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# Effect of Slope on Stormwater Infiltration into Porous Asphalt Pavements

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**Abstract:** Porous asphalt pavements and water-retentive asphalt pavements are widely used because of their ability to infiltrate both rainfall and stormwater runoff. There is very limited information available to assist designers of porous asphalt pavement systems to be installed on sloping sub-catchments. This is because the infiltration performance of these systems has only been investigated experimentally for horizontal pavements, and their performance on sloping terrains has only been investigated theoretically. This experimental study investigates the relationship between rainfall intensity, pavement slope, runoff and infiltration rates for dense-graded asphalt, porous asphalt and water-retentive asphalt concrete pavements. Three rates of simulated rainfall were applied to porous, water-retentive and dense-graded asphalt specimens set at three different pavement slopes, namely 0°, 3° and 5°. The relationship between the porosity and permeability of the porous asphalt pavements was also determined. A porosity of 20% resulted in a permeability of greater than 1 mm/s. It was found that the porous asphalt specimens had excellent runoff retention and infiltration rates at all slopes. The water-retentive asphalt specimens also produced good infiltration rates at horizontal slopes, but these decreased at higher pavement slopes.

**Keywords:** porous asphalt pavement; nature-based solutions; water-retentive asphalt concrete; stormwater infiltration; sloping permeable pavement; water-sensitive urban design

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## 1. Introduction

### 1.1. Background

Many countries have tried to address climate change and subsequent extreme weather events by future-proofing their cities to make them less prone to drought and more flood-resilient [1,2]. For example, China's *Sponge City* program was instigated in 2013 and was aimed at encouraging the adoption of low-impact nature-based solutions to better manage stormwater drainage and reduce urban runoff. The proposed solutions included the increased implementation of porous asphalt, the construction of new detention storages and the restoration of wetlands. With the continuous advancement of China's *Sponge City* program, more attention has been paid to the construction of urban roads in China. In particular, the use of porous asphalt is seen as an important tool to control urban runoff [3].

Porous asphalt pavements differ from ubiquitous, impermeable, dense-graded asphalt in that particles finer than 600 µm are excluded from the aggregate mix, thus facilitating the formation of larger void spaces into which stormwater can infiltrate. Typically, porous asphalt pavement surfaces have air void contents in excess of 18% compared to dense-graded asphalt pavements, which typically have air void contents in the 3 to 8% range [4]. Porous asphalt usually consists of stone aggregate, an asphalt binder material and other modifiers, and it should have a typical air void content of between 18 and 22% [5]. This high air void content allows the expansion of water to ice, and so freeze–thaw cycles have

little effect on porous asphalt pavements. Consequently, these systems have been used in a wide range of climatic conditions, from ice-affected countries such as Canada and Belgium to warm-climate regions such as Southern China. However, like all permeable systems, designers have to be aware of the potential for pollutants leaching into groundwater, for example, where de-icing chemicals might be used. Despite these constraints, these systems offer developers an effective source control measure for managing stormwater. Porous asphalt pavements are used mainly for car parking areas and low-speed residential roads. They allow stormwater to infiltrate through the pavement surface into an underlying gravel base course layer. From there, the harvested stormwater can either infiltrate into the underlying native soil (subgrade) for groundwater recharge or it can be discharged through a system of embedded perforated drainage pipes.

Both rainfall landing directly on the pavement and surface runoff from adjacent contributing areas infiltrate through the porous pavement into the underlying base course layer for detention and storage. This significantly reduces stormwater runoff and subsequent urban flooding [6], improves receiving water quality [7] and promotes stormwater harvesting and reuse [8]. Additional benefits of porous asphalt pavements include reduced splash and spray during vehicle movements and improved wet-weather frictional characteristics [9]. As with any open-graded surface, porous asphalt can become partially clogged due to the deposition of the sediment that is carried in stormwater runoff. While cleaning porous asphalt pavements is not a widespread practice in many countries, maintenance measures can include sweeping, vacuum sweeping or pressure washing to reinstate the infiltration capacity of the pavement [9]. The most effective cleaning strategy is a combination of suction and sweeping, although sweeping alone is almost as effective and far less expensive [10]. Even when cleaning costs are included, a study of 250 installed pavement projects by the UK permeable paving professional organization Interpave showed that porous and permeable pavements are more cost-effective than dense-graded asphalt pavements when whole-of-life costs are considered [11].

The type of porous asphalt concrete (PAC) used in the pavement is usually defined by the nominal maximum aggregate grain size of the PAC gradation. For example, one of the most commonly used types is PAC-13, which has a nominal maximum aggregate size of 13 mm [12]. In recent years, there have been several studies focusing on the runoff performance of PAC, but nearly all of these have considered only horizontal (non-sloping) pavements. For example, Li et al. [13] measured the reduction in permeability of PAC-10 and PAC-13 specimens when subjected to fine particle clogging in a laboratory. They found that the larger the porosity and nominal maximum grain size, the better the PAC's anti-clogging performance. This finding was consistent with an earlier study by Martin et al. [14], who investigated clogging in PAC pavements with 10 different gradations that are commonly used in the USA. They found a strong correlation between maximum aggregate size and permeability before and after clogging. Overall, their results demonstrated that the larger the maximum aggregate size and porosity, the more permeable the PAC. However, none of the above studies considered sloping PAC specimens or pavements. No experimental studies on sloping PAC pavements appear to be available, but Tan et al. [15] developed a finite element model to simulate the effects of slope on these systems. They found that both the longitudinal gradient and the cross slope of a road section significantly affected the infiltration capacity of the porous pavement. They also developed a series of thickness-requirement graphs, plotted as functions of design rainfall, the thickness of the surface course layer, the width of pavement and longitudinal and cross slopes. However, these theoretical curves were neither calibrated nor verified with experimental data.

Water-retentive asphalt concrete (WRAC) is produced by incorporating a water-retentive slurry (WRS) into the PAC [16]. WRS can consist of various amounts of granulated blast furnace fly ash, calcium hydroxide and mixing water. In terms of costs, WRAC is marginally more expensive than PAC because of the water-retentive slurry that is required. Also PAC is slightly more expensive than dense-graded asphalt because of the attention required in its manufacture. However, the actual costs for each type depend on the scale

of the project, and for large construction projects, the incremental cost increases would be relatively low. The use of WRS has been shown to reduce the surface temperature of WRAC pavements and is considered a promising tool for ameliorating the urban heat island (UHI) effect [16]. Yamagata et al. [17] investigated the UHI mitigation potential of spraying recycled wastewater on a WRAC pavement and showed that this could decrease the pavement surface temperature by 8 °C during the day and by 3 °C during the night. Spraying recycled wastewater also reduced the sensible heat flux while increasing the latent heat flux. Nakayama and Fujita [18] evaluated the cooling effect of a WRAC pavement (consisting of porous asphalt and a water-holding filler made of steel by-products based on a silica compound) on water and heat budgets. They compared the results with both PAC and dense-graded asphalt pavements and found that the air temperature above the WRAC pavement was 1 to 2 °C lower than that above a nearby grassed area and 3 to 5 °C lower than that above adjacent rooftops. Elmagarhe et al. [19] investigated the effects of the addition of fly ash (FA) on the overall performance of a PAC-10 mixture. They found that the addition of 4% FA reduced the PAC permeability by approximately 12% while also lowering the PAC air void content from approximately 23.5% to 22.95%. Other studies have investigated the effects of replacing cement with FA in porous concrete. For example, Liu et al. [20] studied FA applied to porous concrete and found that the FA-modified porous concrete (9% FA) designed with an equivalent volume replacement of cement did not affect the porosity, and the permeability of pervious concrete hardly changed with the content of FA compared to the unmodified control pervious concrete. Aoki et al. [21] examined the permeability and compressive strength of porous concrete modified by FA with cement replacement levels of 20% and 50%. The compressive strengths of 20% and 50% FA-modified porous concrete decreased by 12.7% and 43.7%, respectively. However, the permeability of the modified porous concrete was not affected by the addition of FA.

