Assessment of Surface and Subsurface Drainage from Permeable Friction Course (As a Sustainable Pavement) under Different Geometric and Hydrologic Conditions

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Abstract

The permeable pavement seems to be an established stormwater management solution that may be utilized in parking and low-traffic areas. These pavements can reduce the amount of runoff that reduces the environmental impact compared with a traditional drainage system. Traditional drainage systems, which carry stormwater runoff quickly to a stream by piped systems, cause increases in runoff volume, peak flow, and pollutants are taken to rivers. This paper tests permeable asphalt pavement in a purpose-designed laboratory apparatus. To understand the hydraulic flow conditions and the runoff performance that occurred within two layers of permeable and conventional pavement. The thickness of the permeable layer is 25, 37.5, and 50 mm, and the conventional layer is 80 mm. An artificial rainfall covering an area of 1.5 ×1.0 m² is constructed to study the relationship between surface runoff and subsurface runoff from a permeable pavement under different geometric design parameters of a roadway. Five slopes set at 0.0, 2.5, 5.0, 7.5 and 10 % in a short direction, and four discharge as 20, 40,60 and 80 L/min are tested. The result demonstrated that 50 mm thickness is suitable for permeable asphalt pavement under the most slope, increasing subsurface runoff and decreasing surface runoff water.

Keywords: Subsurface drainage; Surface drainage; Permeable friction course; Permeable asphalt pavement; Runoff performance

1. Introduction

The fundamental function of pavement seems to be to disperse the applied loads of automobiles on the subgrade. Pavement comprises stacked layers of processed materials over the natural soil subgrade. The pavement design should provide a roadworthy surface with enough skid resistance, good light-reflecting elements, and minimal noise pollution (Al-Khafaji et al., 2018a; Al-Khafaji et al., 2018b; Hussain & Al-Khafaji, 2020; Hussain, 2020). The most important purpose is to guarantee that the transmitted stresses caused by loading conditions do not exceed the bearing capacity of the subgrade. Storage failure decreases serviceability due to cracking and ruts. We need to look at the causes of bituminous pavements failure before going into the maintenance approaches. Deformation of the pavement is the consequence of weakness in one or more pavement layers after a building has experienced movement. Cracking can accompany the deformation. Surface distortions may be a threat
to traffic. Rutting, Corrugations, Shoving, Depressions, and Swell are the fundamental kinds of surface deformation (Adlinge & Gupta, 2013).

Traditional drainage methods that employ piped systems to transport stormwater runoff fast to a stream result in increased runoff volume, peak flow, and contaminants entering rivers (Wang & Wang, 2018). Furthermore, in cities with combined sewage systems, water from impermeable surfaces is mixed with black and grey water (from toilets, washing machines, and other sources) and routed to wastewater treatment facilities. As a result, combined sewer networks may become overburdened and overflow at peak flow, releasing toxic chemicals into the environment. Climate change is causing certain challenges in tandem with this scenario. According to Stott (2016), since there is a significant association between maximum rainfall intensity and high temperatures, global warming may contribute to an increase in short-term floods. The widespread implementation of a sustainable urban drainage system (SUDS) efficiently increases drainage efficiency in metropolitan areas. SUDS is a stormwater management system that uses infiltration and in-situ storage to minimize runoff discharge. Treating water locally and lowering the danger of overloading stormwater distribution networks reduces urban flooding risk and runoff pollutant discharge considerably (Lu et al., 2019; Marshdi et al., 2021).

The efficiency of the packing relies on how maintenance is carried out. Based on the variables listed, it will deteriorate over time. Maintenance timing is essential. Asphalt pavement maintenance can be expected to include two resurfacing and programmed surface maintenance such as a crack filling. Maintenance costs will be higher for asphalt than for concrete pavements. Open-graded friction course (OGFC) is one solution to avoid this problem. OGFC expenses typically exceed those of standard mixes by 30 to 35 percent. The extra expense is caused by the additional mixture’s materials and the tools required for mixing. Long-term lower costs and maintenance savings balance the higher initial OGFC costs. Considering user expenses and traffic delays, using OGFC will be the cheapest compared to the entire life cycle cost. OGFCs are, therefore, an appealing option, cost-effective over standard pavements. Because water is the biggest pavements enemy, roadways advantage from the rapid water drainage that OGFC mixes permit. The structure of open aggregates enables runoff to flow down and into roadside ditches straight thru the friction course or driving to an impermeable intermediate course below. This removes tire spray and hydroplaning, improves friction on the moist pavement, increases the surface’s reflectivity, and decreases traffic noise, resulting in a more secure pavement (Ralla, 2018).

