POROUS PAVEMENTS:
THE MAKING OF PROGRESS IN TECHNOLOGY AND DESIGN

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SUMMARY

Porous pavements are the fastest developing, most radical, and most controversial way of restoring urban environments. This paper describes the making of the 2005 book *Porous Pavements* (Ferguson, 2005), which is the first comprehensive overview of this technology and its applications.

The research is supported by 800 literature citations, 170 interviews with experts in the field, and the author's firsthand survey of 280 installations of all types of porous pavements in all parts of North America (about 40 of which were open-jointed block pavements). The resulting 577-page book defines and organizes the field for the first time. The making of the book has dispelled unfounded rumors and speculations that formerly inhibited this technology's implementation, and affirmed the necessity of scientific rigor in the development of design technologies.

The book defines nine families of porous paving material, each of which has distinctive costs, maintenance requirements, installation methods, sources of standard specifications, performance levels, and advantages and disadvantages for specific applications.

Where porous pavements are properly selected, designed, and installed, they can detain and reduce stormwater flows, biodegrade the oils from cars and trucks, give long-lived urban trees viable rooting space, make driving safer, and reduce development costs. Where any of these stages is neglected, failures — clogging and structural degradation — result.

The purposes of this paper are:

1) to describe the research process behind the document;

2) to review the range of competing porous paving materials, and the range of purposes for which they are being installed today;

3) to outline the advantages and disadvantages of open-jointed blocks for specific applications, in comparison with those of other materials;

4) to document selected case studies of open-jointed block installations in North America, to explain their successful and unsuccessful aspects, and to point out their lessons for future porous pavement selection, design, and construction.

1. INTRODUCTION

Porous pavements have been called “the holy grail of environmental site design” and “potentially the most important development in urban watersheds since the invention of the automobile.” They are the most radical, most controversial, and most rapidly developing way of restoring large parts of the urban environment.

Recently, an eight-year-long research project concluded with the publication of this technology’s first comprehensive overview (Ferguson, 2005). This paper describes the making of the book *Porous Pavements*, and the current types of applications of open-jointed blocks and other porous paving materials in North America.

2. PROJECT BACKGROUND

The subject was brought to the author in the mid-1990s by previous work in stormwater management, which had included a particular critique of downstream detention basins and a particular contribution to stormwater infiltration (Ferguson, 1998). Porous pavements seemed to be the next step: research had found validity in them (Day, 1978; Thelen et al., 1972); some practitioners were using them repeatedly (www.thcahill.com; www.andropogon.com); they could solve the stormwater problem at the source; and they had vast potential for doing good, because pavements are two-thirds of the potentially impervious surfaces in typical urban watersheds.

However, practitioners’ technical questions about porous pavements have been numerous and detailed. It is valid that their questions be asked, and vital that they be answered.

Therefore the purpose of the book project was to give practitioners what they need to use this technology. This included answering the technical questions up to the limit of scientific knowledge, demonstrating successful and unsuccessful installations in case studies, and making specifications accessible. In other words, the purpose was to define, organize, make accessible, and substantively evidence this potentially powerful new technology.

Completion of the project occupied eight years of research, including 170 interviews with experts in the field, reading 800 technical articles and reports, and a firsthand survey of 280 installations in the field of all kinds of porous pavements, in all parts of North America. Most of the surveyed installations were in the eastern United States, primarily because several kinds of porous pavements, including open-jointed blocks, came to North America first in the East, so the East has the longest history and largest accumulation of installations.

3. POROUS PAVING MATERIALS

Porous pavements are made of the same generic components as other pavements: surface course, base course, and subgrade. Each pavement layer is multi-functional, and can be given alternative materials and configurations by applying the same physical principles that apply to any other pavement design.

The book defines nine families of porous paving materials, each of which presents distinctive costs, installation methods, performance levels, maintenance requirements, and advantages and disadvantages for any specific application. For example:

- Porous aggregate is very inexpensive, and very permeable;
- Porous turf is living and dynamic;
- Open-jointed block is sturdy, attractive and reliable;
- Porous concrete depends for its quality on a qualified installer;
- Porous asphalt's technology is advancing, allowing it to avoid clogging problems which haunted it in the past.

It is vital to put the right material in the right place. No single type of pavement — porous or dense — should be smeared thoughtlessly everywhere. A development site should be analyzed in detail to distinguish pavement settings where different, optimally suited materials can be placed, including different traffic types and levels, and different needs for hydrology, appearance, tree rooting, and cost. The necessity of selecting alternative materials forces designers to pay more attention to pavements, as multi-functional design elements, than in the past.

4. OPEN-JOINTED BLOCKS

Open-jointed blocks are concrete units shaped to leave open spaces between the units; examples are Ecoloc and SF-Rima. Porous aggregate in the openings gives an open-jointed block pavement its porosity and permeability. Compared with most other porous paving materials, properly constructed block pavement is characteristically solid and stable, so it can bear almost any traffic including moving vehicles. The surface has relief at the joints, so it is distinctively useful for traffic calming, but is not always considered universally accessible. The surface looks geometric and crafted, so it is distinctively suited for urban and architectural settings.

