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ANALYSIS AND DESIGN OF VERTICAL-DRAINAGE GEOSYNTHETIC-REINFORCED POROUS PAVEMENT FOR ROADS AND CAR PARKS

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Abstract: Porous asphalt pavement is one solution to increased surface runoff due to urbanization by allowing temporary storm-water retention. This paper aims to establish a rational basis for material selection, drainage design and rutting resistance evaluation of a porous asphalt pavement of this purpose. Selection of suitable design porous asphalt mix and crushed stone base are made by studying the vertical drainage properties and the deterioration trends in permeability caused by clogging using the National University of Singapore (NUS) Falling Head Permeameter. Thickness design of the porous pavement, including the thickness of porous asphalt surface layer and that of the crushed stone base, is based on hydrologic and drainage analysis by means of finite element modeling. Rutting resistance of the pavement structure is evaluated through laboratory wheel tracking tests. Based on these three criteria, a recommended design of the porous asphalt pavement is proposed for car parks and roads in Singapore.

Key Words: Porous asphalt pavement, Geosynthetics, Permeable base, Finite element, Rutting resistance

1. INTRODUCTION

One effect of urbanization on the environment is the increased surface runoff that has to be handled by the drainage systems during storms. This is often caused by an increase in paved areas such as streets and parking lots which have low infiltration rates. The expansion of the existing drainage systems to cater for the associated increased peak runoff is often costly and is not always practical, especially in densely built-up areas. Porous asphalt pavement is therefore a possible alternative solution by allowing temporary storm water retention in the reservoir base course during storms and thus eases the problem of increased peak runoff experienced by the drainage systems (Miller, 1989). Porous pavement allows rainfall and local runoff to flow downward through the pavement surface course of the open-graded asphalt concrete mix and be stored in a reservoir base, which consists of large open-graded crushed stones where water could either be allowed to percolate to the natural ground below or drain to a sump or channel. This has been used as a storm water mitigation technique since the 1970s and is primarily used for parking lots and low volume roads (Ferguson, 1994).

Porous asphalt pavement has to be designed to fulfill its structural and drainage requirements. In terms of the structural design aspect of the porous pavement (both un-reinforced and geosynthetics-reinforced), there is currently no strict design procedures that allow a designer to obtain the layer thickness. Thus most porous pavement design thickness is often based on engineering judgement and experience. This often calls for the need of large-scale experiments such as the accelerated wheel tracking test to aid researchers to understand the structural capacity of the porous pavement structure. In terms of the drainage requirements, there is also no strict design procedure. Guidance that generally covered the subgrade porosity, permeability and classification of base materials, drainage time for stored runoff, restriction of runoff to off-site areas and aggregate gradations required for a porous pavements are provided by the Federal Highway Administration (FHWA, 1999), United States Environmental Protection Agency (EPA, 1999), American Society of Civil Engineers (ASCE and EPA, 2002). In recent years, computational techniques are also employed in the drainage design of porous pavements. PORPAV has been developed by the United states Environmental Protection Agency (Diniz, 1980) to determine the thickness of the porous pavement for temporary storage of rainwater. The USEPA Storm Water Management Model (SWMM) (Kipkie, 1998) is developed to simulate the long term hydrological response of the porous pavement. However the former was not sufficiently verified (Kipkie, 1998) and the latter does not provide the design thickness of the pavement structure, nor take into account the effect of the presence of drainage relief measures.

This paper therefore aims to establish a rational basis for material selection, drainage design and rutting resistance evaluation of a porous asphalt pavement for car parks and roads in Singapore. The selection of suitable porous asphalt surface layer and crushed stone base of the porous pavement is first made by studying the vertical drainage properties and the deterioration trends in permeability caused by clogging using the National University of Singapore (NUS) Falling Head Permeameter. Thickness design of the porous pavement, including the thickness of porous asphalt surface layer and that of the crushed stone base, is based on hydrologic and drainage analysis by means of finite element modeling taking into account the short and long term considerations of the local rainfall conditions. The rutting resistance of the porous pavement structure is evaluated through the use of large-scale laboratory wheel tracking tests to provide an estimate of the structural capacity of the pavement structure and the use of geosynthetics reinforcements is explored. Based on these three criteria, a recommended design of the porous asphalt pavement is proposed for car parks and roads for use in Singapore.

2. DRAINAGE DESIGN AND CLOGGING POTENTIAL OF POROUS ASPHALT LAYER AND RESERVOIR BASE COURSE

2.1. Permeability Studies on Reservoir Base Course

The reservoir base is a key factor that governs the overall drainage and storage capacity of the porous pavement. The design must achieve a balance of permeability and stability of the base material. The approach used in this study is to remove some of the fines from the existing local practice of dense-graded aggregate base gradations to produce the required permeability. The existing base gradation of the Singapore authority was initially tested to check whether it was a suitable permeable base material. Due to its inadequate permeability, it was modified by removing some fines to achieve the required permeability. The modifications were adjusted to lie within the grading bands of the U.S. Army Corps of Engineers rapid draining base (Armstrong, 1992) so as to ensure their ability to serve as a permeable base.

The NUS Falling Head Permeameter (Fwa et. al, 1998) was used in this study for the permeability and clogging tests. The permeability and clogging test setup consisted of the

NUS Falling Head Permeameter, a showering device and a filter apparatus. The showering device was used to introduce the clogging materials into the test specimens.