Permeable pavement (PP) is an established stormwater management solution that may be utilized in parking lots and low-traffic areas. These pavements may reduce runoff volume (Eck et al., 2012). One of the studies demonstrates that water quality in asphalt or concrete PP is almost similar (Welker et al., 2012). PP comes in two varieties: permeable asphalt and permeable concrete. Since they limit runoff volume, porous pavements are frequently referred to as OGFC. PP might be a low-development impact option and the finest stormwater management technique design: the design requirements, construction standards, and maintenance techniques influence PP quality. PP design and construction for various kinds of surfaces need hydrological and structural studies in order for the pavement to perform properly. The structure of the thickness with various that could sustain the design traffic is decided in the structural design of the pavement. The stormwater management goals are met in the hydrological study because runoff water may be filtered via the pavement. Though PP is initially more costly to build than normal impermeable asphalt pavement, the advantages gained over time will make PP highly cost-effective and increase water sustainability in the surrounding region (Terhell et al., 2015).

Completely PP has porous layers on both sides. During storms, the pavement structure acts as a reservoir, holding water and reducing the harmful consequences of stormwater runoff (Jones et al., 2010). A good PP takes into account structural and hydrological design. The pavement strength is considered in structural design to handle automobile loads without the pavement collapsing. The hydrologic design considers the capacity needed to penetrate, store, and release water in a way that helps with stormwater management. There are three design techniques for PP systems. They are first and
foremost utilized to promote total rainwater penetration into the soil subgrade. Second, partial subgrade infiltration occurs when soil subgrade infiltration rates are modest, with the remaining water exiting via underdrains. Third, for designs that do not need infiltration, PP systems are encircled by a geomembrane, preventing detained water from entering the soil subgrade and releasing the stored water via underdrains (Al-Khafaji et al., 2022).

Rainfall on a PFC pavement has two components: flow inside the body and flow over the surface. In dry conditions, with steady rainfall intensity, water flow is as described in the following: Water enters the PFC pavement pores and then flows out laterally without surface ponding. A PFC body’s water flow is classified as laminar or turbulent (Pathak et al., 2020). Rainfall intensity, pavement geometry, and porous asphalt properties affect a PFC’s hydrologic properties. The hydrologic properties of PFC pavement of various lengths and slopes were estimated numerically. The same water flow channel was evaluated with lengths of 10, 15, 20, and 30 m and slopes of 0.5, 2, 4, 6, and 8% (Nguyen & Ahn, 2021).

To assess the time for water to flow across PFC pavements, varied rainfall intensities from 10 to 120 mm/h were simulated. The time for water overflow decreased with increasing pavement length or rainfall intensity but increased with increasing slope. It was also determined as long it would take water to flow over a PFC pavement surface at different rainfall intensities. Because this study used numerical data, further research is required to verify the conclusions experimentally.

The pavement’s structural design is finished to determine the thickness of the various pavement layers needed to support the expected layout traffic to safeguard the subgrade from deformation (Hein & Eng, 2014). This study aims to indicate how much the permeable asphalt pavement (PAP) can reduce runoff quantity under different rainfall storms with a wide combination of roadway geometric design parameters.

2. Experiments Setup

The apparatus demonstrated in Fig. 1 is designed to simulate rainfall events PAP which consist of four parts:

A. The steel box has 1.5 × 1.0 m dimensions and is used to place pavement layers.

B. Rainfall simulator consists of 16 PVC perforated pipes with 97.5mm spacing, 12.5mm diameter, and holes of 2mm diameter are drilled uniformly along each pipe. This part is used for simulating the uniform rainfall event.

C. The water supplying system consists of a pump, flowmeter with a range of flowrate (20 to 110) L/min, and water supplying pipe used to supply water to rainfall simulator.

D. Collecting boxes: The runoff water is collected by a mesh of boxes under pavement layers, one box for surface flow and the other for subsurface flow, as demonstrated in Fig. 2.