Construction can follow established standards. The Interlocking Concrete Pavement Institute (www.icpi.org) provides a guideline specification for *Permeable Interlocking Concrete Pavement*, which acts as a checklist for specification format and content. ICPI's book *Permeable Interlocking Concrete Pavements* (Smith, 2001) provides narrative explanation of requirements implemented in the guideline specification.

Block pavement construction requires edge restraint such as a concrete band to hold the assembled blocks in place. The blocks sit on a bed of relatively small aggregate, often similar to that filling the joints between the blocks. A base course or "base reservoir" of larger aggregate supports the surface course, stores and transmits water, and in some cases provides tree rooting space.

Most block units are manufactured in controlled factory conditions to uniform standards. ASTM C936, *Standard Specifications for Solid Concrete Interlocking Paving Units*, specifies block materials, dimensional proportions, compressive strength, absorption of fluids, resistance to freezing and thawing, abrasion resistance, and dimensional tolerance. Blocks manufactured to this standard are enormously strong and durable.

Aggregate is the other pavement component. Unlike the block units, aggregate is a locally supplied material that is specified *ad hoc* for each project's base reservoir, setting bed, and joint fill. A crucial requirement of aggregate in porous pavement is that it be "open-graded" (single-sized). Open-graded aggregate has a narrow range of particle sizes, with little or no fines. Between the particles, open voids produce 30 to 40 percent porosity. Open-graded aggregate with particles large enough to leave wide voids gives permeability of over 25,000 mm per hour. Examples of standard open-graded gradations are ASTM Nos. 57, 8, and 10.

In the United States it is very convenient to specify aggregate by applying standard state department of transportation (DOT) specifications. Most DOTs have adopted standards for aggregates that are acceptable for road construction. Aggregate suppliers characteristically stock DOT-defined materials as standard products. Such materials are durable, non-plastic, and stable from angular interlock as long as crushed stone or other angular material is specified.

Subgrade compaction during construction greatly reduces soil infiltration rate, but is necessary for stability where the subgrade is plastic clay or fill, or the pavement base course will be too thin to compensate structurally for soft wet soil. Compaction might be omitted, and the native infiltration rate preserved, where the subgrade is native cut (and therefore has *in situ* compaction and stability), and adequate total pavement thickness will compensate for subgrade uncertainties. On plastic soil, a nonwoven geotextile over the subgrade prevents the soil from flowing into the base course's void spaces.

To protect a pavement's surface from sedimentary clogging, it should be laid out to prevent sediment from washing on, and to allow sediment to wash off. Surface drainage should be away from the pavement edge in every possible direction. On the downhill side, large, numerous curb cuts should be added if necessary. On the uphill side, a swale should be added if necessary to divert potentially sediment-laden runoff. These provisions limit most porous pavements to infiltrating the rain water that falls directly upon the pavement, and not stormwater runoff from surrounding earthen slopes.

5. ENVIRONMENTAL PERFORMANCE

Open-jointed block pavement commonly has 12 to 13 percent of its area in porous openings. In installations with clean open-graded aggregate, the infiltration rate of the composite block-aggregate surface is 5,000 to 100,000 mm per hour (Bean et al., 2004). Various researchers have monitored open-jointed block pavements' stormwater-management performance in Ontario, Washington State, North Carolina, England, and Germany.

Like other porous paving materials, open-jointed block pavement reduces stormwater rate and volume. Where rain water infiltrates through the pavement into the underlying soil, stormwater volume is reduced and natural subsurface flow paths are restored. Where slowly permeable soil prohibits significant soil infiltration, a porous pavement can perform detention comparable to that in off-pavement reservoirs and ponds. Where water is discharged through a perforated pipe at the bottom of the pavement, the outflow is later, slower, and smaller in volume than the rainfall entering from above.

Metals like cadmium and lead released by automobile corrosion and wear are captured in porous pavements' voids along with the minute sediment particles to which the ions are characteristically attached. Capturing the metals prevents them from washing downstream and accumulating inadvertently in the environment.

Also in the voids, naturally occurring micro-organisms digest oil leaked from automobiles. The constituents go off as carbon dioxide, water, and very little else. Essentially none of the oil makes it to the bottom of the pavement: it ceases to exist as a pollutant.

Porous pavements combine pavement function with stormwater management in a single structure. Developments planned to benefit from this combination tend to cost less than those having impervious pavements with separate stormwater management facilities that incur costs of land acquisition, excavation, piping, and outlet structures. Because porous pavements are inherently multi-functional, their selection and implementation are integral parts of the multi-faceted concerns of urban design, and all of their effects are considered together in evaluations of benefits and costs.