Test specimens were prepared with crushed granite aggregate base material. The unbound aggregates were compacted into a 152 mm diameter and 180 mm tall cylindrical shaped metal mould within the falling head permeameter by means of a vibratory table according to the ASTM specification D4253-93 (ASTM, 1993). The mix designs used to study the permeability characteristics of base course materials in this research were as follows:

1) LTA base material - existing plant-mixed graded granite aggregate base specified by local road authority
2) MOD 1 - First modification to LTA base material
3) MOD 2 – Second modification to LTA base material
4) OG base material - U.S. Army Corps of Engineers (Armstrong, 1992) open graded base
5) FHWA base material - Federal Highway Administration (FHWA, 1990) Permeable Base

Gradation specifications for these mixes are found in Figure 1. Modification 1 (MOD 1) and Modification 2 (MOD 2) were obtained by modifying the LTA base gradation. These three materials are considered for use as the reservoir base course material for use in Singapore. The OG and FHWA base materials serve as references to aid in the understanding of the factors affecting permeability. A total of 35 test specimens were fabricated for the permeability and clogging tests.

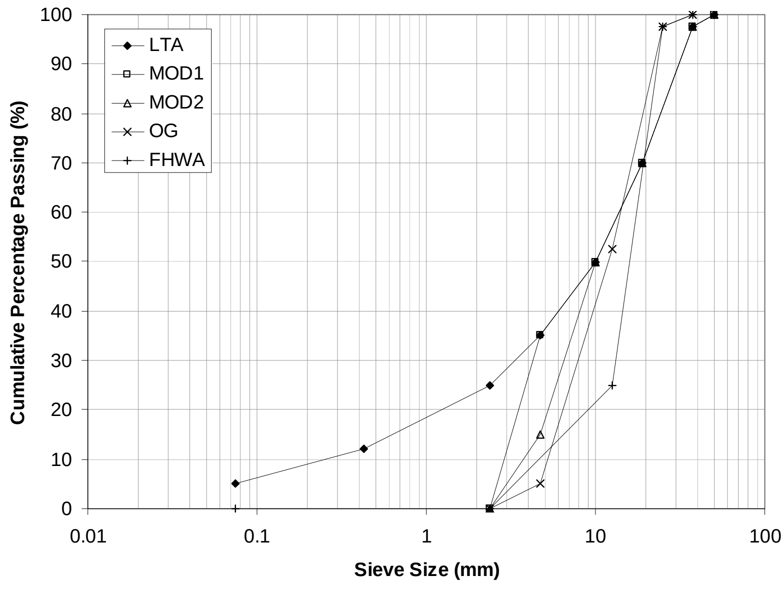


Figure 1. Gradation Specifications for Various Base Materials

Table 1 presents the range of smallest particle sizes in the various gradations, the effective diameter D_{10}, the coefficient of uniformity C_u and their respective permeability values. It is noted that a higher percentage by weight of the aggregates between 2.36 mm and 4.75 mm gave rise to a lower vertical permeability. In the FHWA permeable base, the sizes of the smallest aggregates ranged from 2.36 mm to 12.5 mm. This range of the sizes accounted for the higher permeability measured. In the LTA base gradation, 35% by weight of the specimen were granite fines with sizes ranging from smaller than 75 μm to 2.36mm. This resulted in its low permeability and its unsuitability as a reservoir base course material. Similarly, this unsuitability can be observed in the C_u and D_{10} values, which can be used as indirect indicators of material permeability (FHWA, 1992). It is observed that in general a high range of permeability values was achieved for base gradation with smaller C_u values and larger D_{10} values.

Table 1. Values of Vertical Permeability with respect to Gradation Parameters

Base material	Smallest particle size range	Percentage by weight (%)	Vertical permeability *k* (mm/s)	D_{10} (mm)	C_u (= D_{60}/D_{10})
LTA	<75 μm to 425 μm	11	0.3 – 0.6	0.26	53.8
MOD 1	2.36 mm to 4.75 mm	35	20 - 25	2.8	5.00
MOD 2	2.36 mm to 4.75 mm	15	30 - 35	3.7	3.78
OG	2.36 mm to 4.75 mm	5	35 - 40	5.3	2.64
FHWA	2.36 mm to 12.5 mm	25	45 - 50	4.5	4.00

2.2. Clogging Studies on Reservoir Base Course

The entire experiment was divided into three main parts. They were the permeability measurement, the clogging procedure and the clogging material collection procedure. The clogging test established by Fwa et al. (2001) is adopted. 63.5 g of clogging material was first poured uniformly over the top of the specimen. Water was then showered over the specimen. This allowed the clogging material to slowly penetrate into the specimen with minimal disturbance made to the unbound aggregates. This process ensured that the clogging material was evenly distributed over the entire surface of the specimen. Sand and residual soils were the two clogging materials used in the clogging study. Clogging materials flushed out from the specimens during the permeability tests were collected. The actual amount of clogging materials retained within the specimen was obtained by deducting the flushed out amount from the initial amount of clogging materials added to the specimen. The process was repeated until either low permeability or a near constant permeability is reached. These conditions signify the terminal stage of the experiment, when a blinding layer of clogging material was formed over the top of the specimen.

The deteriorations in the permeability of MOD 1 and MOD 2 due to clogging with sand or residual soil are illustrated in Figure 2 and Figure 3 respectively. The lines depicting the deterioration in permeability are lines of best fit. These lines are obtained by performing non-linear regressions (polynomial and exponential regressions) on the experimental data points. The values of R^2 obtained were more than 0.95. Overall MOD 2 was found to be more resilient against clogging as compared to MOD 1. By comparing Figures 2 and 3, it is observed that MOD 2 could retain a larger amount of clogging material within its void space before the terminal permeability was reached. This can be attributed to the larger pore channels within MOD 2 aggregate matrix as well as its larger void volume. Clogging materials with sizes smaller than the pore channels were able to penetrate deeper into the matrix of the specimens and become trapped within its voids. With a greater volume of void, more clogging materials needed to be retained within the specimen in order to effectively clog up the available drainage paths. Between the two types of clogging materials, residual soil had more severe effect on the permeability of the modified base specimens.

