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Fully Permeable Pavement for Stormwater Management: Progress and Obstacles to Implementation in California

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Fully Permeable Pavement for Stormwater Management: Progress and Obstacles to Implementation in California

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Work Conducted Under Partnered Pavement Research Center Strategic Plan Element No. 2.8:
Advanced Pavement Research for Long-Term Future Needs

PREPARED FOR:

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Fully permeable pavements capture stormwater and infiltrate it into the ground and/or hold it until discharging it into stormwater conveyance. In either case, they offer benefits in terms of reducing or eliminating the need for stormwater conveyance infrastructure, capturing pollutants, and potentially reducing air temperatures around them. This technical memorandum reviews recent advances in structural design, materials, and hydraulic design that have filled many of the gaps in permeable pavement technology. The memo then presents the results of a recent survey in California, with some additional out-of-state responders, regarding awareness of permeable pavements and obstacles to their implementation. Finally, the memo presents recommendations for filling remaining knowledge gaps and overcoming obstacles to implementation.

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PROJECT OBJECTIVES

The objective of this project was to begin to identify gaps in technology, information, benefits and/or incentives that are slowing or stopping the greater implementation of fully permeable pavement in the US, particularly in California. The objective was completed through a survey.

SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	Millimeters	mm
ft	feet	0.305	Meters	m
yd	yards	0.914	Meters	m
mi	miles	1.61	Kilometers	Km
		AREA		
in^2	square inches	645.2	Square millimeters	mm^2
ft^2	square feet	0.093	Square meters	m^2
yd^2	square yard	0.836	Square meters	m^2
ac	acres	0.405	Hectares	ha
mi^2	square miles	2.59	Square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	Milliliters	mL
gal	gallons	3.785	Liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	Grams	g
lb	pounds	0.454	Kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	°C
		ILLUMINATION		
fc	foot-candles	10.76	Lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	Newtons	N
lbf/in^2	poundforce per square inch	6.89	Kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	Inches	in
m	meters	3.28	Feet	ft
m	meters	1.09	Yards	yd
km	kilometers	0.621	Miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	Hectares	2.47	Acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	Milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	Gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	Ounces	oz
kg	kilograms	2.202	Pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact degrees)		
°C	Celsius	1.8C+32	Fahrenheit	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	Poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

*SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380 (Revised March 2003).

1 INTRODUCTION

Fully permeable pavements are defined for the purposes of this study as those in which all layers are intended to be permeable and the pavement structure serves as a reservoir to store water during storm periods in order to minimize the adverse effects of stormwater runoff. The surface can be any permeable paving material, and most surfaces are typically are either pervious concrete, porous asphalt, or permeable interlocking pavers, or combinations of each of these. In this technical memorandum the term *permeable pavement* is used generically for fully permeable pavements with all surface types. The rest of the pavement structure consists of aggregate layers with numerous large interconnected air-voids that can store water and allow it to flow through them. The subgrade is often compacted less than for conventional pavements to help improve its permeability as well.

Permeable pavements can be designed to capture some or part of the rainfall and runoff from storms, and can include features for conveying water to conventional stormwater drainage systems when they reach their capacity for storage and/or infiltration.

1.1 Applications and Benefits of Permeable Pavements

Local governments around the world are interested in the development of fully permeable pavement designs as a potential stormwater management best management practice (BMP). Interest also continues to grow as climate change brings a greater risk of severe rainfall events in many regions, and as the spread of urbanization results in larger areas of impermeable hardscape.

The California Department of Transportation (Caltrans) has been interested in fully permeable pavement for use in state-owned, off-mainline pavement facilities such as maintenance yards and other parking areas, as well as for potential use in retrofitted shoulders that capture the runoff from mainline streets and highways. These applications are of particular interest where permeable pavement is cost-competitive or cost-advantageous compared to other BMPs, and in densely developed urban areas where the space available for BMPs, such as basins and bio-swales, is not available. Although permeable pavement may require specialized vacuum trucks to maintain permeability, some agencies have stated that this is less of a change of operations and easier to budget than the maintenance and purchase of filters and chemicals for mechanical devices or the intensive and specialized landscaping required for other BMPs. The California State Water Resources Control Board has a grant program that helps local government pay for installation of permeable pavement as part of low-impact development to reduce and prevent stormwater contamination of rivers, lakes, and streams. Other federal (including US Environmental Protection Agency [EPA]), regional, state, and local agencies have shown increased interest in permeable pavement for stormwater management. Permeable pavements have also been investigated as a means of helping to control localized heat islands for human thermal comfort *(1)*.