### *1.2. Study Objectives*

The experimental study set out in this paper aims to address the knowledge gaps described above by investigating the relationship between rainfall intensity, runoff and infiltration rates for dense-graded asphalt, PAC and WRAC pavements. In addition, this study aims to understand the influence of longitudinal slope on these relationships.

In terms of risk and reward, there is no denying that even porous asphalt has a low albedo due to its dark colouration. This means it may be viewed in a poor light by sustainability advocates because of its perceived contribution to urban heat island effects. However, its porous nature offsets this effect by allowing water to infiltrate through its surface. This porosity also allows the same water to evaporate, thereby cooling the pavement through the transfer of latent heat. Therefore, the reward for this risk is not only the provision of source control of urban stormwater but also the creation of cool pavements to ameliorate the urban heat island effect, particularly in regions of frequent rainfall in summer.

## 2. Materials and Methods

### *2.1. Experimental Environment*

The experimental tests were conducted in the civil engineering concrete laboratory at the Xi'an University of Architecture and Technology, located in the city of Xi'an in the northwest region of China. All tests were conducted at an ambient room temperature of 13 °C and at an ambient humidity of 61%.

### *2.2. Asphalt Materials*

In the laboratory environment, the infiltration and runoff performance were investigated using three types of asphalt specimens, namely PAC-13, WRAC and dense-graded asphalt.

#### 2.2.1. Porous Asphalt

In this study, PAC-13 porous asphalt concrete specimens were prepared according to the requirements of the relevant standard [22]. The gradation of a porous asphalt mixture with a porosity of 20% was selected (Figure 1). The specific material specifications and the final specimen properties are shown in Table 1.

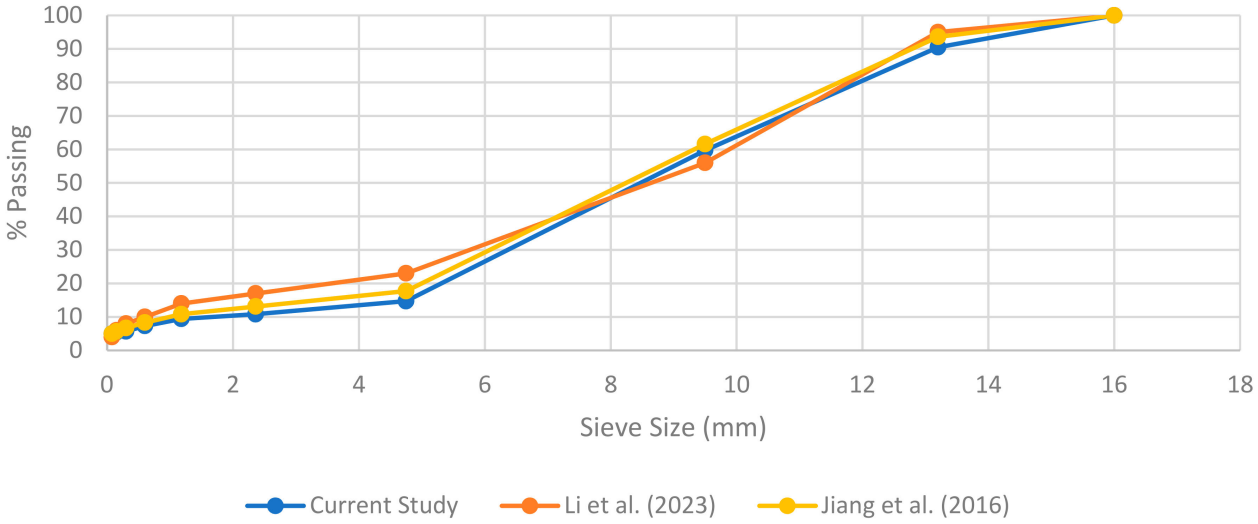


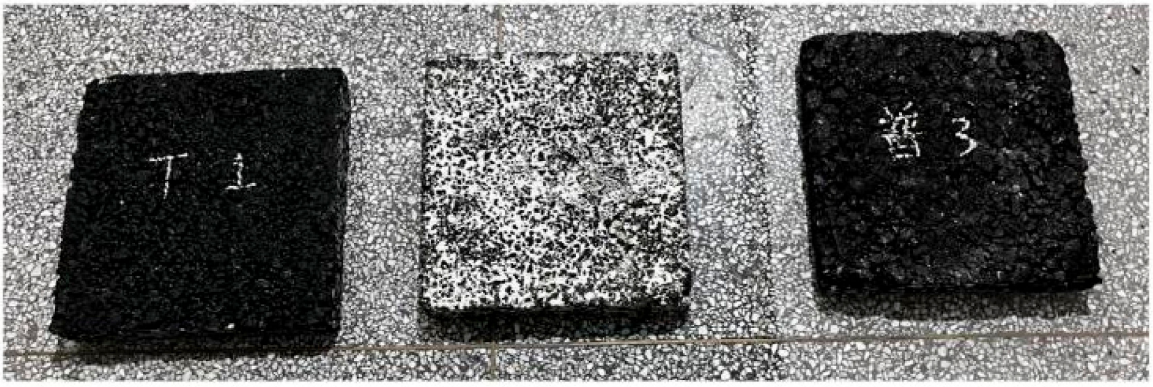

**Figure 1.** PAC-13 particle size distributions [13,16].

**Table 1.** Material specifications and properties for PAC-13 specimens.

| High-Viscosity Asphalt | |
|---|---|
| Coarse aggregate | 10–15 mm and 5–10 mm diabase gravel |
| Fine aggregate | 0–3 mm sand |
| Mineral powder | limestone powder |
| Fibre | 0.3% lignin fibre by weight |
| Mineral ratio | Coarse aggregate (5–10 mm): Coarse aggregate (10–15 mm): Fine aggregate: Mineral powder = 46:43:7:4 |
| Optimum asphalt content | 5.39% |
| Gross weight | 5000 g |
| Asphalt dosage | 5.1%, 255 g |
| Aggregate weight (gross weight–bitumen–fibre mass) | 4730 g |

For comparison, Figure 1 shows the PAC-13 mixture gradation used in this study plotted against PAC-13 gradations used in two other recent studies [13,16]. It can be seen from Figure 1 that the materials used in this experimental investigation are comparable to those used in previous studies.

According to the requirements of the Chinese National Standard *JTG E20–2011: Standard Test Methods of Bitumen and Bituminous Mixtures for Highway Engineering* [23], porous asphalt test specimens of size 300 mm (length) × 300 mm (width) × 50 mm (thickness) were prepared (Figure 2a). The permeability coefficient was tested using a falling head laboratory permeameter for each of the three PAC-13 specimens, and the average of the three tests was 0.108 cm/s.



(**a**) PAC-13 (**b**) WRAC (**c**) Dense-graded

**Figure 2.** Three types of asphalt specimens used in this experimental study.

#### 2.2.2. Water-Retentive Asphalt Concrete

Water-retentive asphalt concrete (WRAC) includes a water-retentive slurry (WRS). The composition of the WRS used in this study and the performance requirements of the raw materials are shown in Table 2. Fly ash powder is a common additive to WRAC and is a good example of sustainable reuse of waste materials.