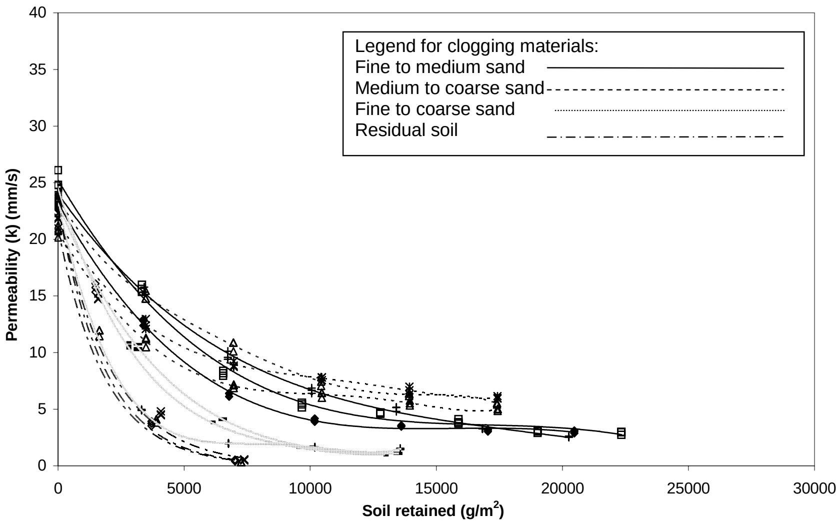


Figure 2. Permeability Deterioration Curves for MOD 1 Specimens caused by Different Types of Clogging Materials

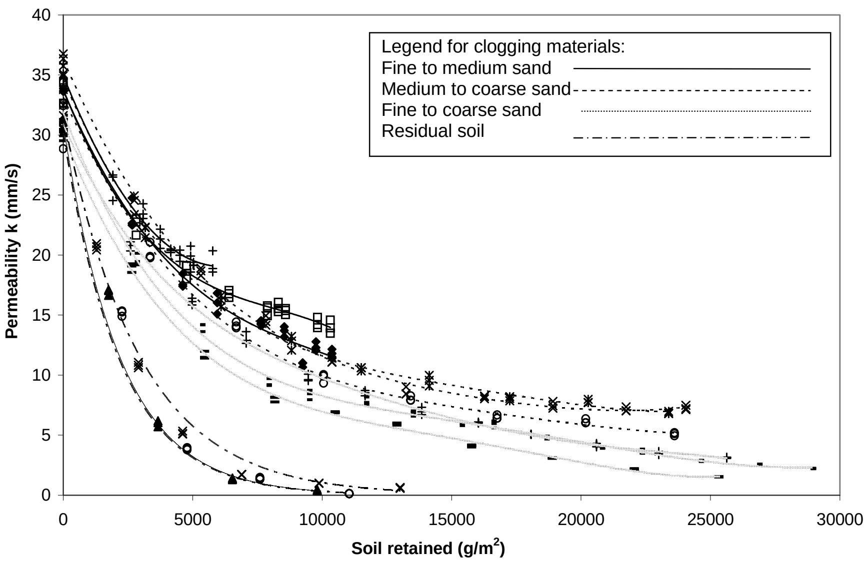


Figure 3. Permeability Deterioration Curves for MOD 2 Specimens caused by Different Types of Clogging Materials

Based on these studies, it was found that the LTA plant-mixed graded granite aggregate base was not suitable as a permeable base for a porous pavement due to its low permeability of water. It was modified by removing some fines to achieve the required permeability and the modifications were adjusted to fall within the grading bands of the U.S. Army Corps of Engineers rapid draining bases so as to ensure their ability to serve as a permeable base. The two modified base gradations called MOD 1 and MOD 2 were found suitable as permeable bases because of their sufficiently high permeability. MOD 2 was superior to MOD 1 in terms of permeability and susceptibility to clogging.

2.3. Permeability and Clogging Studies on Porous Asphalt Surface Course

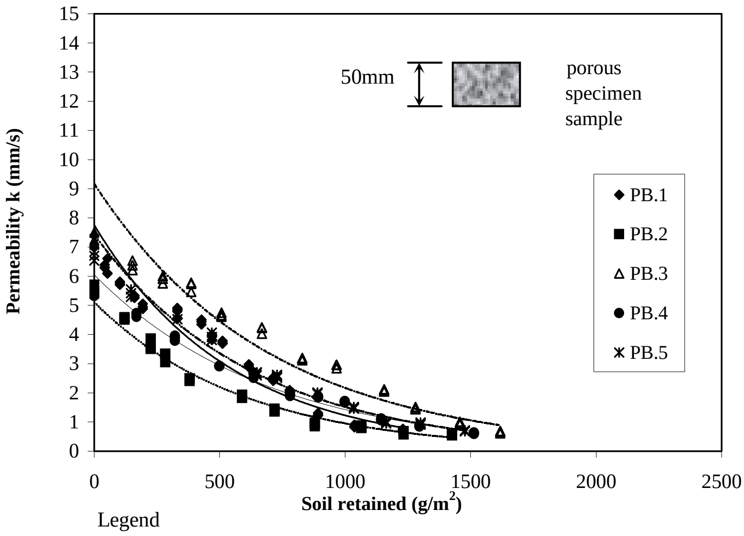
Besides the crushed stone base course, there is also a need to evaluate the permeability and clogging potential of the porous asphalt surface course. Prior research by Fwa et al. (1999)

has indicated the use of the NUS Falling Head Permeameter to study the permeability and clogging potentials of several porous mixtures used in Singapore. From that study, it is found that the use of Porous B mix, one of the porous asphalt mixes used by the local road authority is suitable for local road construction in terms of its superior drainage performance. In this study, the same apparatus and procedure as described in the previous section is used to evaluate the permeability and clogging potential of the porous asphalt surface course using the Porous B mix. A total of 18 porous asphalt B mix specimens are used. The gradation of the mix is shown in Table 2.