1.2 Challenges 10 Years Ago

Since the late 1970s, a range of fully permeable pavement projects intended for light vehicles traveling at slow speeds have been constructed in a number of US states. Most of the information available in the literature features successful projects, although a few failed applications of the technology have been reported. However, further inspection has revealed that failures occurred in localized areas due to clogging of the permeable surface or to construction processes that resulted in severe surface raveling or cracking *(2)*.

Most applications of permeable pavement in North America have been for pavements with no high-speed traffic or truck traffic (e.g., automobile parking lots), which is a reflection of road-owner concerns about durability.

Structural design methods for permeable pavements have mostly been empirical in nature, but success with this approach requires a supporting collection of comprehensive, long-term performance data for all of the expected design conditions—including different materials, climates, subgrades, and structural cross sections—along with a large factorial set of performance data that considers all of these design variable permutations. To date, little of this data is available, limiting the speed of technology development for fully permeable pavements because of the high cost of learning from inevitable failures.

A review of design practice across the United States *(2)* published in 2012 showed the very limited scope of applications at that time for fully permeable pavements, even by the leading firms specializing in that type of design. That limited scope of applications in 2011 was also reflected in the then recently produced National Asphalt Pavement Association (NAPA) *(3)*, American Concrete Pavement Association *(4)*, and Interlocking Concrete Pavement Institute *(5)* manuals for design of porous asphalt, pervious concrete pavements, and permeable interlocking concrete pavements, respectively.

In summary, these major challenges appeared to be stalling implementation of fully permeable pavements five to eight years ago:

- Lack of designs for applications other than light traffic
- Lack of information about hydraulic and structural performance (functional life), maintenance (frequency, best practices), and life cycle cost
- The use of land development standards that require full stormwater handling systems intended for impermeable pavement even when a permeable pavement is used, which essentially doubles costs

2 RECENT ADVANCES

2.1 Recent Advances in California

Beginning in 2008 and ending in 2013, the California Department of Transportation funded a multi-year series of projects at the University of California Pavement Research Center (UCPRC) that looked at the hydraulic performance of permeable pavements in the field and under accelerated pavement testing *(6,7,8)*.As a part of that program, Caltrans also funded the development of mechanistic-empirical (ME) structural design methods for fully permeable pavements to handle heavy trucks with surfaces of porous asphalt, pervious concrete and concrete slabs cast with drainage holes *(2)*. The structural design procedure developed used fatigue data for the respective surface materials from laboratory bending beam fatigue results and shear stress to strength data for porous granular base materials, and considered axle load spectra for loading as well as traffic speed for the asphalt designs. The procedure and resulting design tables also included consideration of an optional 150 mm (6 inch) pervious concrete subbase below the granular reservoir layer to provide greater confinement and therefore greater stiffness and shear strength. The results of this research were implemented in a design guidance document *(9)*.

In addition, a life cycle cost analysis (LCCA) was performed to evaluate the net present value (NPV) economic costs of full-depth permeable pavement compared with conventional stormwater management alternatives *(10)* for stand-alone pavements and for shoulder retrofit of highways. The LCCA used materials and construction costs in California and conservative estimates of permeable pavement life and compared the life cycle costs with those estimated for other best management practices (BMPs) in another Caltrans study *(11)*. The LCCA found that the fully permeable shoulder retrofit was cost-effective compared with the currently practiced BMPs in most scenarios.

The design procedure developed for Caltrans and based on laboratory testing and mechanistic analysis was not validated or calibrated with field data or accelerated pavement testing. Starting with the work done for asphalt- and concrete-surfaced fully permeable pavements, the Concrete Masonry Association of California and Nevada in partnership with the Interlocking Concrete Pavement Institute (ICPI) engaged the UCPRC in 2013 to develop an ME design procedure for permeable interlocking concrete pavement (PICP), and to calibrate the method using accelerated pavement testing with the Heavy Vehicle Simulator (HVS). The results of this work *(12,13)* are being incorporated into a new ASCE design method for PICP *(14)*.

