly less expensive than a dense pavement with the large drainage and treatment systems it requires.

Even more expensive porous paving materials can reduce the total development cost by avoiding the larger cost of land acquisition for off-pavement stormwater management facilities. Figure 1.17 shows an example where a shopping center's porous asphalt parking lot protects stream water quality. The stream is visible just beyond the curb in the background; the shopping center had no additional land for single-purpose stormwater facilities. The porous asphalt absorbs rainwater and biodegrades automotive pollutants within the pavement structure; only rarely does excess stormwater overflow through the surface grate. In valuable, densely developed locations like this, the selection of porous pavement makes sustainable development economically feasible.

FIGURE 1.17 Porous asphalt parking lot protecting stream water quality at Exton Square Mall in Exton, Pennsylvania.

Porous pavements have also helped reduce the long-term costs of taxes and fees required from urban properties. Many municipal stormwater "utilities" and stormwater management departments impose taxes or fees based on impervious coverage (http://stormwaterfinance.urbancenter.iupui.edu). Converting pavements to porous, pervious materials reduces the basis for the tax or fee. Some other agencies reduce the fees for properties where runoff controls such as porous pavements are installed.

THE PROMISE OF MEETING DEVELOPMENT REGULATIONS

Municipal jurisdictions impose requirements on new developments for their effects on stormwater, tree preservation, and impervious coverage, all of which can be partly or wholly satisfied by the selective and appropriate use of porous pavements. Where developers do not perceive a direct interest for themselves in the effects of porous pavements, they still have a vital interest in obtaining permission to build. Information on methods of development regulation is available from the American Planning Association (www.planning.org).

Governments regulate stormwater quality and quantity during small "first-flush" storms and large flood-hazard storms. A New York State law specifies soil infiltration as the preferred approach to stormwater control and "pervious surfaces" as one of the specific techniques that would fulfill the infiltration goal. The town of Hilton Head Island, South Carolina, requires that 1 inch of runoff from all impervious surfaces be dissipated by percolation into the soil, and expects routinely that part of that requirement will be met by porous pavements. In Washington State, the Puget Sound Water Quality Management Plan aims for developments to make no net detrimental change in natural surface runoff and infiltration and requires municipalities to adopt stormwater ordinances that make infiltration "the first consideration in stormwater management." Porous pavements assist in meeting these regulations by reducing and detaining runoff, increasing infiltration, and treating water quality.

Some municipalities require preservation of trees over a certain size or planting of a certain quantity of new trees as part of new developments. In Savannah, Georgia, this type of requirement has been a major motivation for constructing porous pavements of blocks, grids, geocells, and porous concrete. Figure 1.18 shows a grid pavement at a Savannah restaurant, satisfying the city's requirement for tree preservation while letting commercial activities move forward.

Some jurisdictions directly limit impervious cover to protect water quality and the environment in general. Figure 1.19 shows a plastic geocell grid being installed in a parking lot at a fraternity in Athens, Georgia. The geocell is to reinforce porous aggregate which will be placed in the grid's cells. When the fraternity moved into its new building, a local ordinance required it either to reduce its impervious cover or to control the excess runoff from impervious surfaces. There was no room for stormwater control basins on this small in-town lot. So the fraternity made its parking lot pervious by surfacing it with geocell-reinforced aggregate. This provision

FIGURE 1.18 Open-celled concrete grids filled with porous aggregate preserving live-oak tree roots at a restaurant in Savannah, Georgia.

satisfied the city's requirements and permitted the new use to go forward, while providing the number of parking spaces required for the property's new use.

THE PROMISE OF PRESERVING NATIVE ECOSYSTEMS

Figure 1.20 shows a boardwalk crossing a fragile marsh ecosystem. A boardwalk is a porous surrogate for a pavement. It is supported by footings that touch the soil only at discrete points or lines. Because the decking surface is isolated from the ground, it preserves the dispersed flows of surface and subsurface waters. Water percolates through the decking without concentration and infiltrates native soil below. The continuous flows of water and sediment build ecological equilibrium, rebuild it with changing circumstances, and maintain reservoirs of soil, water, and propagules. During the construction of a deck the only necessary disturbance of soil and roots is that for the discrete footings. A finished deck floats suspended through a functioning ecosystem.