Table 2. Gradation Specification of Porous Asphalt B Mix used in Singapore

Grading	19	13.2	9.5	6.3	4.75	3.35	2.36	1.18	0.6	0.3	0.15	0.075
% Passing	100	98.1	45.6	18.8	18.4	17.2	15.6	12.4	10.1	8.2	6.3	3.6

The permeability and clogging tests are carried out using the NUS Falling Head Permeameter and the procedures stated in the previous sections. It is found that the initial permeability of the asphalt specimens was in the range of 5 mm/s to 8 mm/s. The deterioration of permeability due to clogging is shown in Figure 4. It is noted that the permeability deteriorates rapidly in the first few increments of clogging materials and the deterioration rate slows down until an approximately constant terminal permeability value.



Legend
PB.x : Porous asphalt B mix with specimen reference x

Figure 4. Clogging behavior of the porous B mix specimens with thickness of 50 mm

3. DRAINAGE DESIGN OF POROUS PAVEMENT USING FINITE ELEMENT ANALYSIS

The procedures adopted in the present research for material selection and clogging resistance evaluation of surface and base courses have been presented in the preceding section. Based on the current Singapore practice of porous asphalt surface course construction, a thickness of 50 mm was adopted as the surface layer thickness for the porous pavement system. The thickness of the reservoir course of the porous pavement system was to be determined through the finite element drainage analysis based on the storage capacity requirement.

3.1. Short Term and Long Term Drainage Control

Two aspect of drainage control have to be considered, namely a short-term and a long-term drainage control design. The short-term drainage control design refers to the case where the aim was to relieve the peak runoff flow or for flood control. This can be achieved by temporarily holding rainwater within the pavement structure and discharging the water through the normal drainage system at an appropriate time after the rainfall has stopped. Under this requirement, the porous pavement structure is to provide a storage capacity to hold the precipitation of a single design storm.

The long-term drainage control becomes necessary when there is a need to store rainwater within the porous pavement structure for a prolonged period of time. This means that multiple rainfalls over the period of storage must be considered. The period of storage, and hence the storage capacity required, is dependent on the time interval that water was discharged from the storage and the quantity of water discharged each time. It was assumed in the design that a pump would be used to extract water from the storage. The required storage capacity of the pavement system was based on a design monthly precipitation and prescribed water extraction rate and frequency.

3.2. Determination of Design Precipitation

The rainfall intensity and the total amount of precipitation were the main concerns in the determination of the design precipitation. The permeability of the porous asphalt surface course as well as those of the underlying porous pavement layers, with values higher than 1 mm/s, were higher than the normal design rainfall intensity of about 150 mm/h in Singapore by more than 20 times. Therefore, the governing design consideration was the total amount of precipitation of a single rainfall. To determine the design rainfall that would provide the most critical total precipitation, the intensity-duration-frequency (IDF) curves for different return periods were examined and the intensity-duration combination that produced the largest total precipitation for a given return period was selected as the design rainfall for the return period. Table 3 shows the results of this analysis for different return periods.

Table 3. Design Rainfalls for Short-Term Drainage Control

Return Period (Years)	Intensity (mm/hr)	Duration (Minutes)	Total Precipitation (mm)
2	93.33	700	93.33
3	110.00	600	110.00
5	128.33	700	128.33
10	151.67	700	151.67
15	163.33	700	163.33
25	180.83	700	180.83
50	192.50	700	192.50
100	210.00	700	210.00

The long-term drainage control analysis presented in this study was for a design storage period of one month. Similar to the case of short-term drainage control, it was the total precipitation that governed the storage capacity design. For long-term drainage control over the period of one month, it was necessary to determine the most critical design monthly precipitation. A statistical method was employed to determine the design monthly precipitation. Table 4 shows the results of the data analysis for the most recent 20 years, indicating the total rainfall depth and the assumed rainfall intensity of each return period. The case where all the rainy days in the selected design month fell consecutively from the beginning of the month was considered.

Table 4. Design Rainfalls for Long-Term Runoff Control

Return Period (Years)	Total Precipitation (mm)	Intensity (mm/h)
2	547.58	1.69
3	596.97	1.84
5	647.25	2.00
10	704.27	2.17
15	734.10	2.27

3.3. Material Properties

The properties of porous asphalt mixture surface course, and the coarse granular reservoir course, as well as those of the subgrade soil had to be determined as they were inputs to the finite element analysis. Table 5 summarizes the properties for the three materials. In addition, the following two properties were required for unsaturated flow and transient flow analysis: hydraulic conductivity function, and water content characteristic function.

Table 5. Materials Properties of Porous Asphalt, Reservoir Course and Subgrade

	Porous asphalt	Reservoir Course	Subgrade
% Asphalt	5	-	-
% air void	23.6	37.4	-
Liquid limit (%)	-	-	46.2
Plastic limit (%)	-	-	21.6
Density (kg/m^3)	1883.6	1659.1	1521 (Bulk)
Permeability (m/s)	6.404E-03	3.224E-02	9.565E-09

3.4. Finite Element Analysis

The finite element code used for the study was SEEP/W (GEO-Slope, 2001). This special purpose finite element program for seepage analysis was selected because it had the capability to simulate unsaturated flow and transient flow analysis. Three types of boundary conditions were applied to the finite element model. A flux boundary was used at the top pavement surface to simulate rainfall falling onto the pavement. Along the vertical line of symmetry that cut through the center of the pavement system, a no-flow boundary was applied. It did not allow any seepage of water across it. A third type of boundary, known as the infinite boundary, was specified for the vertical boundary of residual soil away from the pavement system and the bottom horizontal boundary of the subgrade residual soil. The infinite boundary was specified because the seepage problem is unbounded.