**Table 2.** Material specifications and properties for WRS.

| Material Composition | Composition Ratio | Raw Material Properties |
|---|---|---|
| S95 grade slag micro-powder | 90% | Average particle size of slag powder < 75 μm and specific surface area > 400 kg/m$^2$ |
| Fly ash powder | 10% | Average particle size of fly ash < 75 μm |
| Calcium hydroxide (% of S95 + fly ash powder) | 17% | pH of the liquid phase > 11 during mixing |
| Water (% of S95 + fly ash powder) | 70% | Normal tap water |

According to the requirements of the relevant standard [24], three WRAC test specimens of size 300 mm (length) × 300 mm (width) × 50 mm (thickness) were prepared (Figure 2b). The permeability coefficient was tested for each WRAC specimen using a falling head laboratory permeameter, and the average of the three tests was 0.107 cm/s.

#### 2.2.3. Dense-Graded Asphalt

According to the requirements of the Chinese National Standard *JTG D50-2006: Specifications for Design of Highway Asphalt Pavement* [25], the mix design of the AC-20F anti-rutting dense-graded asphalt concrete surface course with 70#A grade road petroleum asphalt was used. An asphalt mixture gradation with a porosity of 4.0% was selected, and the optimal asphalt content was 4.05%. The mixture gradation is shown in Table 3.

**Table 3.** Dense-graded asphalt mixture gradation.

| **Mesh Size (mm)** | **26.5** | **19** | **16** | **13.2** | **9.5** | **4.75** | **2.36** | **1.18** | **0.6** | **0.3** | **0.15** | **0.075** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Passing Percentage (%) | 100.0 | 94.6 | 85.8 | 74.4 | 63.5 | 45.7 | 32.5 | 22.3 | 14.1 | 10.6 | 7.8 | 6.1 |

According to the requirements of the relevant standard [23], three dense-graded asphalt test specimens of size 300 mm (length) × 300 mm (width) × 50 mm (thickness) were prepared (Figure 2c). The permeability coefficient was tested for each dense-graded asphalt specimen, and the average of the three tests was 0.00593 cm/s.

### *2.3. Experimental Methods*

#### 2.3.1. Rainfall Application Device

A rainfall application device (RAD) was used to apply various uniform rainfall intensities to the paver surfaces. The RAD consisted of a shower rose of the same dimensions as the asphalt specimens (300 mm × 300 mm), and its purpose was to simulate various intensities of incident rainfall. Three rainfall intensities were used in the experiments [6], namely *light rain* (33 mm/h), *moderate rain* (93 mm/h) and *heavy rain* (173 mm/h).

#### 2.3.2. Infiltration Chamber

In total, nine asphalt specimens were tested, which consisted of 3 × PAC-13, 3 × WRAC and 3 × dense-graded asphalt specimens. This allowed the testing of two additional replicates for each asphalt type. Before testing, each specimen was placed in a drying oven at 25 °C for more than 6 h until the weight of the specimen did not change. The dry weight was then recorded. In order to investigate both the infiltration through and the runoff over the asphalt specimens, these were sealed into an infiltration chamber, as shown in Figure 3. The chamber was fixed within a steel frame that could be set at three slopes, namely 0°, 3° and 5°.

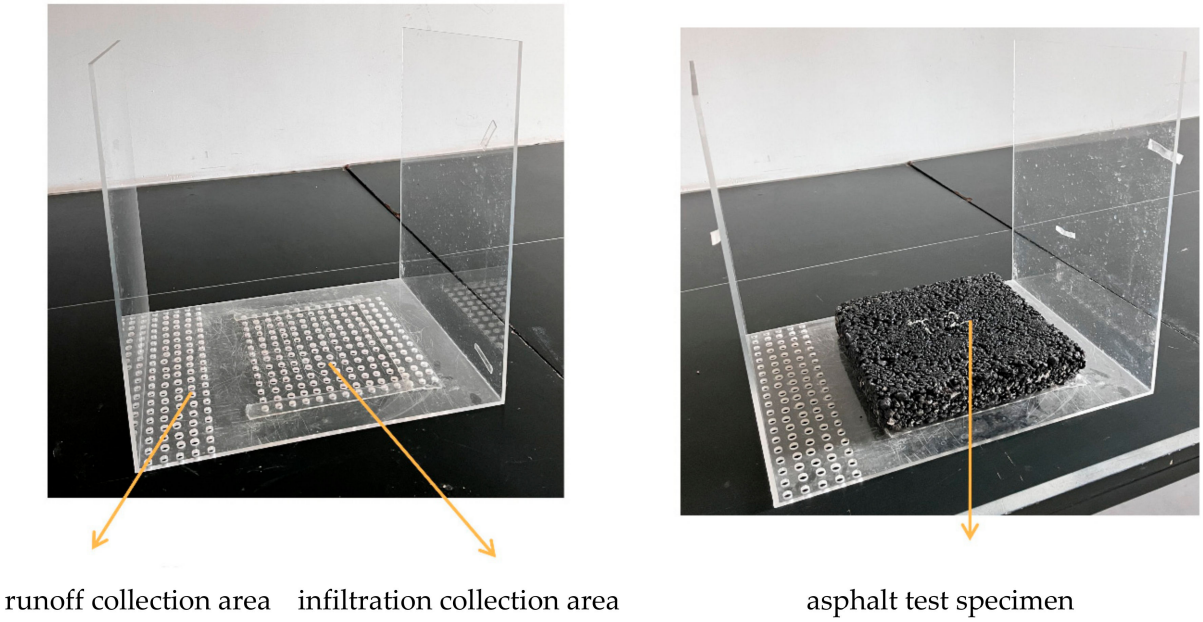



**Figure 3.** Experimental infiltration chamber.

The RAD was then used to apply the rainfall intensities to the asphalt test specimens in the experimental setup shown in Figure 4.

To avoid water seepage from the specimen edges, their sides were wrapped in plastic sheeting prior to installation in the infiltration chamber. Simulated rainfall was then applied across the asphalt specimens through a 300 mm × 300 mm square shower rose. Once each rainfall rate was set, the time taken for infiltrated water to penetrate through to the underside of the specimen was recorded. Two electronic weighing scales (model: ACS-HY-809B; accuracy: ±5 g) were employed to record the weight of both the infiltrating water and the runoff water from the asphalt specimens.