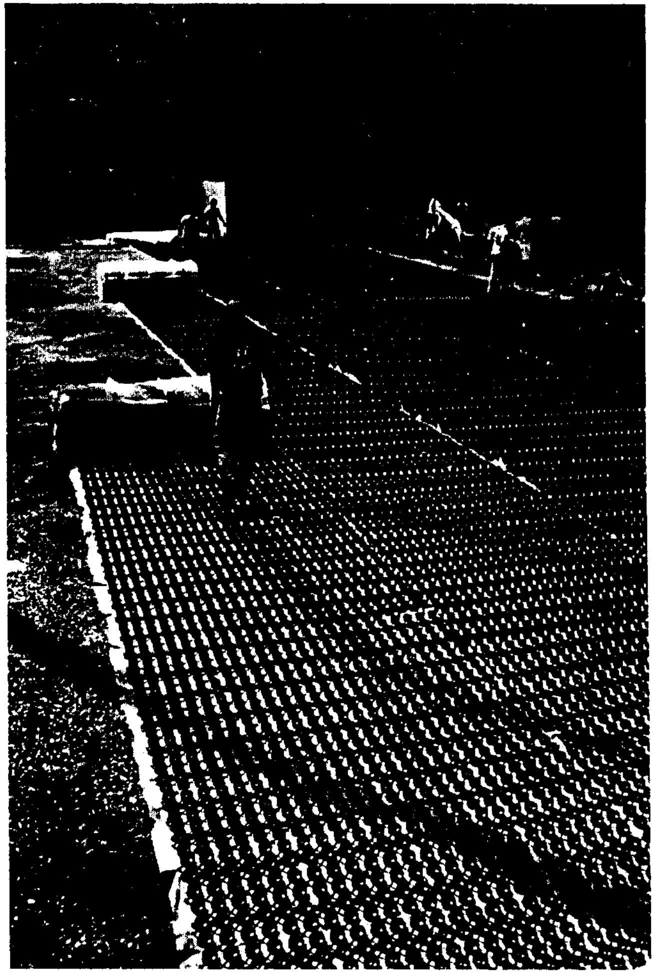

FIGURE 1.19 Plastic geocell being installed to reinforce a porous aggregate parking lot at an office building in Athens, Georgia.

Figure 1.21 shows a porous concrete road meandering through a pine-forest preserve. Rainwater that falls on the pavement infiltrates the underlying sandy soil as it did before the road was built. An on-the-ground porous pavement like this is one degree more intrusive on an ecosystem than a boardwalk, but in return it carries the weight of cars. For the road in the picture there are no curbs, no gutters, no drainage inlets, not even any drainage swales: all drainage is immediately downward through the pavement to the soil, wherever the rain falls, as it is through the adjacent forest

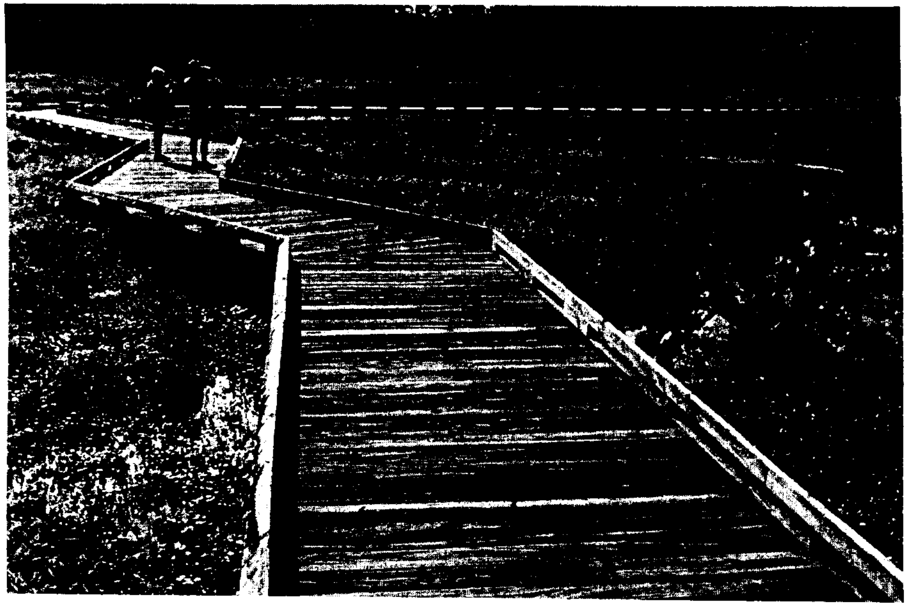

FIGURE 1.20 Boardwalk over wetland preserve at Huntley Meadows Park near Alexandria, Virginia.

floor. The trees have a continuous rooting medium with a natural regime of moisture and aeration. Far below, excess soil moisture replenishes a natural limestone aquifer whence it discharges as the base flow of streams and the habitat of the preserve's aquatic organisms.