Finite element mesh design and the time steps for the transient analysis were the main considerations for the convergence analysis of the finite element model. It was found that when the element sizes were decreased to 0.0625 m for the fine size elements and 0.125m for the coarse size elements, the results of the simulations stabilized and further reductions of element sizes produced negligible improvements. An example of mesh design is shown in Figure 5.

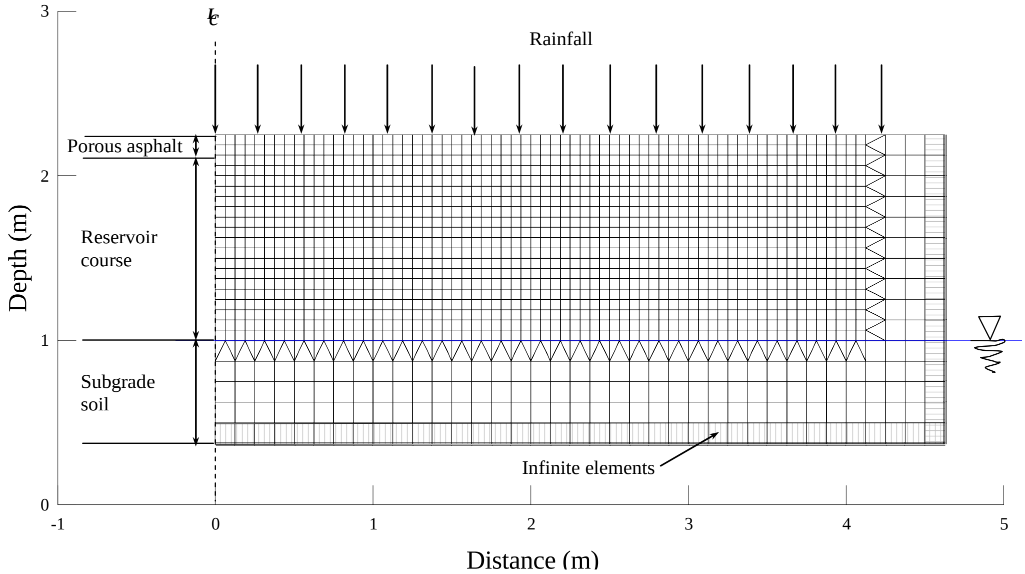


Figure 5. Finite Element Model

3.5. Results of Finite Element Analysis

For short-term runoff control, finite element analyses were performed for return periods of 2 to 50 years. After the rain had started, the phreatic surface within the porous pavement slowly rose from the initial ground water-table level. The rising of the phreatic surface continued until shortly after the rain had stopped. The phreatic surface continued to rise briefly after the rain had stopped due to the time taken by rain water to reach the phreatic surface from the top pavement surface. Table 6 presents the pavement thickness requirements computed by the finite element analysis for different return periods. The thickness requirement of the porous pavement system increased with the length of the return period selected. For a return period of 10 years, which was the common return period adopted for drainage design locally, the pavement thickness required was 1.375 m.

Table 6. Pavement Thickness for Short-Term Runoff Control

Return Period (Years)	Depth of Pavement (m)
2	1.125
3	1.250
5	1.250
10	1.375
15	1.500
25	1.500
50	1.625

For long-term runoff control, a storage period of one month was selected for the analysis. However, since the pavement thickness required was too large if storage were to be provided for the full design monthly precipitation, a scheme that included intermediate discharging of stored water was considered so that the same pavement thickness design in the short term runoff control could be retained. The analysis was to determine the frequency, pumping rate and duration that were required so that the pavement thickness design for the short-term runoff control would be sufficient for the long-term runoff control. Based on the design monthly precipitations for return periods ranging from 2 years to 15 years, and assuming the worst case of having all the rainfalls in the month to fall successively in the beginning of the month, the same pavement thickness as determined by the short-term runoff control could be adopted if pumping was to be performed 4 times a week for 30 minutes each time. The pumping rate required was 2.5 liters per minutes for square meter for return periods of 5 years or less, and 3 liters per minutes for square meter for return periods of 10 and 15 years.

4. RUTTING RESISTANCE OF POROUS PAVEMENT

The thickness design based on drainage consideration is structurally thicker than the typical total thickness of a standard expressway pavement in Singapore. This means that under the local wet tropical climate, the relevant structural test for the thick porous asphalt pavement is one to ensure that there would not be excessive surface deformation under traffic loading. In this paper, the structural resistance of the porous pavement against excessive deformation was evaluated by assessing its resistance to rutting. A wheel tracking machine was used to evaluate rutting potential in this research. It was a modification of a three-wheel immersion tracking machine first adopted by the Transport and Road Research Laboratory (1951) of the United Kingdom (Tan et al, 1992).

4.1. Experimental Test Program

To accurately represent the structural sections of the asphalt pavement, a large metal box in the wheel tracking machine was filled with three layers of materials, namely a subgrade residual soil, a base layer of granular aggregates and the surface layer of asphalt wearing course. The plan dimensions of the specimens was the same as that of the wheel tracking machine steel box, 735 mm x 685 mm. A schematic representation of the specimen cross-section is shown in Figure 6.