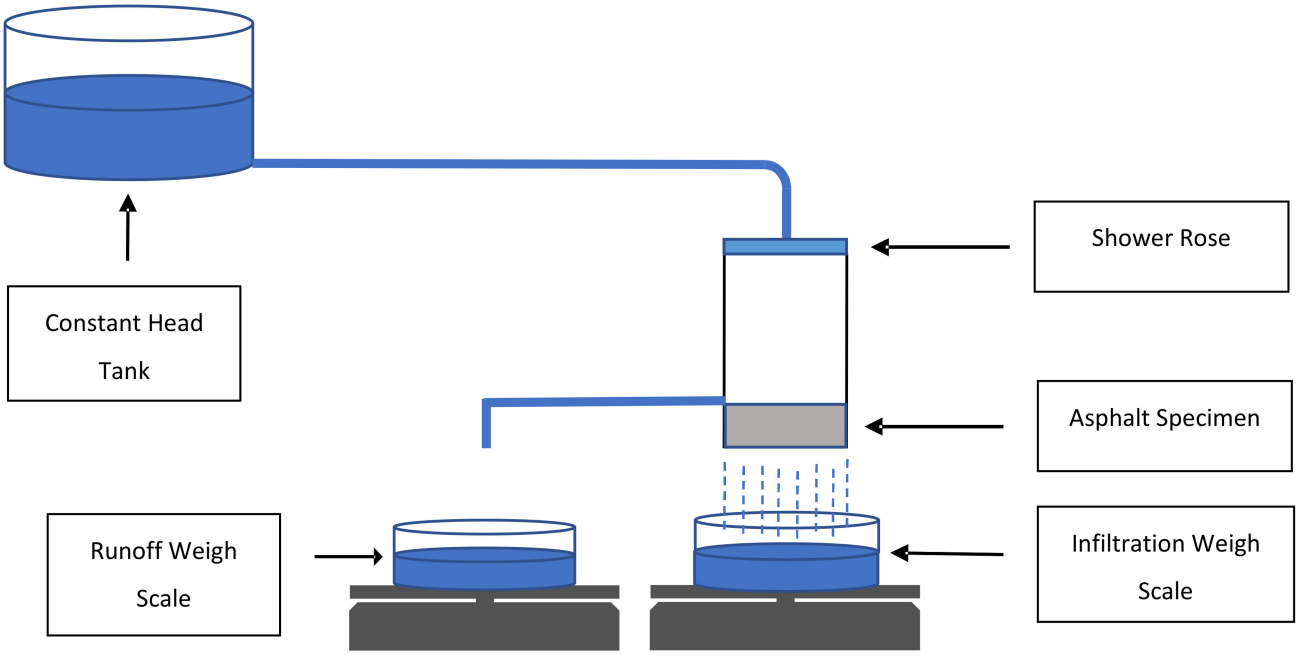



**Figure 4.** Infiltration apparatus for testing asphalt specimens.

A pre-experiment verified that after 30 min the system became stable for all three rainfall rates, so the experiment duration was set to 30 min. The earliest time of rainwater infiltrating through each test specimen, the earliest time of rainwater runoff, the amount of infiltrated rainwater and the amount of runoff every 1 min were recorded for a total of 30 min. At the end of each experiment, the specimens were removed immediately, and their wet masses were recorded. This procedure was repeated for all three specimens of each asphalt type (PAC-13, WRAC and dense-graded) and for all three rainfall rates, namely light rain (33 mm/h), moderate rain (93 mm/h) and heavy rain (173 mm/h). The entire experiment was repeated for slopes of 0°, 3° and 5° by tilting the steel frame in which the infiltration chamber was mounted.

## 3. Results and Discussion

### *3.1. Runoff and Infiltration Response Times*

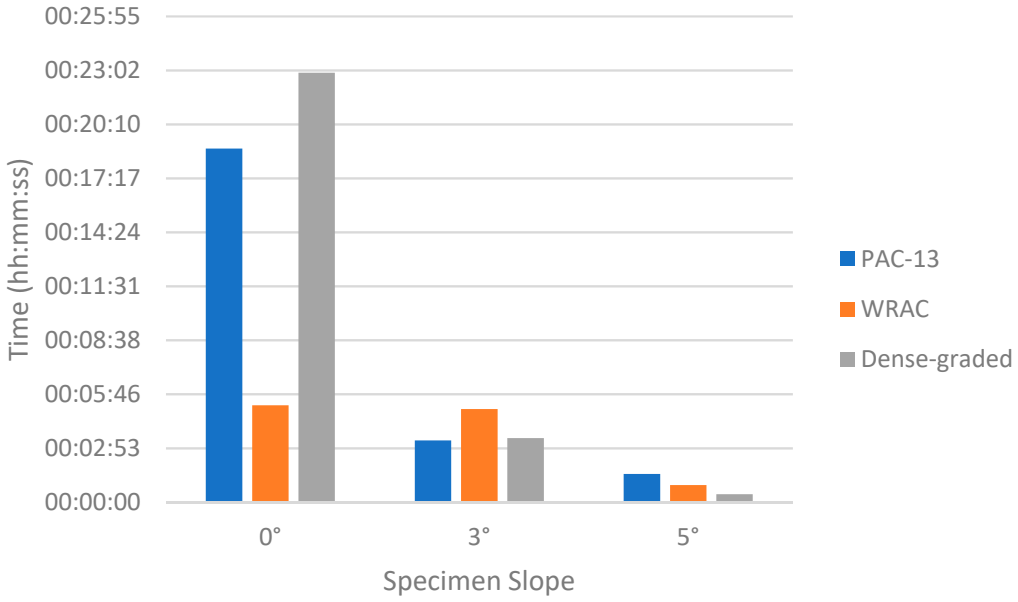
#### 3.1.1. Runoff Times

Figure 5 shows the results of the time taken before runoff was recorded for each type of asphalt specimen for light, moderate and heavy rain. All time readings represent the average of three specimen values for each asphalt type.

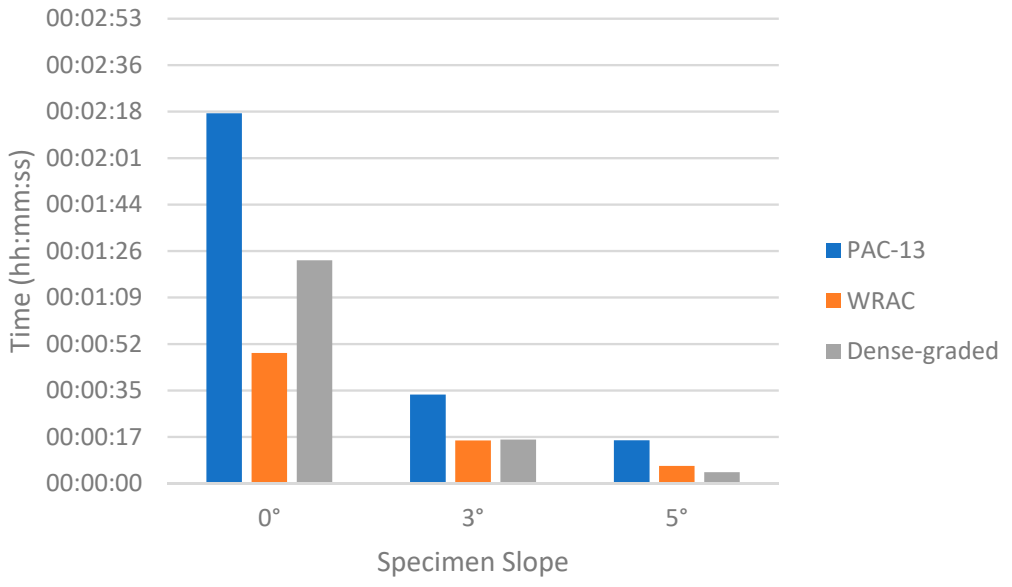
It is clear that for light rain (33 mm/h), all three asphalt types were able to produce no runoff for longer periods at lower slopes (Figure 5a). In other words, the time to runoff commencement was greater at 0° than at 3°, which in turn was greater than at 5°. This is likely to be because the infiltration capacity of the two porous asphalt specimens (PAC-13 and WRAC) and the wetting and ponding capacity of the dense-graded specimens were sufficient to retain the light rainfall rate that was applied. However, once the slope was increased, this capacity was reduced. This is particularly evident for the impermeable, dense-graded asphalt, which produced runoff after only 25 s at a slope of 5°, probably because the ponding capacity at this slope is minimal.

It is also clear that the WRAC specimens were able to detain potential runoff at both 0° and 3° slopes despite having a slightly lower permeability (k = 0.107 cm/s) than the PAC-13 specimens (k = 0.108 cm/s). This is likely to be due to two inter-related factors. The first is the capacity of the water-retentive slurry (WRS) that allows WRAC specimens to hold on to infiltrated water. The second factor is the different flow pathways that exist in

the three asphalt types, which are described by Li et al. [13] and are shown schematically in Figure 6.

