Retrofitted fully permeable shoulders as a stormwater management strategy on highways

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ABSTRACT: This paper summarizes the results of laboratory testing, computer performance modeling, and life-cycle cost analysis of fully permeable shoulder retrofits as a stormwater management strategy for highways. The use of these types of pavement is being considered as a potential best management practice for managing stormwater in a number of states. The deliverables from this research are a preliminary design procedure and an example set of catalogue-type design tables that can be used to design pilot and experimental fully permeable pavement test sections. The results obtained from the analyses in this study indicate that fully permeable pavements could be a cost-effective stormwater best management practice alternative as a shoulder retrofit on highways, as well as for maintenance yards, parking lots, and other areas with slow moving truck traffic. However, these results need to be validated in controlled experimental test sections and pilot studies before wider-scale implementation is considered. The findings from these full-scale experiments will be used to identify situations where fully permeable pavements are an appropriate best management practice, validate and refine the design method, undertake detailed life-cycle cost and environmental life-cycle assessments, and to prepare guideline documentation for the design and construction of fully permeable pavements.

Keywords: Fully permeable pavements, stormwater management, shoulder retrofit

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.

Since the late 1970s, a variety of fully permeable pavement projects have been constructed in a number of U.S. states for low traffic areas and light vehicles. Most of the information available in the literature is about successes [1], while few failures have been reported for these applications. Observations of several projects by the authors indicate that failures have occurred in localized areas due to clogging of the permeable surface, and to construction processes that have resulted in severe raveling (loss of particles from the surface) or cracking. Structural design methods have been empirical in nature, with little or no long-term monitoring data to support the empiricism. Purely empirical design methods require good comprehensive empirical data for all of the expected design conditions, which has limited the speed of technology development for fully permeable pavements because of the high cost of learning from inevitable failures. For this reason it is difficult for purely empirical design methods to consider different materials, climates, subgrades, and structural cross sections because of the need for a large factorial set of performance data that considers all of these design variable permutations. A review of design practice across the United States [2] shows the very limited scope of current applications for fully permeable pavements, even by the leading design firms specializing in this type of design. The limited scope of current applications is also reflected in the 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.

2 PROJECT OBJECTIVES

The study discussed in this paper was part of a larger development program being undertaken by the University of California Pavement Research Center (UCPRC) for the California Department of Transportation (Caltrans), with the objective of developing guidelines and inputs for specification language, for the appropriate use of fully permeable pavements as a potential Best Management Practice (BMP) for controlling stormwater runoff from highways, maintenance yards, rest stops, and other pavements that Caltrans owns and manages. This objective would be met after completion of laboratory testing to characterize the mechanical and hydrological properties of fully permeable pavement materials; structural and hydrological performance modeling to develop initial designs; life-cycle cost analyses and environmental life-cycle assessment studies; and full-scale testing in the field and/or using accelerated load testing (using the Caltrans Heavy Vehicle Simulator [HVS]) to validate the structural and hydrological designs, or if necessary, to calibrate them to match the observed field performance. This paper covers the materials characterization and structural performance modeling components of the first phase of the study completed prior to full-scale testing. The hydrological performance modeling is discussed elsewhere in the literature [6,7].

3 MATERIALS CHARACTERIZATION

3.1 Subgrade materials

On most pavements, subgrade materials are usually compacted as densely as possible to provide a platform for the overlying pavement layers and to provide added structural integrity to the pavement. However, on fully permeable pavements, compaction of the subgrade is generally restricted where possible to facilitate infiltration of water. This requires a thicker overlying pavement structure to compensate for the reduced subgrade strength. In this study, testing of subgrade materials focused on the influence of different levels of compaction and different moisture contents on the stiffness of those materials.

Initial studies of the properties of clays in California revealed that there is little difference in the strength and permeability characteristics of these materials. Consequently, only one clay and one silt material were tested. The testing of CH clay was considered unnecessary given the known poor bearing capacity and permeability characteristics of these materials, and the unlikelihood that a fully permeable pavement would be constructed on this type of material. Sand and gravel subgrades were also not included because they are expected to perform well in terms of both structural capacity and permeability, and are not as sensitive to the saturation levels expected in permeable pavements in California. A broad range of moisture contents and compaction levels were assessed. Tests on subgrade materials included standard indicator tests as well as permeability, resilient modulus (AASHTO T-307) and repeated load triaxial tests.