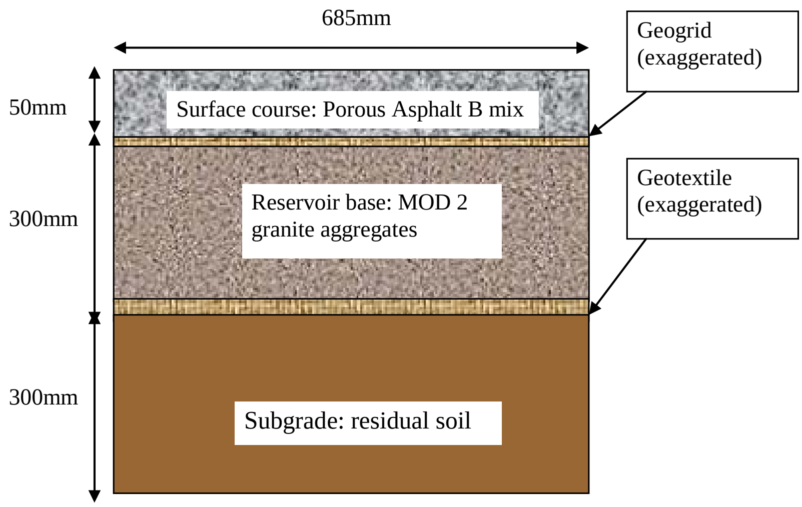


Figure 6. Schematic Representation of the Cross-Section of Test Specimen

The surface layer was 50 mm thick of porous asphalt mix with the target porosity of 20%. The asphalt slab had to be prefabricated as it was not possible to compact the loose mix in the wheel tracking machine. The base course was 300 mm thick of granular aggregates of MOD 2 gradation with a target porosity of 40%. The subgrade soil was a 300 mm thick of Bukit Timah Granite residual soil and is compacted to give a CBR value of 1–2%.

Three specimen types were fabricated for the test program. They were described in Table 7. The test codes are used throughout the rest of the paper.

Table 7. Description of Test Conditions and Test Specimens

Test conditions	Specimen code	Test description
	C-1	Control test 1 with no geotextiles or geogrid
Wheel speed = 20 passes/min	C-2	Control test 2 with no geotextiles or geogrid
	TS-1	Test with non-woven TS 30 geotextile as separator at the subgrade-base interface
Temperature = 60^0C	TS-2	Test with non-woven TS 80 geotextile as separator at the subgrade-base interface
Wheel Contact Pressure = 700 kPa	ST-1	Test with Stratagrid 200 geogrid as reinforcement at the interface of base and surface courses
	ST-2	Test with Stratagrid 200 geogrid as reinforcement at the interface of base and surface courses

Two types of geosynthetics were selected for this wheel-tracking test. They were two grades of non-woven geotextiles (designated as TS 30 and TS 60) and a flexible geogrid (known as Stratagrid 200). Table 8 gives the properties of these geosynthetics materials. The non-woven geotextiles were placed at the interface between the subgrade soil and the base layer. They were tested for their reinforcement and separation function. They were polypropylene continuous filament non-woven needle punched geotextiles designed for general stabilization and filtration applications. The geogrid was placed between the base course and the surface course. The geogrid was cast together with the porous asphalt slab to increase the strength of the surface course in order to simulate the field conditions. Stratagrid 200 was a high tenacity coated polyester geogrid with its main function as reinforcement. It has square apertures making it suitable for permeability applications such as the asphalt pavement structure in the present research.

Table 8. Properties of Geosynthetics used in Wheel Tracking Test

Property	Unit	TS 30 Non-woven geotextile	TS 80 Non-woven geotextile	Stratagrid 200 geogrid
Tensile strength	kN/m	11.5	28.0	33
Tensile elongation	%	75/35	80/35	15/13
CBR puncture	N	1700	2850	-
Rod puncture	N	310	490	-
Opening size O_{90}	mm	0.12	0.09	-
O_{95}	mm	0.24	0.18	-
Vertical 2 kPa	m/s 10^{-3}	3	3	-
permeability 200 kPa	m/s 10^{-4}	5	5	-
Weight	g/m^2	155	250	340
Thickness 2 kPa	Mm	1.5	2.2	-

The wheel pressure applied was 700 kPa to simulate heavy-duty truck traffic loading. The test temperature was 60^{o}C. The wheel speed used was 20 passes/min, which corresponded to wheel speed of 0.3 km/h. In view of the high frequency of rainfall in Singapore, the test was conducted in saturated conditions. The rut depth was measured with a laser device (Micro Laser LM10) and recorded by an Autonomous Data Acquisition Unit (ADU). The sensor was located at the center of the wheel path and measured from a steel reflector mounted on the wheel. The longitudinal and transverse rut profiles were also recorded as the test progressed. The final profiles of the top surfaces of the surface course, base course and the subgrade were measured respectively at the end of a test.

4.2. Experimental Results

In the analysis of rutting potential, either the rut depth after 10000 wheel passes or the number of wheel passes that produced 20 mm rut depth was selected as the basis. The test results plotted in Figure 7 for the control specimens show that 20 mm rut depth occurred at about 6000 wheel passes. Initially the rut developed slowly until it reached around 4000 number of wheel passes. Thereafter rut depth increased rapidly and reached its failure state at about 8000 wheel passes. The test results of the two control specimens are also plotted in the figure for comparison. For the TS-1 specimen with TS 30 geotextile, the surface course began to fail after 5000 wheel passes. It reached 20 mm rut depth at about 6000 wheel passes. The rut depth of TS-2 specimen with TS 80 geotextile reached 20 mm at about 10000 wheel passes, displaying much higher rutting resistance than the TS-1 specimen and the two control specimens.

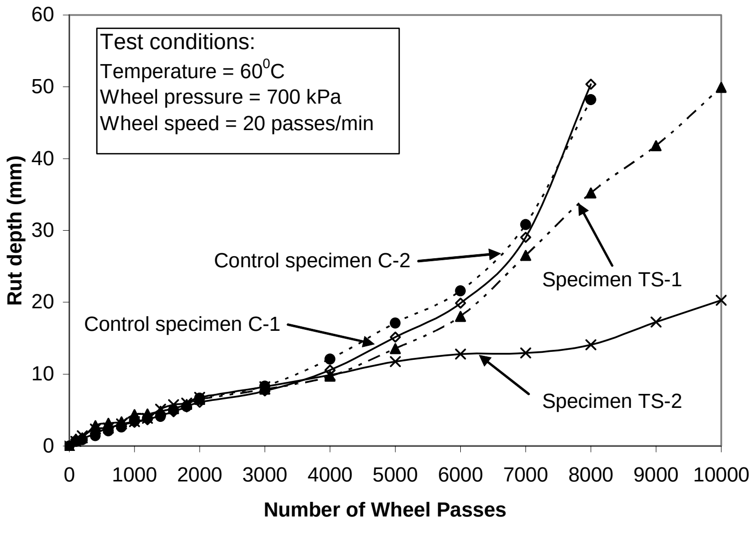


Figure 7. Comparison of Rut Depths of Control Specimens and Specimens with Non-Woven Geotextile