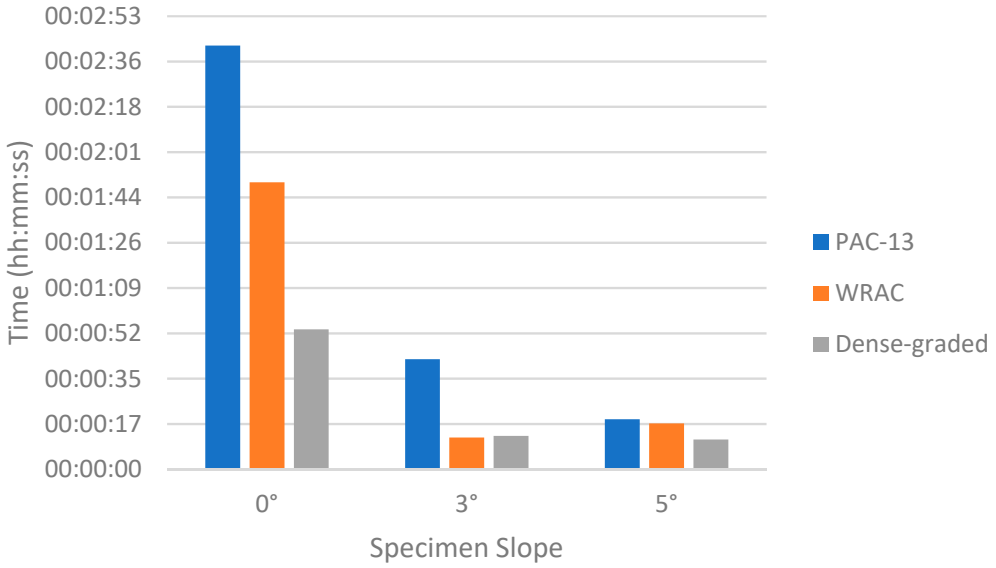



(**a**) Light rain




(**b**) Moderate rain

**Figure 5.** *Cont.*




(**c**) Heavy rain

**Figure 5.** Time to commencement of runoff from asphalt specimens.

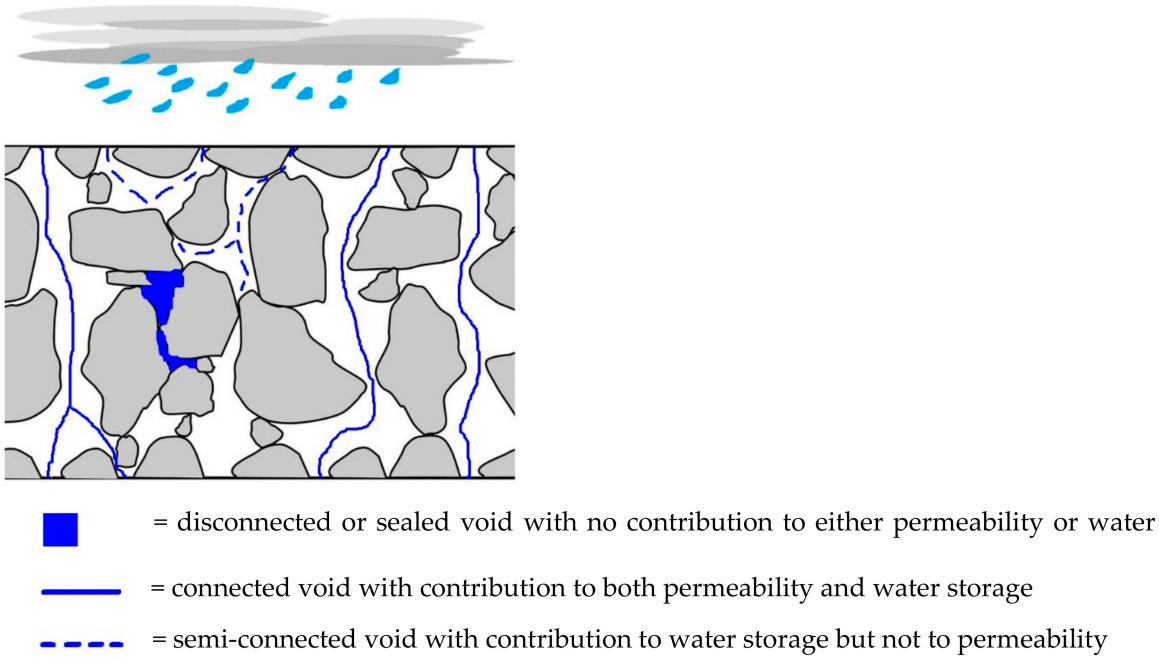



**Figure 6.** Schematic diagram of void connections in porous asphalt.

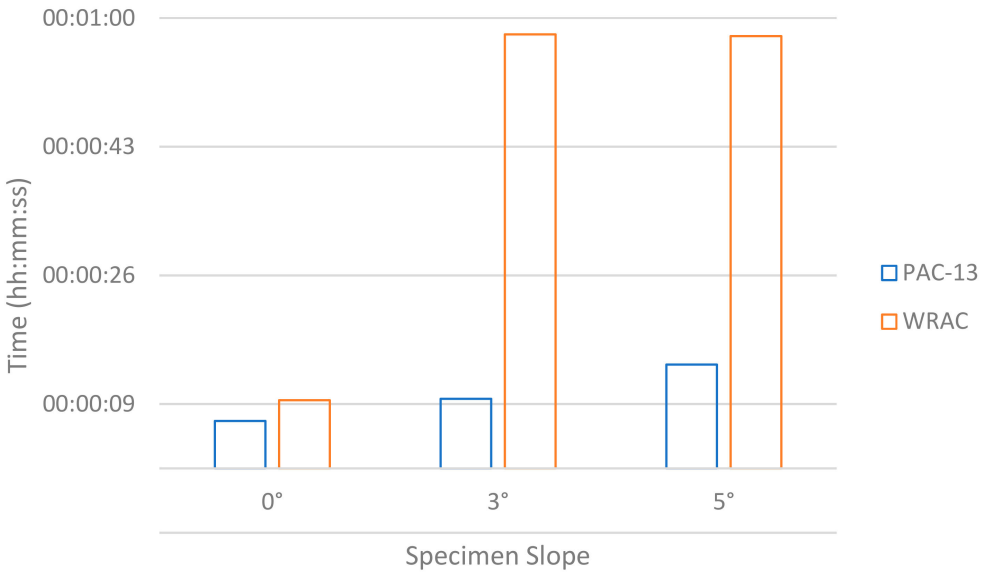
The PAC-13 specimens have more connected voids, as demonstrated by their having the highest permeability values. In the WRAC specimens, some of those connected voids will have been converted to semi-connected voids by the presence of the WRS material, although the WRS material itself will be able to absorb more infiltrating water. The dense-graded specimens will have mostly disconnected or sealed voids, as illustrated by the very low permeability values. Sun et al. discussed this effect for dense-graded asphalt mixtures modified with super-absorbent polymers [26].

The times to commencement of runoff for moderate (Figure 5b) and heavy rain (Figure 5c) were much lower (up to three minutes) than for light rain (up to 23 min)

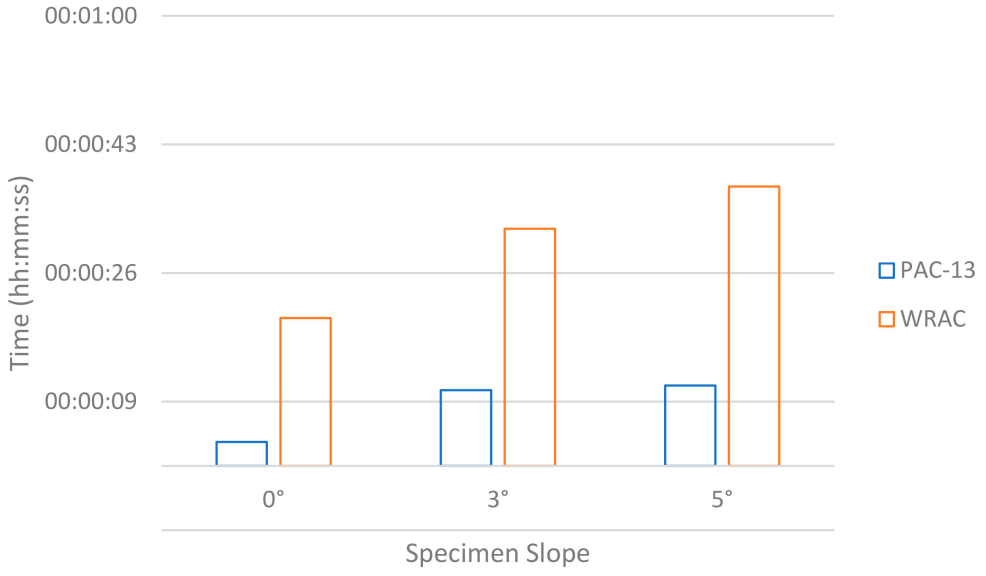
but showed the same trends. The PAC-13 detained runoff for the longest periods, partly because of its higher permeability.