THE PROMISE OF BEAUTY

The selection of pavement material sets the stage for the character of an urban place. Figures 1.22 and 1.23 illustrate pavements of porous grass that "soften" the character of the paved areas, making them "green" and consonant with residential communities and relaxed pedestrian activity.

Aesthetics integrates values in which symbolism and functional information are as important as neatness and attractiveness (Nassauer, 1995). Design is capable of revealing and integrating. It can embed the solution to environmental problems in land use, transportation, and the urban way of life. The characteristics of a place can make the processes through which hydrologic and ecological restoration take place visible and comprehensible. What a system looks like, how it functions ecologically and socially, and what it symbolizes in the way of stewardship can be congruent. One can lay hands on the details of construction materials to bring restorative processes to every inch of an inhabited place. Permeable materials are visibly distinctive with their open voids and, in some cases, their living vegetation. Wherever we go in cities, they can make us conscious of the careful return of water and air to the soil.

FIGURE 1.21 Porous concrete road amid native longleaf pine and wiregrass at Jones Ecological Research Center near Newton, Georgia.

Some observers believe that the American landscape is a battleground between opposing values: those embodied by the machine (control, architecture, technology, human dominance) and those represented by wild nature (Marx, 1964). Urban pavements are a locus in the struggle to resolve this opposition of values: wherever land is paved, technological materials displace vegetated soil to exert force and impose character on urban environments. One type of resolution of this conflict is the pastoral landscape (Marx, 1964), in which machine-like urban features are dispersed through nature in a park-like, garden-like "middle landscape." This compromise, which avoids the excesses of both sides, has been criticized as losing the full and best aspects of both (MacElroy and Winterbottom, 1997): dispersed, fragmented, garden-like landscapes are neither intensely used by people, nor rioting in natural regeneration.

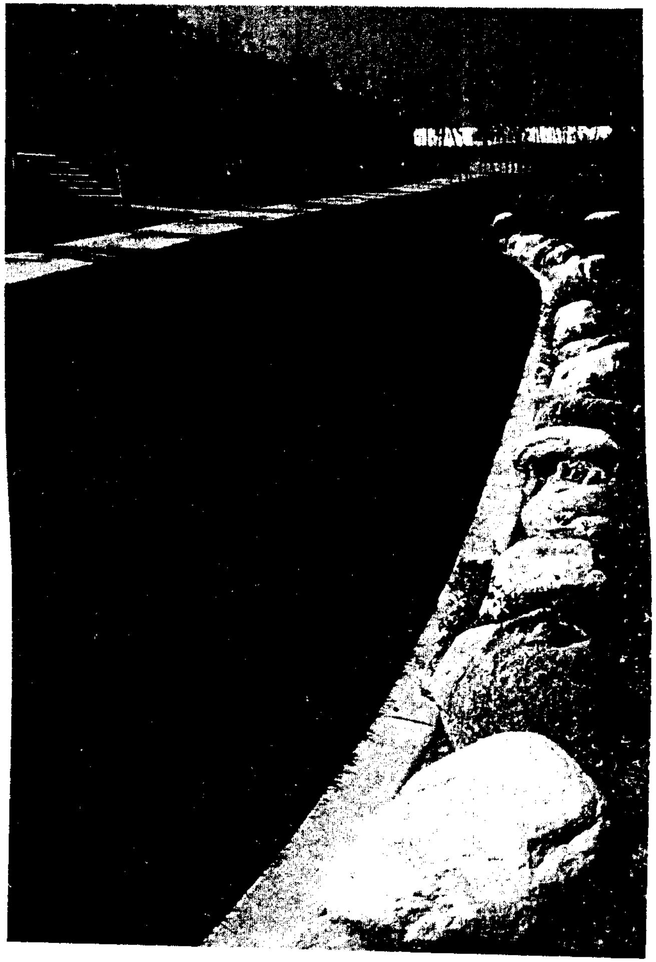

FIGURE 1.22 Emergency access lane of grass reinforced by concrete grids at the Saddleback Church in Lake Forest, California.

Hough (1995) proposed another type of resolution: "living machines" that represent symbioses between technology and natural process. "Grass pavements" and all other porous pavements are examples of living machines. They are functional components of cities that support the natural processes of the environments they change; they merge environmental process with urban infrastructure. Percolation through pavements every time rain falls makes the natural process visible to the people who live and work in cities. As porous pavements restore natural functions, they also restore the perceptual connection between environment and society. Unlike stormwater detention basins and treatment wetlands which are added to development sites without changing the developments themselves, porous pavements are under people's feet all the time. Porous pavements make no distinction between the quality of the environment and the quality of the human life. They give everyone who uses them a role in restorative environmental processes.