Two specimens ST-1 and ST-2 with Stratagrid 200 geogrid were tested and the rut depth results are shown in Figure 8. The rut depths of both specimens were about 6 mm after 10000 wheel passes. This suggests that the geogrid was able to improve the rutting resistance significantly. There were no signs of rutting failure up to 10000 wheel passes and the rate of rut depth increase remained at a relatively low rate compared with those of the control

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specimens. It is evident that the reinforcement function of the geogrid was effective in arresting rut depth development.

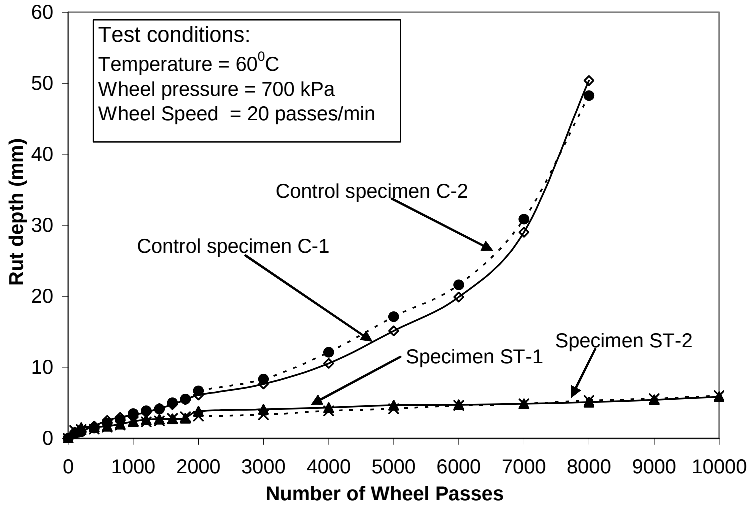

Figure 8. Comparison of Rut Depths of Control Specimens and Specimens with Geogrid

There were relatively little deformations in the subgrade in either direction for all the specimens. The depth of the subgrade layer was sufficiently large that it would not be affected much by the wheel loading whether there were geosynthetics or not. However, it was observed that there were downward intrusions of base course aggregates into the subgrade for specimens C-1, C-2, ST-1 and ST-2. This shows the importance of the use of geotextile in between the base and subgrade, and in preventing the loss of the base aggregates into the subgrade.

Specimens TS-1 and TS-2 were tested to study the role of non-woven geotextile as a separator between the base course and the subgrade. There are two possibilities of intermixing of base aggregate and subgrade soil, namely base clogging by migration of subgrade soil with rising water table and stone loss by the intrusion of base aggregates into the subgrade. It was observed that both specimens were able to withstand the wheel loading and the 10000 wheel passes. By visual inspection there was no damage or holes in the geotextiles, except some partial staining seen on them.

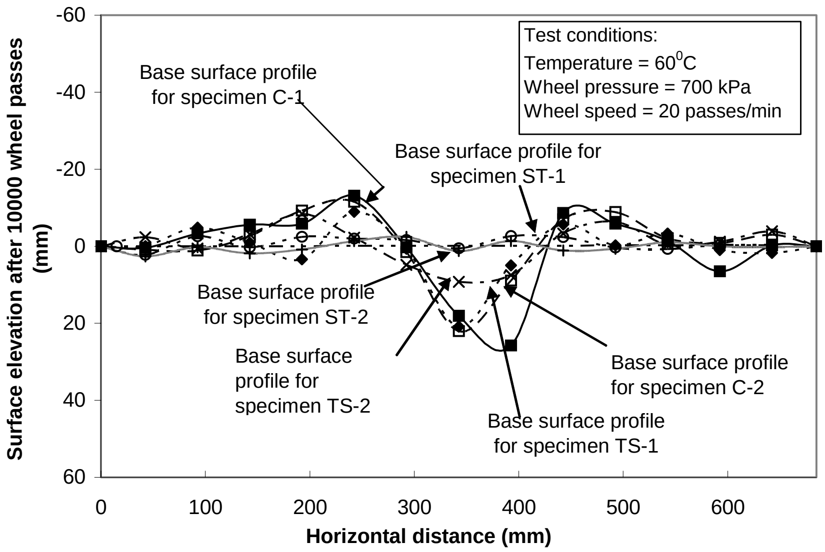

Figure 9. Transverse Surface Profile of Base Course

Figure 9 show the final rut profiles of the base course for all specimen types after 10000 wheel passes. The control specimens C-1 and C-2 and specimens TS-1 and TS-2 produced the largest rut depths of about 20 mm and 10 mm respectively. The base profile of ST-1 and ST-2 specimens showed very little deformation, indicating that the geogrid was effective in spreading the load to reduce localized deformation in the base. These findings were true for the deformation patterns along both longitudinal and transverse directions. It was noted that the geotextile in TS-1 specimen was not effective in restraining deformation in the base course, while the stronger geotextile in TS-2 specimen had some effect in doing so.