2.2 Advances Outside of California

There have been a number of advancements outside of California as well, although only a few can be covered in this technical memorandum. A recent evaluation (2015) completed for the National Center for Sustainable Transportation identified recent advances and current knowledge as well as remaining gaps in knowledge and experience *(15)*. The report found that large advances have been made across the country (this report includes references to a large number of studies) and addressed many of the gaps identified at the start of the Caltrans-sponsored UCPRC program in 2008. It also found that some gaps remained in the areas of materials, structural performance and their full-scale validation; hydraulic and water quality performance and their validation; information regarding maintenance and clogging resulting in loss of permeability; and life cycle cost analysis (LCCA) and environmental life cycle assessment (LCA) information.

Similar conclusions were drawn in a report prepared for the American Association of State Highway and Transportation Officials (AASHTO) on permeable shoulders *(16)* and the Federal Highway Administration (FHWA) reference document on sustainable pavements *(17)*. The FHWA document states that preliminary research, although not yet validated by field sections or accelerated pavement testing, indicates that it may be possible to design and construct permeable pavements for the highway environment. All three of these documents *(15,16,17)* and the ASCE book *Permeable Pavements (18)* cover research needs, including the need for structural testing.

The Toronto and Region Conservation Authority completed a five-year paver and concrete permeable pavement parking lot evaluation that demonstrated that geotextiles do not impede flows to the subgrade, as well as comparisons of surface water runoff and groundwater quality which showed improvement compared to impermeable asphalt pavement *(19)*. The study included an LCCA comparison to impermeable asphalt with an oil and grit separator and the permeable pavements showed cost savings when differences in water quality were included *(20)*.

3 SURVEY REGARDING OBSTACLES TO IMPLEMENTATION

3.1 Survey Description

Considering the great advances made in the technology of fully permeable pavements over the past 10 years, a number of practitioners and researchers in the field have questioned the apparent slow pace of acceptance and use of permeable pavements. This has been the subject of panel discussions at recent pavement and stormwater management conferences.

To get a better idea of the reasons for this slow pace of market penetration, the California Department of Transportation recently commissioned a survey of practitioners and agencies in California regarding the implementation of fully permeable pavement. It was also extended to include some out-of-state responses. The survey aimed to understand the respondents' level of knowledge regarding fully permeable pavement (FPP), and the obstacles and gaps that must be addressed if there is to be more widespread implementation of this technology in California. The survey was composed of eight questions, with separate question sections targeting practitioners who have implemented FPP and those who have not. The primary subjects of the survey were city civil engineers and consultants in both road construction and storm drain departments.

The survey was developed in a way that directed respondents to specific questions based on whether or not they have experience implementing FPP. For those without FPP experience, the questions asked about their level of familiarity with FPP design layout, environmental benefits, cost effectiveness, and potential risks and challenges. For engineers with experience with FPP, the survey focused more on the results of the projects, the selection of state code and manuals, the method of hydraulic design, and what they believed are the reasons for resistance to widespread implementation of FPP.

Initially, representatives from all California cities with population over 25,000 were contacted (246 of the 478 cities in the state) via email or telephone. Representatives in 206 cities were reached and 39 responses were initially received. Additional outreach was made both within the state and to selected experienced persons outside the state. The breakdown of the final 64 respondents and their level of experience is summarized below:

- Californians with experience: 26
- Californians without experience: 31
- Non-Californians with experience: 7

The survey results are summarized in the following tables, separated by location (California and non-California cities) and by type of experience with FPP (with experience or without experience). In each table the question is shown along with the number of respondents to that question, and the percentage of respondents for each answer. All non-Californian responses are with previous experience of FPP.

3.2 Californians with Permeable Pavement Experience

The first question put to those with experience asked them to identify their three most significant issues with FPP. The responses are shown in Table 3.1. The results show that maintenance, which likely means maintaining the permeability of the surface, was by far the most cited issue, appearing in nearly one fifth of the responses. Water ponding, which was cited by eight percent, is related. Higher cost, installation issues, quality of construction, conflicts with utilities, and lack of familiarity with the design methods were the next most prevalent issues.