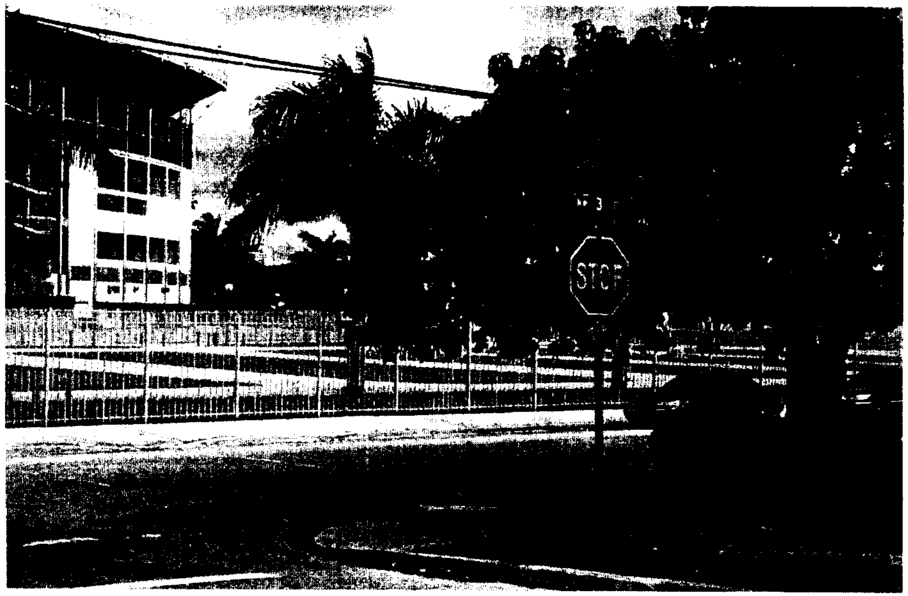

FIGURE 1.23 Parking of grass reinforced by plastic geocells at the Orange Bowl Stadium in Miami, Florida, as seen from an adjacent residential street.

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REFERENCES

Akbari, Hashem, Susan Davis, Sofia Dorsano, Joe Huang, and Steven Winnett, Eds. (1992). *Cooling Our Communities, A Guidebook on Tree Planting and Light Colored Surfacing*, Washington: U.S. Environmental Protection Agency.

Nassauer, Joan Iverson (1995). Messy Ecosystems, Orderly Frames, *Landscape Journal* 14, 161–170.

Norwine, James R. (1973). Heat Island Properties of an Enclosed Multi-Level Suburban Shopping Center, *Bulletin of the American Meteorological Society* 54, 637–641.

Nowak, David J., Jack C. Stevens, Susan M. Sisinni, and Christopher J. Luley (2002). Effects of Urban Tree Management and Species Selection on Atmospheric Carbon Dioxide, *Journal of Arboriculture* 28, 113–120.

Otto, Betsy, Katherine Ransel, Jason Todd, Deron Lovaas, Hannah Stutzman, and John Bailey (2002). *Paving Our Way to Water Shortages: How Sprawl Aggravates Drought*, Washington: American Rivers, Natural Resources Defense Council, and Smart Growth America; downloadable from www.americanrivers.org.

Quigley, Martin F. (2004). Street Trees and Conspecifics: Will Long-Live Trees Reach Full Size in Urban Conditions? *Urban Ecosystems* 7, 29–39.

Richman, Tom and Associates (1997). *Start at the Source, Residential Site Planning and Design Guidance Manual for Stormwater Quality Protection*, Oakland, CA: Bay Area Stormwater Management Agencies Association.

Robinette, Gary O. (1972). *Plants, People, and Environmental Quality*, Washington: U.S. National Park Service.

Rosenfeld, A.H., H. Akbari, J.J. Romm, and M. Pomerantz (1998). Cool Communities: Strategies for Heat Island Mitigation and Smog Reduction, *Energy and Buildings* 28, 51–62.

Rosenfeld, Arthur H., Joseph J. Romm, Hasem Akbari, and Alan C. Lloyd (1997). Painting the Town White — and Green, *Technology Review* 100, 52–59.

Sabey, B.E. (1968). The Road Surface and Safety of Vehicles, in *Symposium on Vehicle and Road Design for Safety*, Cranfield 3–4 July 1968, London: Institution of Mechanical Engineers.

Schueler, T. (1994). The importance of imperviousness, *Watershed Protection Techniques* 1, 100–111.