#### 3.1.2. Infiltration Times

Figure 7 shows the time taken before infiltrated water first appeared on the underside surface of the two types of porous asphalt, namely PAC-13 and WRAC. The three graphs are for light, moderate and heavy rain, respectively. All time readings represent the average of three specimen values for each asphalt type.

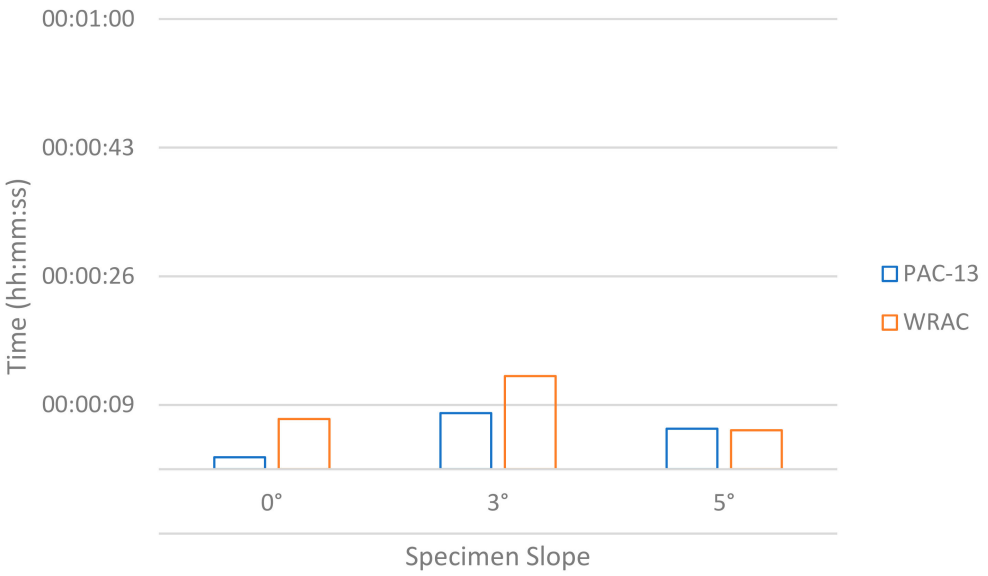



(**a**) Light rain




(**b**) Moderate rain

**Figure 7.** *Cont.*




(**c**) Heavy rain

**Figure 7.** Time to commencement of infiltration through porous asphalt specimens.

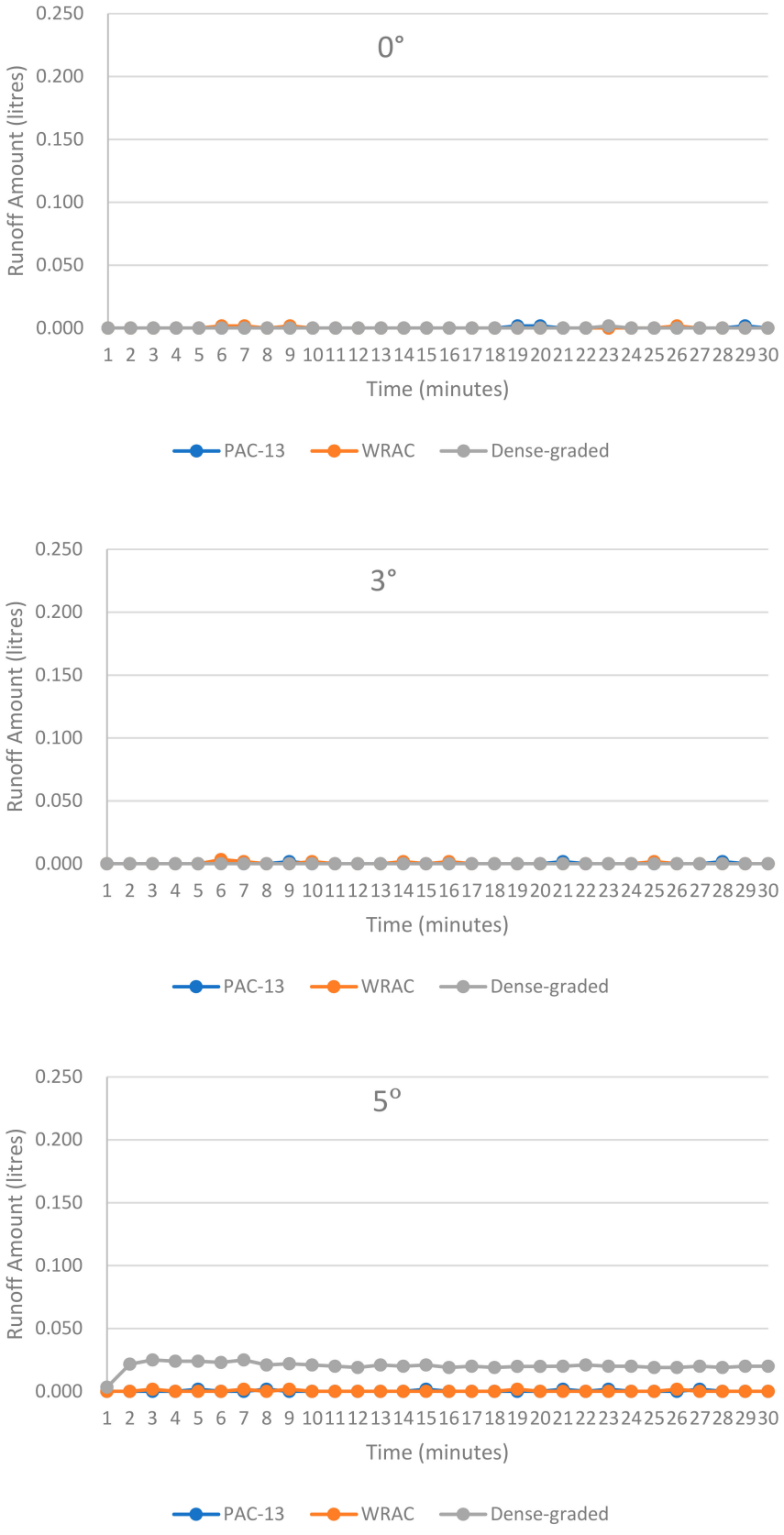
In Figure 7, the water retention capacity of the WRAC specimens is clearly evident, with much longer times than PAC-13 before infiltrated water appeared for both light and moderate rain. This delay is likely to be due to water absorbance with the WRS, which only occurs in the WRAC specimens. For heavy rain, this effect is reduced, presumably due to the faster rate of infiltration as more rainfall impacts the upper surface per second.

The effect of slope on the time taken before infiltrated water first appeared is again clearer for light and moderate rain, with the time being less at 0° than at 3°, which in turn was less than at 5°. This is probably because higher slopes cause more runoff and, therefore, less infiltration. However, for heavy rain, the time taken before infiltrated water first appeared actually decreases between 3° and 5°. This is probably due to the very quick time involved (≈5 s).