The flow of the runoff water was through the pavement. Then it was collected in two containers. Using the slope in a steel box, the water runoff is collected by a mesh of boxes under pavement layers. One box for surface flow and the other for subsurface flow; this apparatus could allow runoff drainage from porous pavement surface during wet conditions, containers with length =1000 mm, width=150 mm, and height =200 mm.
3. Pavement Structure

The structural pavement consists of the conventional layer and the permeable friction course layer. The permeable surface layer is designed to a thickness of (25, 37.5, and 50 mm) according to Table 1. The conventional subsurface layer is designed to a thickness of (80 mm), and the aggregate gradation has met the gradations required by SCRB specifications (SCRB, R/9 2003), as demonstrated in Table 2. The optimal binder amount is found by using asphalt contents which are limited from (5.5 to 6.5) % (OAC±0.5%) by Satyakumar et al. (2013). The optimum asphalt content achieved condition is 6.3%. Data from a restricted amount of literature research depend on the design structure of permeable pavement. Considering the more critical structural demands of the permeable pavement layer, if the pavements are needed to perform truckloads, the gradation of aggregate used in the permeable pavement should be as suggested by ASTM (2013), as demonstrated in Table 3 and Fig. 3.
Table 1. Possible applications for various OGFC mixtures (Ballestero et al., 2008)

<table>
<thead>
<tr>
<th>Size of Mix (mm)</th>
<th>Asphalt is kind</th>
<th>Application</th>
<th>The thickness of the layer (in)</th>
</tr>
</thead>
<tbody>
<tr>
<td>9.5</td>
<td>OGFC</td>
<td>Parking recreational facilities</td>
<td>1.5 - 3.5</td>
</tr>
<tr>
<td>12.5</td>
<td>OGFC</td>
<td>Wearing surface, road, streets, heavy commercial</td>
<td>2.0 - 4.0</td>
</tr>
<tr>
<td>19</td>
<td>OGFC</td>
<td>Wearing surface, road, heavy commercial</td>
<td>2.0 - 5.0</td>
</tr>
<tr>
<td>19</td>
<td>Asphalt treated permeable base</td>
<td>Base course</td>
<td>3.0 - 6.0</td>
</tr>
</tbody>
</table>

Table 2. According to SCRB, R/9 (2003), aggregate gradation of a conventional mixture

<table>
<thead>
<tr>
<th>Sieve size</th>
<th>mm</th>
<th>Midpoint gradation</th>
<th>Base Course gradation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 ½ in</td>
<td>37.5</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>1</td>
<td>25.0</td>
<td>95</td>
<td>90-100</td>
</tr>
<tr>
<td>¾</td>
<td>19.0</td>
<td>83</td>
<td>76-90</td>
</tr>
<tr>
<td>½</td>
<td>12.5</td>
<td>68</td>
<td>56-80</td>
</tr>
<tr>
<td>⅛</td>
<td>9.5</td>
<td>61</td>
<td>48-74</td>
</tr>
<tr>
<td>No. 4</td>
<td>4.75</td>
<td>44</td>
<td>29-59</td>
</tr>
<tr>
<td>No. 8</td>
<td>2.36</td>
<td>32</td>
<td>19-45</td>
</tr>
<tr>
<td>No. 50</td>
<td>300 µm</td>
<td>11</td>
<td>5-17</td>
</tr>
<tr>
<td>No. 200</td>
<td>75 µm</td>
<td>5</td>
<td>2-8</td>
</tr>
</tbody>
</table>

Table 3. The gradation of aggregate for a porous binder of asphalt.

<table>
<thead>
<tr>
<th>Sieve size (mm)</th>
<th>(ASTM, 2013)</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Minimum</td>
</tr>
<tr>
<td>19</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>12.5</td>
<td>85-100</td>
<td>85</td>
</tr>
<tr>
<td>9.5</td>
<td>35-60</td>
<td>35</td>
</tr>
<tr>
<td>4.75</td>
<td>10-25</td>
<td>10</td>
</tr>
<tr>
<td>2.36</td>
<td>5-10</td>
<td>5</td>
</tr>
<tr>
<td>0.075</td>
<td>2-4</td>
<td>2</td>
</tr>
</tbody>
</table>

Fig. 3. The gradation of aggregate depending on (ASTM, 2013)
4. Experimental Work