Table 3.1: Three Most Significant Issues Affecting Implementation of FPP

Three Significant Issues (37)*	Maintenance	None so far	Higher cost
	18.9%†	**13.5%**	**10.8%**
Installation	Quality of construction	Conflict with utilities	Water ponding
10.8%	**8.1%**	**8.1%**	**8.1%**
Unfamiliarity with design	Not strong enough to withstand traffic	Non-compliance with current codes	Poor mix design
8.1%	**2.7%**	**2.7%**	**2.7%**
Public perception	Maintaining native soil stability		
2.7%	**2.7%**		

* Number in parenthesis indicates number of respondents.
† Number in boldface indicates percentage of respondents who considered this issue to be one of the top three in significance.

The remaining questions posed to the Californians with FPP experience are shown in Table 3.2. The results show that nearly two thirds of respondents thought that their FPP projects were successful, and about the same number thought that their stakeholders held that same opinion. Just over ten percent thought that the projects were not successful, and about the same percentage thought that their other stakeholders felt the same way. Nearly three quarters of practitioners would definitely consider using FPP again, and more than 90 percent would consider it.

The survey results indicate that the primary reason FPP was chosen was for its environmental benefits, followed by owner's preference. About 10 percent of the respondents selected FPP for its long-term cost savings. The results also show that a wide range of design manuals and methods were used, while hydraulic design generally did not follow any established standards.

For those with FPP experience, it was generally thought that the top four reasons for the rare implementation were higher initial cost, maintenance costs and issues, general industry conservatism, and a lack of guidance and specifications.

3.3 Non-Californians with Permeable Pavement Experience

The answers from non-Californians with FPP experience were very similar to those from Californians, although they were somewhat more positive about their experiences. Conflict with existing regulations was an additional reason cited for lack of widespread implementation.

3.4 Californians without Permeable Pavement Experience

The answers to the questions posed to Californians without prior FPP experience are shown in Table 3.3. More than a third of those without experience were not convinced that FPPs work. About 35 percent were happy to evaluate FPP or were waiting for the right project to try it on (some overlap in the two possible answers). Those without experience cited maintenance concerns and the possibility that FPP might not work well as a pavement as the two most likely reasons for the lack of widespread implementation. There were also concerns about greater initial cost and that FPP might not work as a catchment. The predominant methods for stormwater runoff treatment used by these respondents are detention ponds, retention ponds, and no treatment (straight to receiving waters).

Only one third were aware of the reductions in pollutants generally attributed to FPP, and less than 15 percent were aware that FPP can reduce peak flows. About 10 percent were aware that FPP can help replenish groundwater.

Table 3.2: Responses to Remaining Questions to Californians with FPP Experience

Did you think the project(s) a success? (26)*									
Yes	Both yes and no	No	Too soon to tell						
65.4%†	**19.2%**	**11.5%**	**3.8%**						
Did stakeholders think the project(s) a success? (24)									
Yes	Too soon to tell	No	Mostly	Unaware of the problems during construction	Both yes and no				
62.5%	**12.5%**	**8.3%**	**8.3%**	**4.2%**	**4.2%**				
Would you consider FPP again? (25)									
Yes	Depends on application	No	Maybe						
72.0%	**20.0%**	**4.0%**	**4.0%**						
Reasons for choosing FPP (33)									
Environmental benefits	Owner's preference	Long-term cost savings	Helping meet requirements	Lack of drainage system	Previous experience	To have an alternative	For pilot evaluation purpose	Aesthetics	Location
45.5%	**18.2%**	**9.1%**	**9.1%**	**3.0%**	**3.0%**	**3.0%**	**3.0%**	**3.0%**	**3.0%**
Reference manuals used (26)									
None/Unknown	ICP Institute	CA C3 stormwater guidebook	Caltrans	SFPUC 2016 GI Typical Details	Roller Compacted Concrete Specs	Field Engineers	APWA	Developed own specs	City codes
30.8%	**23.1%**	**11.5%**	**7.7%**	**7.7%**	**3.8%**	**3.8%**	**3.8%**	**3.8%**	**3.8%**
Hydraulic design method used (17)									
Literature + design manuals	Outsourced to consulting firms	In-house design	Collaboration with university						
35.3%	**35.3%**	**29.4%**	**0.0%**						
Reasons for rare implementation of FPP (46)									
High initial cost	Cost, frequency, method of maintenance	Conservatism in industry	Lack of guidance/ specs	Difficulties introduced by dense urban areas	Requires special equipment	Aesthetics	Difficulty in installation	Water infiltrating to buildings	Lack of knowledge in managing FPP projects
26.1%	**21.7%**	**19.6%**	**17.4%**	**4.3%**	**2.2%**	**2.2%**	**2.2%**	**2.2%**	**2.2%**

* Number in parenthesis indicates number of respondents.