### *3.2. Runoff and Infiltration Rates*

#### 3.2.1. Runoff Rates

Figure 8a shows that for light rain (33 mm/h), the two porous asphalt specimens (PAC-13 and WRAC) generated hardly any runoff (<0.003 L/min), even at a slope of 5°. The dense-graded asphalt specimens were the only ones to produce sustained runoff, but only at the 5° slope, when their maximum runoff rate increased to 0.025 L/min. For moderate rain (93 mm/h), the dense-graded asphalt and WRAC specimens produced runoff for all three slopes, but the PAC-13 specimens again generated very little runoff (<0.015 L/min) even at the 5° slope (Figure 8b). From Figure 8c, even at the heavy rainfall rate (173 mm/h), the PAC-13 specimens only generated reasonable runoff (>0.007 L/min) once the slope increased to 3° and 5°, when their maximum runoff rates reached 0.038 and 0.091 L/min, respectively. At this rainfall rate, the dense-graded asphalt specimens produced the highest runoff rates for all three slopes, while the WRAC specimens produced the second-highest runoff rates. It is interesting to note that there are only two out of nine graphs in Figure 8 where dense-graded asphalt does not produce the highest runoff. Both of these occur with moderate rainfall, and even then, the differences are not large.




(**a**)

**Figure 8.** *Cont.*

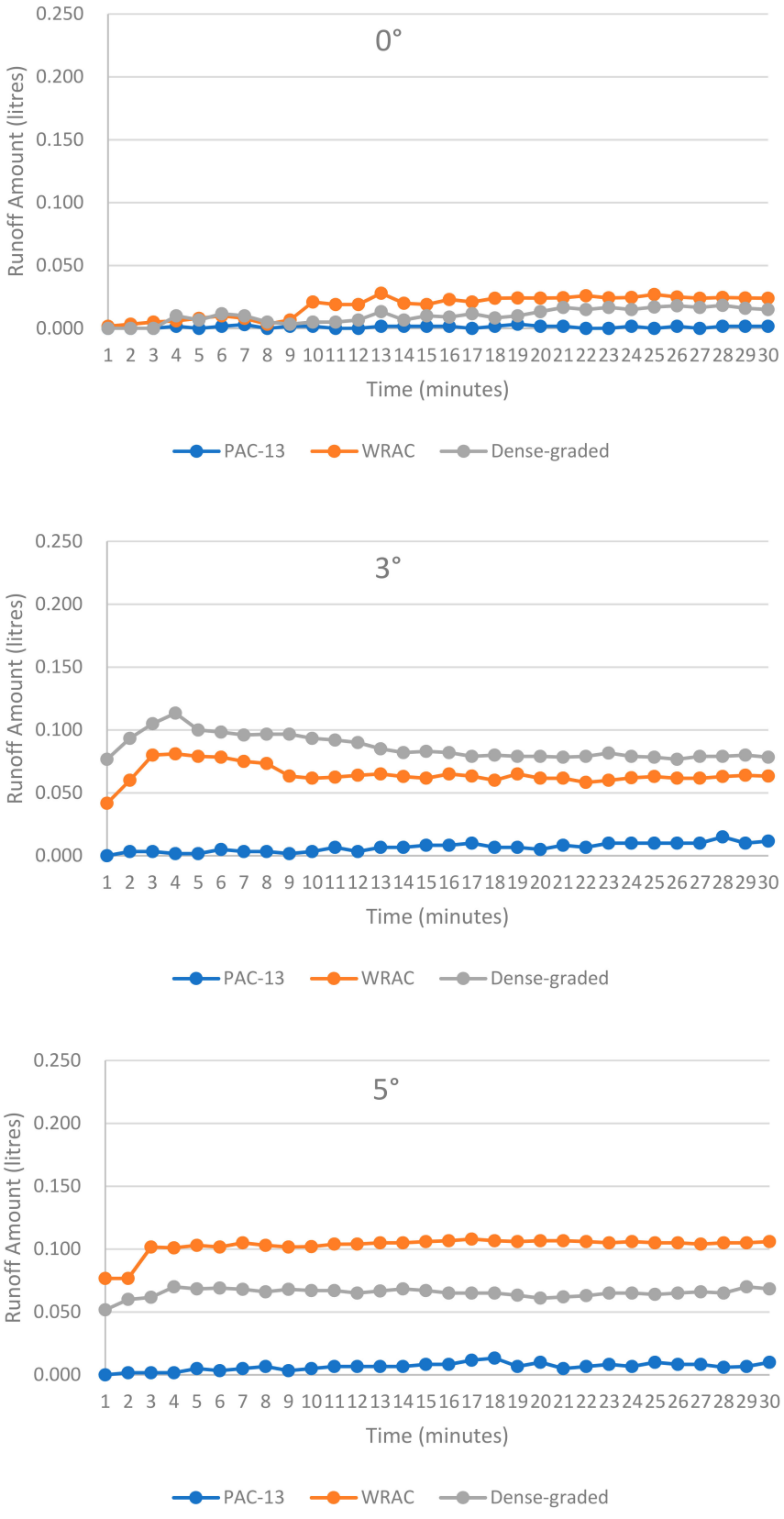



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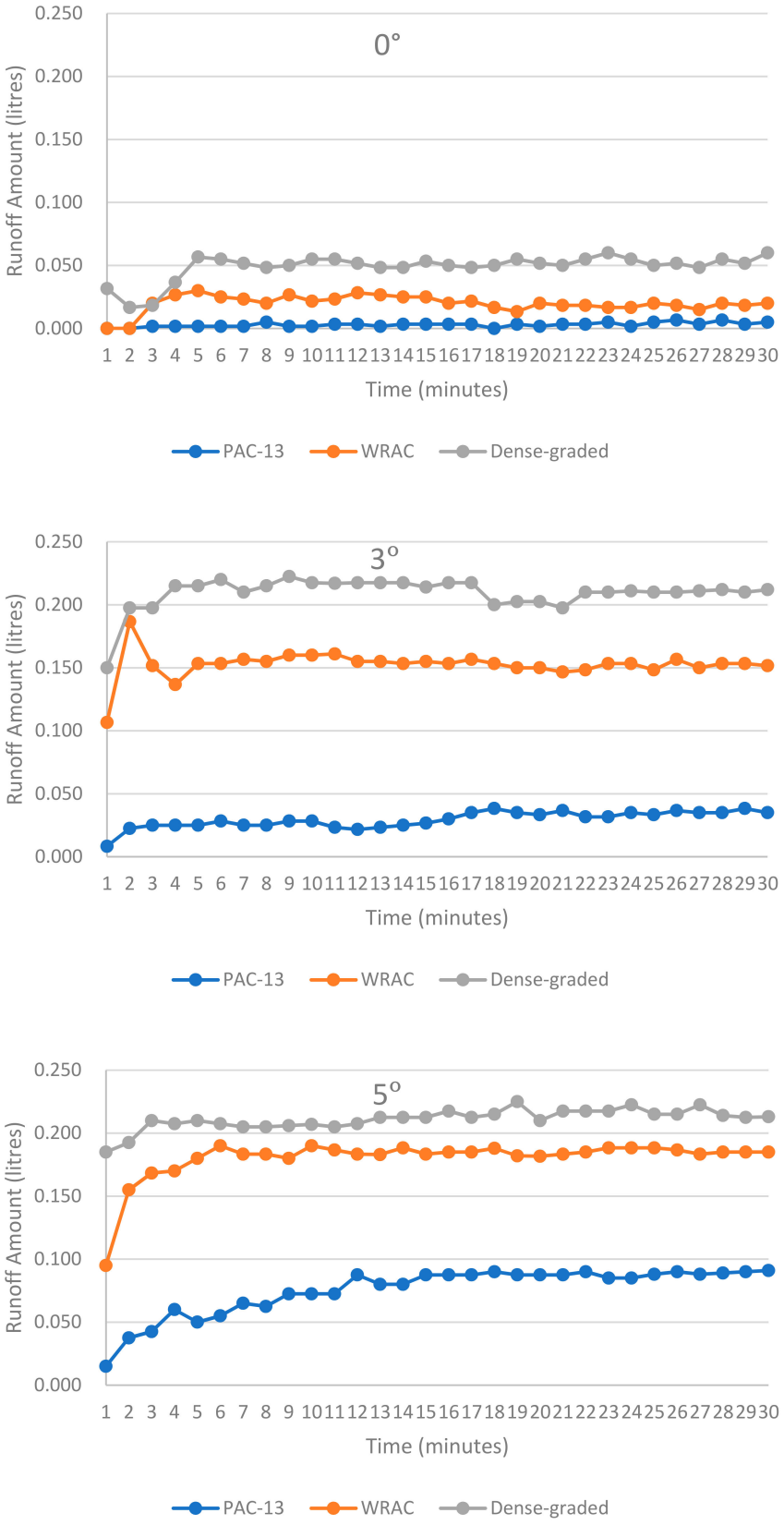
**Figure 8.** *Cont.*