An installation for the purpose of stormwater management is the 2003 visitors' parking lot at the Morton Arboretum in Lisle, Illinois. On one side is a river and on another side a lake, motivating the selection of a porous pavement to protect water quality. The surface is of Ecoloc blocks on a bed of open-graded 5 to 10 mm aggregate. Different aggregate, about the same size, was selected for joint fill in order to match the block's reddish color; the surface infiltrates water rapidly. The base course is made of 12 to 25 mm aggregate. Beneath the base course is a subbase layer of 50 to 60 mm aggregate, up to one meter thick, installed to raise the parking lot up to grade after excavating out a layer of unbuildable plastic soil. The open-graded aggregate subbase fortuitously — but considerably — enlarged the pavement's hydraulic storage capacity. Thus the thick pavement structure has porous, permeable, open-graded aggregate from top to bottom, producing very large water storage capacity. Although the subgrade soil below the pavement was compacted, monitoring through a perforated pipe in the subbase has as yet shown no significant lateral discharge (Sikich and Kelsey, 2005). The parking lot's perimeter curbs have notches every 6 meters, to let any pavement overflow into vegetated swales. In the swales, drainage inlet rims are raised to force infiltration into the vegetated soil before discharge begins. The pavement's very large hydraulic capacity and its redundant layers of backup treatment make this parking lot, if anything, hydraulically overdesigned, and extremely successful in stormwater treatment.

An installation for stormwater management in different circumstances is at the Robson Center, an office building in Gainesville, Georgia. In 2003, the parking lot was built on heavy, compacted clay soil, where infiltration would be negligible. The turning lane was made of Rima blocks set on a bed of uniformly sized 5 to 10 mm aggregate; the joints were filled with more of the same permeable aggregate. The bottom of the base reservoir slopes to a perforated pipe at the center of the parking bay. Flows that exit through the pipe to the city's storm sewers are smaller, slower, and cleaner than the rainfall and automotive oil at the surface. Dense asphalt parking stalls drain gently to the permeable turning lane, making the whole parking lot act like a permeable pavement.

Porous pavements can also give urban trees the rooting space they need to grow to full size, providing the shade, cooling and air quality for which the trees are planted. As a rule of thumb, a tree's rooting zone must be at least as large in area as the tree's canopy at maturity. In a porous pavement, the rooting zone is the pavement's base course, made of single-sized aggregate that bears the pavement's load. Into the aggregate's void space is mixed nutrient- and water-holding soil; the remaining unfilled void space provides aeration, drainage, and rooting space. The mixture makes the base into a "structural soil." A porous surface admits air and water to the base to make it a viable rooting zone. This is a revolutionary new way to integrate healthy ecology and thriving cities: living tree canopy above, the city's traffic on the ground, and living tree roots below.

An installation to support viable urban trees is Pier A Park in Hoboken, New Jersey. The park was built in 1999 on an unused cargo pier, the concrete slab of which was in effect sterile bedrock for the park site. Enormous pedestrian traffic comes into the urban waterfront park. A tree rooting soil had to be built to support viable tree rooting while bearing the traffic. A continuous rooting zone was made of a structural-soil base 0.5 to 1.5 m thick. The surface course is a custom-specified open-graded block with 16 mm joints filled with small open-graded aggregate, on a setting bed of the same aggregate. The permeable surface supplies air and water to the rooting zone, supporting large, healthy plane trees that make a full canopy over the park.

6. POROUS PAVEMENT'S POTENTIAL

Porous pavements can solve urban environmental problems at the source. In new suburban growth, they protect pristine watersheds. In old town centers, redevelopment and reconstruction are opportunities for environmental rehabilitation simultaneously with urban renewal. To date, porous pavements constitute only a minute fraction of the paving done each year in the United States. But their rate of growth, on a percentage basis, is very high, primarily because of public concern about and legal requirements for stormwater management. The hydrologic and structural success of open-jointed block depends on correct selection, design, installation, and maintenance. Failures — clogging and structural degradation — result from neglecting one or more of these steps.

Comprehensively reviewing porous pavements' scientific research and on-the-ground experience has dispelled unfounded rumors and speculations that formerly inhibited implementation of this useful technology. The following are now known to be myths: that porous pavement does not work on clay soil, that it always fails because the subgrade gets wet and soft, that it fails where there is freezing in winter, that it always gets clogged and fails quickly, that it costs too much, and that there is no experience with it in most regions. In their place, the following truths are now illuminated: responsible professionals have to select, design, and build a porous pavement installation right; they can design it to fail; they can alternatively design it to succeed; it requires the practitioners' knowledge and care; and every installation is site-specific.

This project exemplifies progress in urban design, advancing together with science and technology. Such progress requires that unfounded rumor and speculation be recognized and rejected, and that observed facts be recognized and adhered to. Factual science is the answer to technical controversies like those that once plagued porous pavements.

7. REFERENCES

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Porous ceramics are categorized as those ceramics having high percentage porosity between 20 and 95%. These materials composed of at least two phases like solid ceramic phase, and the gas-filled porous phase [7]. The gas content of these pores usually regulates itself to the environment, as an exchange of gas with the environment is possible through pore channels.Â In recent years, with the development of new needs and technologies, there was an increasing request for porous ceramic. Hence their fabrication methods are being widely studied and the subject of inclusive research.Â The 3D printing can be used in the making of porous ceramics in a different of applications.