Test results [8] indicated that both soil types would add very little support to a pavement structure, and that the stiffness and the associated strength of the materials would decrease significantly as the moisture content increases. Any fully permeable pavement structure on these materials would need to compensate for this poor bearing capacity with thicker base and surfacing layers. Testing was not undertaken in the saturated condition given the already poor performance recorded at compaction moisture contents, and the difficulty in preparing specimens for testing (i.e. specimens “failed” before the test could be started).
3.2 Permeable concrete subbase materials

This phase of testing was included to determine whether an “inverted pavement design” approach would be suitable for fully permeable pavements. A stiff subbase would theoretically compensate for the loss of structural stiffness resulting from not compacting the subgrade and provide a stiff platform to confine the base course materials. It might also reduce the overall thickness of the pavement. Testing was limited to compressive strength only (ASTM C-35). Fatigue resistance and flexural strength testing were not undertaken given that cracks in this lower pavement layer would not significantly influence the pavement performance, and would actually improve the flow of water through the structure.

As expected, test results indicated a clear relationship between aggregate grading, cement content, water-to-cement ratio, and strength and permeability \[8\]. All specimens tested exceeded the anticipated permeability requirements, indicating that aggregate gradings and cement contents could be adjusted to increase the strength of the material whilst still retaining adequate water flow through the pavement. The water-to-cement ratio appeared to be critical, as expected, in ensuring good constructability and subsequent performance of the pavement.

3.3 Base course materials

The testing of fully permeable base course materials focused on four commercially available aggregates in the state with different geological origins. Performance of these materials was then compared with the results obtained by other researchers elsewhere in the United States. The aggregate gradations of three of the aggregate sources used smaller stone than is currently recommended by the National Asphalt Paving Association’s (NAPA) permeable pavement guidelines. Discussions with northern California aggregate producers revealed that the larger stone gradations (approximately 38 mm to 50 mm maximum aggregate size) in the guidelines are generally not widely commercially available in California or are much more expensive to produce than products with a maximum aggregate size of approximately 19 mm to 25 mm. Tests on base course materials included standard indicator, permeability, and resilient modulus tests (AASHTO T-307).

Test results \[8\] on the different commercially available permeable base-course aggregates indicated that these materials would probably provide sufficient support for typical traffic loads in parking lots, basic access streets and driveways, and on highway shoulders, whilst serving as a reservoir layer for the pavement structure. Although three of the four materials tested had smaller maximum aggregate sizes than those typically discussed in the literature, the permeability was still adequate for California rainfall events.

3.4 Asphalt wearing course materials

A total of 19 mixes, including a dense-graded control, were assessed. Limited testing was carried out on a European mix, specimens of which were provided to UCPRC from a test track in Spain. These 19 mixes included five different binders and three different aggregates. A range of aggregate sizes, gradations, and air-void contents were covered in the mixes. Tests included standard indicator tests, permeability (ASTM PS129), flexural stiffness and fatigue resistance (AASHTO T-321), rutting resistance (AASHTO T-320), moisture sensitivity (AASHTO T-324) and raveling resistance (ASTM D7064).

Test results \[8\] indicated that the aggregate particle size distribution in the mix and the binder type will be the two most critical factors in designing permeable asphalt concrete wearing courses. Sufficient permeability for anticipated needs in California \[9\] was obtained on a range of mixes tested. Adequate resistance to rutting of the surface material appeared to be mostly a problem for the 9.5 mm mixes with conventional and rubberized binders, based on shear modulus. The 9.5 mm rubberized asphalt and 12.5 mm Georgia-gradation mixes had better rutting resistance in the Hamburg Wheel Tracking Test (which also considered moisture sensitivity), in particular the 12.5 mm mix containing polymers and fibers. Some moisture sensitivity was evident, but this could be overcome by the use of appropriate
anti-strip treatments. Most of the mixes of interest had adequate durability (resistance to raveling) compared to the dense-graded control. Fatigue cracking resistance at a given strain was better for the 9.5 mm rubberized and 12.5 mm polymer-modified mixes compared with the conventional mixes at a given strain. The polymer-modified 12.5 mm mix was stiffest at higher temperatures and under slower traffic (lower frequency of loading), while the conventional 9.5 mm mix had similar stiffness to the 12.5 mm mix at lower temperatures and under faster traffic. The rubberized 9.5 mm mix generally had lower stiffness than the other two mixes.