Scott, Klaus I., James R. Simpson, and E. Gregory McPherson (1999). Effects of Tree Cover on Parking Lot Microclimate and Vehicle Emissions, *Journal of Arboriculture* 25, 129–142.

Shackel, Brian, and Alan R. Pearson (1997). Concrete Segmental Pavements, *Constructional Review*, Vol. 70 February 42–47.

Stankowski, Stephen J. (1972). *Population Density as an Indirect Indicator of Urban and Suburban Land-Surface Modification*, Professional Paper 800-B, pp. B219–B224, Washington: U.S. Geological Survey.

Thayer, Robert L. (1994). *Gray World, Green Heart: Technology, Nature, and the Sustainable Landscape*, New York: John Wiley and Sons.

Trowbridge, Peter J. and Nina L. Bassuk (2004). *Trees in the Urban Landscape: Site Assessment, Design, and Installation*, New York: John Wiley and Sons.

Truax, Barry, Ed. (1999). *Handbook for Acoustic Ecology*, 2nd ed., Cambridge Street Publishing (www.sfu.ca/sonic-studio/index.html).

United States Census Bureau (no date). *Statistical Abstract of the United States*, downloadable from www.census.gov/prod/www/statistical-abstract-us.html.

United States Federal Highway Administration (1980). *Highway Traffic Noise*, Washington: U.S. Federal Highway Administration.

University of Georgia School of Environmental Design (1997). *Land Development Provisions to Protect Georgia Water Quality*, Atlanta: Georgia Department of Natural Resources, Environmental Protection Division; downloadable from the *Technical Guidance — Water Quality Engineering & Design* page at www.dnr.state.ga.us/dnr/environ/.

Urban, James (1996). Room to Grow, *Landscape Architecture* 86, 74–79, 96–97.

Urban, James (2000). Environmental Effects of Trees, in *Architectural Graphic Standards*, 10th ed., p. 177, John Ray Hoke, editor in chief, New York: John Wiley and Sons.

Wagar, J. Alan and Albert L. Franklin (1994). Sidewalk Effects on Soil Moisture and Temperature, *Journal of Arboriculture* 20, 237–238.

Watson, Gary W. and E. B. Himelick (1997). *Principles and Practice of Planting Trees and Shrubs*, Savoy, IL: International Society of Arboriculture.

Webster Len F. (2000). *The Wiley Dictionary of Civil Engineering and Construction*, New York: John Wiley & Sons.

Wells, Cedar (1994). *Impervious Surface Reduction Study*, Olympia, Washington: City of Olympia Public Works Department.

Willson, Richard S. (1995). Suburban Parking Requirements and the Shaping of Suburbia, A Tacit Policy for Automobile Use and Sprawl, *Journal of the American Planning Association* 61, 29–42.

Wolf, Kathleen L. (2003). Public Response to the Urban Forest in Inner-City Business Districts, *Journal of Arboriculture* 29 (http://joa.isa-arbor.com).

Wyman, Donald (1965). *Trees for American Gardens*, revised and enlarged edition, New York: Macmillan.

Zion, Robert (1968). *Trees for Architecture and the Landscape*, New York: Reinhold.

Koerner, Robert M. (1998). *Designing with Geosynthetics*, 4th ed., Upper Saddle River, NJ: Prentice-Hall.

Mathis, Daniel M. (1989). Permeable Base Design and Construction, *Stone Review* August 1989, pp. 12–14.

Moulton, Lyle K. (1980). *Highway Subdrainage Design*, Report No. FHWA-TS-80-224, Washington: Federal Highway Administration.

Moulton, Lyle K. (1991). Aggregate for Drainage, Filtration, and Erosion Control, in *The Aggregate Handbook*, Richard D. Barksdale, Ed., Washington: National Stone Association, chap. 12.

Nichols, Frank P. (1991). Specifications, Standards, and Guidelines for Aggregate Base Course and Pavement Construction, in *The Aggregate Handbook*, Richard D. Barksdale, Ed., Washington: National Stone Association, chap. 15.

Palmer, Arthur E. (1981). *Toward Eden*, Winterville, NC: Creative Resource Systems.

Rabb, William (1999). Paved with Good Intentions, *Mobile Register*, March 7, 1999.

Rollings, Marian P. and Raymond S. Rollings, Jr. (1996). *Geotechnical Materials in Construction*, New York: McGraw-Hill.

Thompson, J. William (2001). Roots Over the River, *Landscape Architecture* 91, 62–69.

3 Porous Pavement Structure

CONTENTS

All pavements, porous and dense alike, must bear the traffic loads imposed on them in the soil and weather conditions where they are located. This chapter introduces important considerations in pavement structural design and the kinds of treatments

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