Figure 10 presents the rut profiles of the porous asphalt surface course for all the specimen types tested. The control specimens and the TS-1 specimens showed the highest deformations whereas specimens ST-1 and ST-2 showed the least deformations. For all the profiles measured, it was observed that the heaves on both sides of the rut had approximately equal volume to the volume of the rut. This suggests that displacement of material rather than densification of the layers had contributed to the rut formation. In comparison, there were hardly any heaving observed in specimens ST-1 and ST-2. It appeared that the geogrid was effective in resisting shear deformation and hence heaving of the surface course materials. Comparing the rut depths of the base surfaces and those of the surface courses, it could be concluded that about 60% or more of the final rut depths at the top surfaces were caused by deformation within the surface course of the various specimens. Geosynthetics were required to limit rutting in the surface and base course and the test results suggest that geogrid was necessary for this purpose.

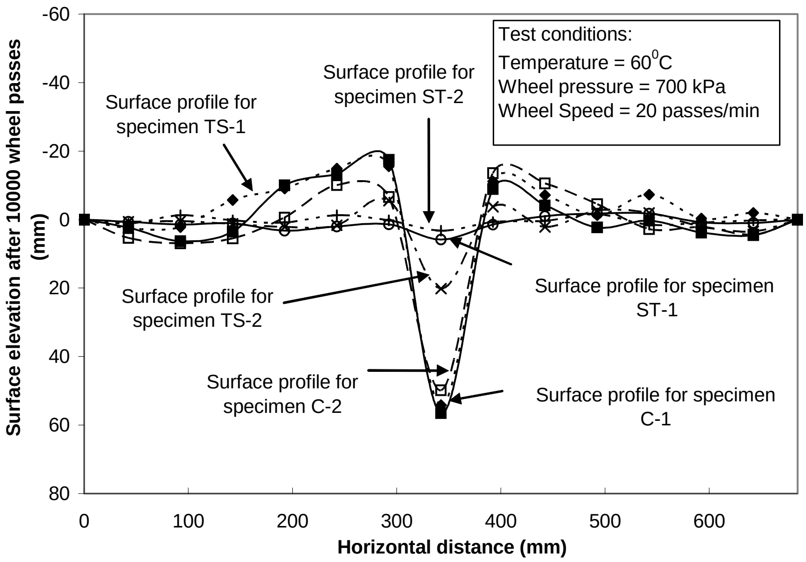

Figure 10. Transverse Surface Profile of Porous Asphalt Course

The above findings lead to the following recommendations for the proposed porous asphalt pavement system: (a) A geogrid reinforcement is recommended to be installed at the interface between the porous asphalt surface drainage course and the reservoir base course. The reinforcing function of the geogrid assists in load spreading, relieves tensile stresses at the bottom of the porous asphalt surface course, and resists lateral movement of pavement materials below and above it, thereby achieving the effect of reducing rutting resistance in the upper layers of the pavement structure. It is also useful to provide a stable base for the laying and compaction of the porous asphalt surface course. (b) A geotextile filter layer is recommended to be laid at the interface between the reservoir base course and the subgrade soil. Its main function is to prevent the fines of the subgrade soil from migrating upward into the reservoir base course which could be contaminated and become clogged. It also helps to provide a firm platform for the laying of the reservoir base course.

5. PROPOSED DESIGN FOR SINGAPORE ROADS AND CAR PARKS

Figure 11 presents the cross-sectional view of the recommended design of the porous asphalt pavement.

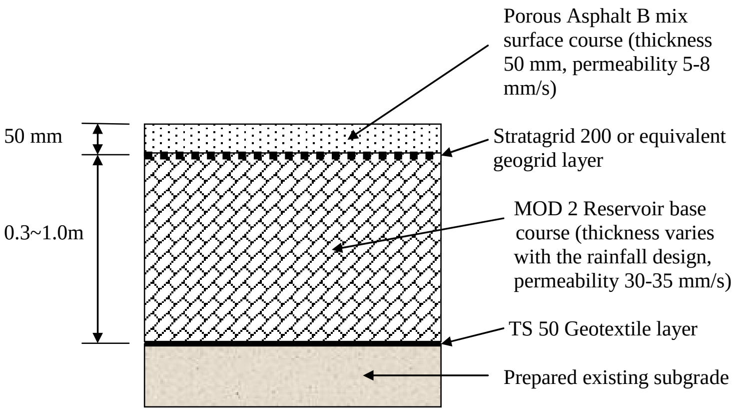

Figure 11. Cross section of the Designed Porous Asphalt Pavement

The thickness of the porous asphalt surface layer is 50 mm. The Stratagrid 200 or equivalent geogrid is placed in between the surface course and the reservoir base course to strengthen the surface course in order to improve the structural capacity and rutting resistance of the surface course. The thickness of the reservoir base course depends on design return period of rainfall. The TS 50 geotextile is placed in between the reservoir base course and subgrade soil in order to avoid the movement of the subgrade soil particles into the base course.

6. CONCLUSION

This paper provides a rational basis for the analysis and design of porous asphalt pavement for car parks and roads in Singapore. The selection of a suitable permeable base mix gradation is first described by studying the vertical drainage properties and the deterioration trends in permeability caused by clogging using the National University of Singapore (NUS) Falling Head Permeameter. Based on this study a suitable crushed stone gradation for the reservoir base course is recommended. Thickness design of the porous pavement based on hydrologic and drainage criterion is achieved through finite element modeling. This paper shows that there is a need to consider both the short term and the long term drainage control in the design. It has demonstrated that finite element simulation could be employed effectively to study the storage capacity need of a porous asphalt system. A porous pavement structure of a total thickness of the order of 1.2 m to 1.6 m was found to be adequate for the Singapore conditions and there is a need for a pumping scheme. Rutting resistance of the pavement structure is evaluated through large-scale laboratory wheel tracking tests. The use of geosynthetics for reinforcement and separation is explored. It is found in the experiments that the use of geogrid in the surface course-base course interface for reinforcement and the use of non-woven geotextile in the base-subgrade interface for separation are needed for the porous pavement structure to provide adequate rutting resistance under local conditions. Based on these three criteria, a recommended design of the porous asphalt pavement is proposed for car parks and roads for use in Singapore.

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