4 PERFORMANCE MODELING

A mechanistic-empirical design approach was used to evaluate a range of permeable pavements to produce a set of designs for different truck traffic, climate, and soil conditions. A full factorial considering asphalt material types, layer thickness, material properties, climate zone, season, diurnal peak temperature, axle type, axle load, traffic speed, and traffic volume resulted in a total of 15,552 different cases being run \[1,10,11\]. The results of the analyses were used to produce a catalog of designs, similar to the catalog designs prepared by the UCPRC for the Caltrans Rigid Pavement Design Catalog currently used in the Caltrans Highway Design Manual (HDM).

All calculations considered two subbase options, namely no subbase and a 150 mm thick open-graded portland cement concrete subbase to provide support to the granular layer, and help protect the saturated subgrade. Material properties for each of the layers were obtained from the laboratory study. Three types of open-graded asphalt were considered in the calculations. Climate details were obtained from a database of California climatic data, and the temperatures at one-third of the depth of the asphalt layer were calculated from 30 years of data (1961 to 1990) using the Enhanced Integrated Climate Model (EICM). The maximum, minimum, and average of the 30-year temperatures at one-third depth at each hour in each day for January, April and July were calculated. The maximum and minimum of the average day for each of those three months were chosen as the day and night temperatures, respectively for layer elastic theory calculations.

Axle loads were obtained from a database of California Weigh-In-Motion (WIM) stations. The allowable truck traffic (ESAL or Traffic Index) during the design life was calculated using a set of factors, including seasonal factor, day/night factor, axle type factor, ESAL factor (the average ESALs per axle), and load bin factor (percent of total axles in each load range). The value for each factor was determined based on the statistical analysis of statewide traffic information from the UCPRC/Caltrans WIM database. Axle loads less than half the legal load were ignored in order to keep the number of required calculations to an acceptable value, which was considered reasonable since they contribute very little to fatigue damage.

Two truck traffic speeds (7 and 40 km/h) were included in the calculations. The slower speed was selected to represent truck operations during traffic congestion on highways (in this case a detour onto the shoulder) and in maintenance yards or parking areas. The faster speed was selected to represent truck operations on a street or on a shoulder which has had traffic diverted on to it but which is not severely congested.

The stiffness at one-third thickness of the asphalt was calculated from the master curves for each combination of temperature and load frequency corresponding to loading time from flexural beam frequency sweep testing during the laboratory study. The stiffness of each type of asphalt material was averaged for the thickness of each layer to reduce the number of calculation combinations. Consequently, the stiffness of the asphalt used in the calculations was independent of the thickness of the layer.

The distresses analyzed included fatigue cracking of the asphalt layer associated with the tensile strain at the bottom of the asphalt layer, and unbound layer rutting associated with the vertical stresses at the top of the base, subbase (where included) and subgrade. Mechanical responses in terms of the tensile strains from different load configurations were determined using the layer elastic model in the LEAP software package [12]. Prior to the layer elastic
analysis, the stiffness of the granular base was evaluated using non-linear elastic models in the GT-Pave software package [13]. A range of values for different structural factors were selected for the structural response values of the granular base stiffness. The Uzan model [14] was used to consider the non-linear behavior of the granular base using GT-Pave. The procedure proposed by Tutumuller and Thompson [15] was used to obtain cross-anisotropic parameters of the granular base for GT-Pave. Based on the results of these calculations, three representative values of granular base stiffness, namely 60 MPa, 90 MPa, and 120 MPa, were chosen for the final structural calculations.

These data were then used as input in a Miner’s Law equation to calculate the fatigue performance of the asphalt in terms of an allowable traffic index [1,10]. The actual repetitions to failure were calculated using this equation to determine the number of ESALs (later converted to Traffic Index) for each combination of asphalt type, thickness, and climate region.

5 PROPOSED STRUCTURAL DESIGN PROCEDURE

A preliminary catalogue-type design procedure based on region (rainfall), storm event design period, design, traffic, design truck speed, surfacing, subbase type, and the shear stress-to-shear strength ratio at the top of the subgrade was developed for preliminary design of fully permeable pavement test sections in California. Example design tables [1] were prepared from the computer modeling cases and calculations run as part of the computer modeling task described above. The example hydraulic design table includes 2-year, 50-year, and 100-year storm design events (considering infiltration and draw down for full storm duration and repeat storm events) for three California regions (north coast, Central Valley, and Los Angeles Basin). These three storm design events were selected to test the sensitivity of the design to a wide range of events (e.g., effect of storm intensity, storm duration, geometry, draw down, and degree of clogging on infiltration) and were not necessarily intended to be representative of typical Caltrans storm event design procedures. Example design tables for the asphalt concrete include three different open-graded mix designs (conventional 9.5 mm, 9.5 mm asphalt rubber, and 12.5 mm polymer modified), two truck speeds (7 km/h and 40 km/h), and two subbase options (no subbase and PCC-O subbase). All example tables assume a shoulder width of 3.0 m and cover designs up to a Traffic Index of 18 (~300 million ESALs). The shoulder is considered as a lane for drainage design purposes. The design tables have not been validated in full-scale experiments and are currently only intended for the design of experimental test sections. The proposed procedure generally entails the following:

1. Select the permeability of the subgrade, subbase type, region, storm design event period, and number of lanes drained. This information is used to determine the thickness of the gravel base/reservoir layer in terms of hydraulic performance. Consideration should be given to whether occasional overflows are permitted (e.g., during a series of heavy storms on consecutive days, prolonged rainfall, etc.) or not, as this will influence the choice of storm design period and dictate the thickness of the base/reservoir layer. Permeability should be measured for each project at a range of depths around the expected depth of the top of the subgrade after excavation of material for the reservoir layer(s). The lowest permeability should be used in the design. It should be noted that clay lenses between silt layers are common in the Central Valley of California, and these will influence permeability.

2. Select the surface type. Base thickness, design traffic, and design speed are used to identify the thickness of the HMA layer. Once the HMA layer thickness has been determined, this and base thickness are used to determine whether the shear stress-to-shear strength ratio at the top of the subgrade is adequate to prevent permanent deformation in the subgrade.

The design method assumes that water should only reach the top of the granular base layer for the design storm, and not be stored in the surface layer during the infiltration period, in order to improve the durability of the surface material.
The preliminary tables can be used for designs of test sections for both shoulder retrofit of highways and for parking lots, maintenance yards, and similar facilities. Two typical cross sections for shoulder retrofits were developed (one shown in Fig. 1) and two contractors asked to review them in terms of constructability. Both contractors indicated that construction appeared to be feasible and that they would be comfortable to bid on projects with similar designs. The selection of the most appropriate structure will depend on whether the existing pavement structure can maintain a vertical cut face equal to the height of the fully permeable pavement shoulder structure or not. A drain between the existing travelled way and the new fully permeable shoulder will need to be installed to allow any water in the travelled way to drain away from the road, while not allowing any water from the permeable area to flow into the pavement structure. An impermeable composite liner is included in the diagrams to prevent water flowing sideways from the reservoir layer and causing a slip failure in the embankment. The inclusion of this liner will be project dependent and not always required.

5.1 Example

An example design for a rubberized open-graded asphalt shoulder retrofit with no subbase to a three lane highway in Sacramento, CA is discussed below. The project design includes compacted subgrade permeability of $10^{-4}$ cm/s, a storm design of 50 years, design traffic index of 13 (~22 million ESALs), design truck speed of 7 km/h (due to congestion), and a surface layer of 9.5 mm Nominal Maximum Aggregate Size (NMAS) open-graded Rubberized Hot-Mix Asphalt (RHMA-O).

- **Step 1: Choose the base thickness based on hydraulic performance.**

  Using the appropriate table (Table 1 [Table B.1 in Appendix B in Reference 1]), the minimum thickness of granular base is selected for a subgrade soil permeability of $10^{-4}$ cm/s and 50-year design storm in the Sacramento region. These variables require a minimum
Table 1. Preliminary granular base thickness based on hydraulic performance simulations.

<table>
<thead>
<tr>
<th>Storm design (years) (full storm duration)</th>
<th>Number of highway lanes</th>
<th>Sacramento (Sac)</th>
<th>Rainfall Region</th>
<th>Eureka</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Thickness of Granular Base + PCC-O Subbase (mm)</td>
<td>Thickness of Granular Base + PCC-O Subbase (mm)</td>
<td>Thickness of Granular Base + PCC-O Subbase (mm)</td>
</tr>
<tr>
<td>1.00E-05</td>
<td>2</td>
<td>270</td>
<td>450</td>
<td>600</td>
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<tr>
<td>1.00E-04</td>
<td>3</td>
<td>130</td>
<td>180</td>
<td>250</td>
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<tr>
<td>1.00E-03</td>
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<td>5</td>
<td>130</td>
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<td>1.00E-01</td>
<td>6</td>
<td>130</td>
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<tr>
<td>1.00E-00</td>
<td>7</td>
<td>130</td>
<td>130</td>
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</tbody>
</table>

**Note:** The number of highway lanes must include the shoulder. Shoulder width is 10 ft. (3.0 m).

**Table 2.** Design chart for selecting RHMA-O thickness.

<table>
<thead>
<tr>
<th>Granular Base + PCC-O Layer Thickness (mm)</th>
<th>500</th>
<th>600</th>
<th>700</th>
<th>800</th>
<th>900</th>
<th>1000</th>
<th>1100</th>
<th>1200</th>
<th>1300</th>
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<td>200</td>
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<td>250</td>
<td>Y</td>
<td>Y</td>
<td>G</td>
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<td>350</td>
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<td>Y</td>
<td>G</td>
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<td>400</td>
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**Note:** G: Stress-to-Strength Ratio > 0.7; Y: Stress-to-Strength Ratio < 0.7; O: Stress-to-Strength Ratio < 0.3.