† Number in boldface indicates percentage of respondents who considered this issue to be one of the top three in significance.

Table 3.3: Responses to Questions to Californians without FPP Experience

First impressions (37)*									
Unconvinced of applicability	Happy to evaluate it	Other	Waiting for the right projects	Unfamiliar topic	Would like to know more				
35.1%†	**18.9%**	**18.9%**	**16.2%**	**5.4%**	**5.4%**				
Speculated obstacles in implementation (78)									
Maintenance	May not work as a pavement	Greater initial cost	May not work as a catchment	Lack of design guidelines	Conflicts w/ utilities	Industry resistance	Other	Contractors' lack of knowledge	
29.5%	**26.9%**	**15.4%**	**10.3%**	**5.1%**	**3.8%**	**3.8%**	**3.8%**	**1.3%**	
Level of familiarity (29) 1=lowest familiarity, 5=highest familiarity									
2	3	1	4	5					
37.9%	**31.0%**	**17.2%**	**10.3%**	**3.4%**					
Current stormwater runoff treatment (46)									
Detention pond	Retention pond	Straight to receiving water	Treatment plant	Other	Permeable pavement				
30.4%	**30.4%**	**19.6%**	**8.7%**	**8.7%**	**2.2%**				
Environmental benefits of FPP known to you (36)									
Reduction in ultimate pollutants in runoff	Reduction in peak volume	No knowledge	Replenishing groundwater	Infiltration & storage of stormwater	Less treatment space occupied	Reducing surface grade	Less noise when rains	Erosion control	Helping meeting ADA standard
36.1%	**13.9%**	**11.1%**	**11.1%**	**11.1%**	**5.6%**	**2.8%**	**2.8%**	**2.8%**	**2.8%**
Expectation of life cycle cost of FPP compared to conventional pavements? (26)									
More	Do not know enough about overall cost	Lower	Not sure, but maintenance cost higher	Lower if a retention space is needed					
53.8%	**30.8%**	**7.7%**	**3.8%**	**3.8%**					

* Number in parenthesis indicates number of respondents.
† Number in boldface indicates percentage of respondents who considered this issue to be one of the top three in significance.

4 CONCLUSIONS AND RECOMMENDATIONS

The following are the conclusions from the search of existing literature:

- Significant progress has been made in the technical aspects of designing FPP.
- Improved information regarding good design will become available due to updates to various design methods and to ASCE standards.

Although it was not addressed in the survey reported in this technical memorandum, earlier UCPRC work for Caltrans identified the need to improve the mix designs for pervious concrete and porous asphalt to obtain both better durability and better long-term permeability. The conclusions that follow have been drawn solely from the survey reported here:

- Those who have used fully permeable pavement (FPP) and their stakeholders generally consider that the projects were successful.
- Although a significant percentage of practitioners remain unconvinced that FPP can work, many of those practitioners lack detailed knowledge of FPP and are unaware of its environmental benefits.
- Concerns about maintenance efficacy and the cost of FPP remain, as do issues with initial cost and construction quality and expertise.
- Potential users of FPP appear to lack sufficient information and/or knowledge about the information available covering subjects such as initial costs, maintenance frequency and methods, design guidelines, and the selection of projects for which FPP may be applied.
- Another major obstacle to increased use of FPP appears to be the inherent risk-averseness of would-be practitioners, due to a lack of rewards for innovation and a low tolerance for failure that is common in many areas of civil engineering.

Following are recommendations for the research and development community working to improve and more fully implement permeable pavement technology:

- Develop more definitive information regarding the following items and make it more widely available. These should include basic information, how to determine the information for specific projects, and case study examples:
    - Cost comparisons with alternatives (initial costs and life cycle costs)
    - Better documentation of benefits, disbenefits, and costs relative to alternatives in different design contexts
    - Functional lives, for both structural and hydraulic (permeability) requirements
    - New design information for all FPP types as it is produced
    - Develop and make known additional alternative best practices for maintenance and tradeoffs regarding their costs, difficulty, availability, and how frequently to perform them

- More field and accelerated pavement testing validation of designs
- Improvement of porous asphalt and pervious concrete mix designs

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