In this study, 60 experiments of different combinations of hydraulic and roadway geometric conditions are done: The simulator system used four distinct flow rates such as 20, 40, 60, and 80 L/min, and each had five slopes (0.0, 2.5, 5.0, 7.5 and 10) % in the brief path. The rainfall is applied into 3 min period; the runoff water is collected and measured into a collecting box along the length of the apparatus. The designer may consider using paving patterns appropriate for rapid building machine installation. The permeable pavement consists of fine and coarse aggregates coupled with mineral filler to fulfill the SCRБ specifications (SCRБ, R/9 2003) at the mixer machine; the mixed aggregate was then heated up to 160 degrees centigrade before blending with asphalt cement. The properties of the mixer meet the specifications of EN 12697-35 (2004) with a max container volume of 30 liters, a container velocity of 5 to 35 rpm, and a max temp of 220 degrees centigrade. The use of crumb rubber altered asphalt in combination was established in two significant procedures; the moist process describes any technique that adds Crumb Rubber to bitumen, then mixed well before integrating the modified binder in the blend. The dry process describes any technique that adds CR to the HMA blend. In such a study, the wet method was used using a blending machine with a blending speed of 2620 rpm, and the blending temp in this work was in the range of 190-200 degrees centigrade for 60 minutes blending time. Crumb Rubber was 15% of Asphalt cement by weight. These additive levels were chosen by literature review. To generate a kinematic viscosity of 170±20 centistokes, the asphalt cement was heated in the oven at a temp of 150 degrees centigrade in order to achieve the desired amount, then modified asphalt cement was added to the heated aggregates thoroughly mixing by mixer operation at speed 20 rpm for a couple of minutes until whole the aggregates coated with asphalt cement mixture. The same procedure is applied to the conventional pavement except that the mixture does not contain additives.

5. Results and Discussion

The results are approaching as they were obtained in the laboratory; figures present the results obtained for surface and subsurface flow. For the low rainfall intensities and zero slopes roadways (flow rate of 20 L/min at 0.0% slope), runoff water from the subsurface layer is higher than the surface layer because the runoff water firstly fills the pavement voids and the layers below it before flowing through the bottom of the pavement in the container direction. At higher side slopes with high rainfall intensities, the runoff water from the surface layer is greater than the subsurface layer. The runoff water from the subsurface layer increased with increasing thicknesses of PAP until the surface runoff water was zero.

5.1 At 25 mm Thickness

As shown in Fig. 4, for the low rainfall intensities (20 and 40)L/min and slopes roadways at 0.0, 2.5, 5, 7.5, and 10 %, the surface runoff water is less than the subsurface water. Surface runoff water increased with increasing rainfall intensities (60 and 80) L/min at all slopes, and there was no infiltration rate (Charbeneau & Barrett, 2008).
Fig. 4. Surface and subsurface drainage from the permeable pavement at (25) mm thickness with different roadway slopes (0, 2.5, 5, 7.5, and 10) and different rainfall intensities (20, 40, 60, and 80 L/min).

5.2 At 37.5 mm Thickness

As shown in Fig. 5, the surface runoff water is less than the subsurface water by increasing the thickness of PAP. For the low rainfall intensities 20 L/min and slopes roadways at 0.0, 2.5, 5, 7.5, and 10 %, the surface runoff water is less than the subsurface water, and there is no infiltration rate. Surface runoff water is augmented with the rainfall intensities (40, 60, and 80) L/min and slopes roadways at 0.0, 2.5, 5, 7.5 and 10 %, but it remains less than the subsurface water.
Fig. 5. Surface and subsurface drainage from the permeable pavement at (37.5) mm thickness with different roadway slopes (0, 2.5, 5, 7.5, and 10) and different rainfall intensities (20, 40, 60, and 80 L/min)
5.3. At 50 mm Thickness

As shown in Fig. 6, the surface runoff water is equal to zero for the low rainfall intensities (20 and 40) L/min and slopes roadways at (0.0) %. In this case, the surface runoff water is much less than the subsurface runoff water for all rainfall intensities with all slopes. This is the best thickness for permeable asphalt pavements to decrease the negative impacts of stormwater runoff, and the infiltration rate is also equal to zero.
6. Conclusions

The use of crumb rubber improves the asphalt and develops the characteristics of a permeable asphalt mixture. The material was compacted until getting the required thickness of the material. Permeable asphalt pavements increased subsurface runoff water and decreased surface runoff water depending on the corresponding combinations of rainfall intensities, thicknesses, and slopes. The effect of thickness is highly significant compared to slopes, and rainfall intensities, where increasing the thickness from 25 mm to 50 mm leads to an increase in the slopes and rainfall intensity that causes runoff for pavement surface to decrease until it reaches zero.

Acknowledgements

The authors would like to thank Al-Mustaqbal University College for providing technical support for this research. The authors are very grateful to the reviewers, Editor in Chief Prof. Dr. Salih M. Awadh, the Secretary of Journal Mr. Samir R. Hijab, and the Technical Editors for their great efforts and valuable comments.

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