**Table 3.** Design chart for checking stress-to-strength ratio at top of subgrade.

**Step 2:** Choose RHMA-O layer thickness based on RHMA-O fatigue damage for TI.

Using the appropriate table (Table 2 [Table E.5 in Appendix E in Reference 1]), select the minimum RHMA-O layer thickness for a base thickness of 700 mm (rounded up base/reservoir layer thickness of 680 mm for a shoulder retrofit of a highway draining three lanes plus the shoulder (i.e., 4 lanes are selected in the table).
from 680 mm from Step 1), and a traffic index of 13. The minimum required thickness of RHMA-O is 395 mm.

• **Step 3: Check the stress/strength ratio at the top of the subgrade.**

  Using the appropriate table (Table 3 [Table E.6 in Appendix E in Reference 1]), check the shear stress-to-shear strength ratio at the top of the subgrade based on the minimum required thickness of granular base of 700 mm and minimum required thickness of RHMA-O of 395 mm. The stress/strength ratio is “G,” which implies that the shear stress is less than 0.3 of the shear strength. Consequently, permanent deformation in the subgrade should not be a problem for this pavement design.

Therefore, in this example, the minimum required thickness of granular base is 700 mm and the minimum thickness of RHMA-O is 395 mm for the design requirements and site conditions.

### 6 LIFE-CYCLE COST ANALYSIS

Example Life-Cycle Cost Analysis (LCCA) comparisons with conventional stormwater Best Management Practices (BMPs) for the Sacramento region [16] indicated that fully permeable pavements should cost less than conventional BMPs over a 40-year life-cycle. However, LCCA should be undertaken on a project-by-project basis because alternatives and costs for different types of fully permeable pavement will vary by region and over time.

A framework for environmental Life-Cycle Analysis (LCA) was reviewed; however, it was found that insufficient data were available at this time to complete an example LCA for fully permeable pavements.

### 7 CONCLUSIONS

Key findings from the computer modeling of structural capacity and development of structural designs phase of the fully permeable pavement study include:

• The use of mechanistic-empirical pavement design equations developed in this project was effective in estimating required structural thicknesses for fully permeable pavements to carry slow moving (between 7 and 40 km/h) truck traffic. Tens of thousands of layer elastic theory calculations to find critical stresses and strains in fully permeable asphalt pavements were performed in order to estimate thicknesses required for structural capacity. Statewide truck axle load spectra from Caltrans Weigh-In-Motion (WIM) measurements (captured in a UCPRC database) were used to select representative axle loads. Representative pavement temperatures were selected from a database of Enhanced Integrated Climate Model (EICM) calculations to estimate asphalt stiffnesses.

• The results of strain calculations in asphalt were used to estimate the required thicknesses for preventing fatigue cracking. Nonlinear layer elastic theory calculations were used to estimate the stiffness of the granular base, which were then used to estimate shear stress-to-strength ratios in the subgrade. Together, these results were used to develop structural design tables that can be used with hydraulic design calculations to determine required layer thicknesses. The pavement structures were considered feasible, with all pavement structures less than 1.5 m in total thickness for the heaviest traffic. The use of an open-graded portland cement subbase offers considerably greater protection against the risk of subgrade rutting for asphalt pavements.

• Preliminary design tables for pilot studies were developed considering structural and hydraulic performance based on the following design input variables:
  – Subgrade permeability,
  – Truck traffic level in terms of Traffic Index or ESAL,
  – Two temperature climate regions (Sacramento and Los Angeles),
  – Three design storms (2, 50, and 100 years) for three climate regions,
Two traffic speeds (7 km/h and 40 km/h), and
Various numbers of adjacent impermeable lanes.

- Design cross sections developed for shoulder retrofit of highways as well as low-speed trafficked areas such as parking lots and maintenance yards were reviewed by construction and maintenance experts and were considered to be feasible to construct and maintain.

REFERENCES