(**c**)

**Figure 8.** (**a**). Runoff rates from asphalt specimens for light rain. (**b**). Runoff rates from asphalt specimens for moderate rain. (**c**). Runoff rates from asphalt specimens for heavy rain.

3.2.2. Infiltration Rates

Figure 9a shows that for light rain (33 mm/h), the PAC-13 specimens had higher infiltration rates than the WRAC specimens, although this difference decreased with increasing slope. For moderate rain (Figure 9b), the PAC-13 specimens more than doubled their infiltration rates compared to the same slopes for the light rain case. For the 0° slope, the WRAC specimens also more than doubled their infiltration rates compared to the 0° light rain case. However, the WRAC infiltration rates decreased at both the 3° and 5° slopes. Similar trends were evident for the case of heavy rain (Figure 9c), where again, the PAC-13 specimens were able to infiltrate at higher rates than for the moderate rainfall case at all three slopes. This demonstrated the high infiltration capacity of PAC-13. For the 0° slope at the heavy rainfall rate (173 mm/h), the WRAC specimens also increased their infiltration rates compared to the 0° light rain case. However, the WRAC infiltration rates again decreased at both the 3° and 5° slopes.

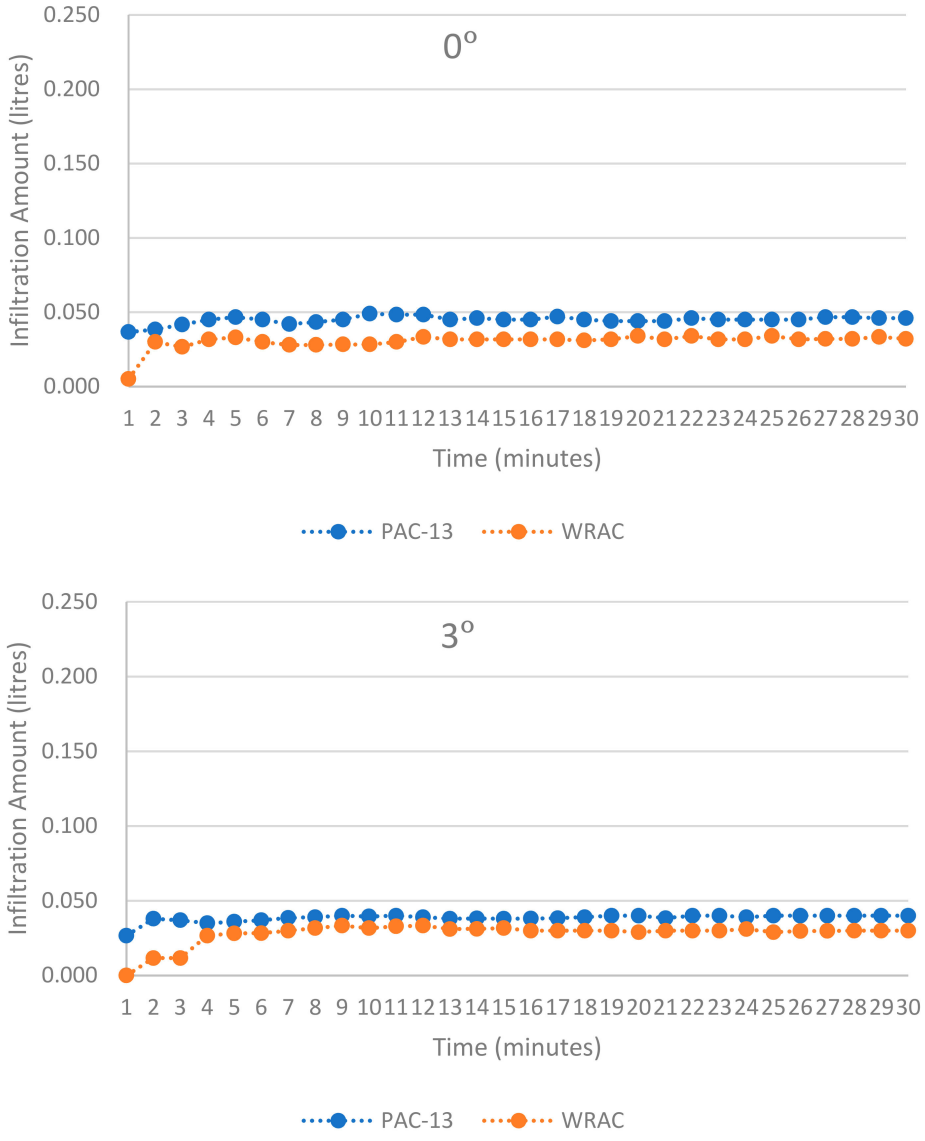
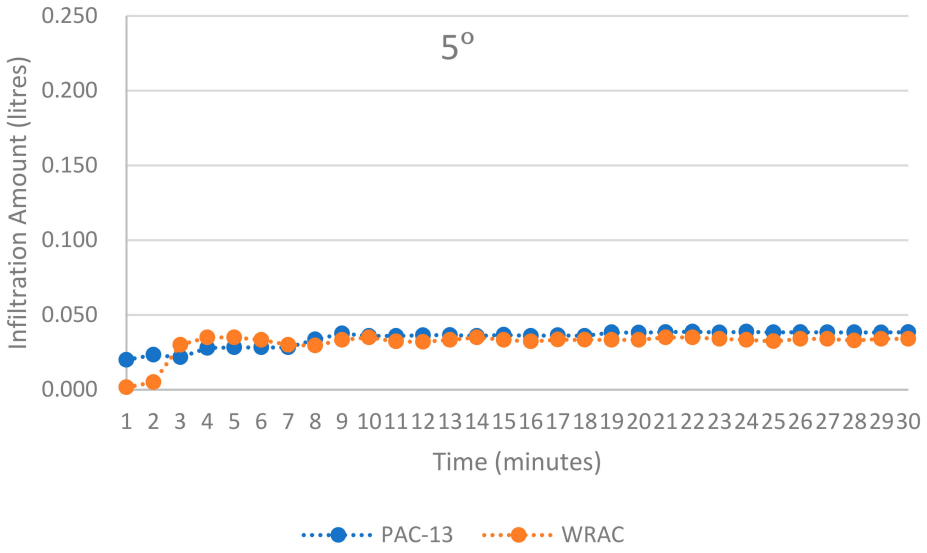
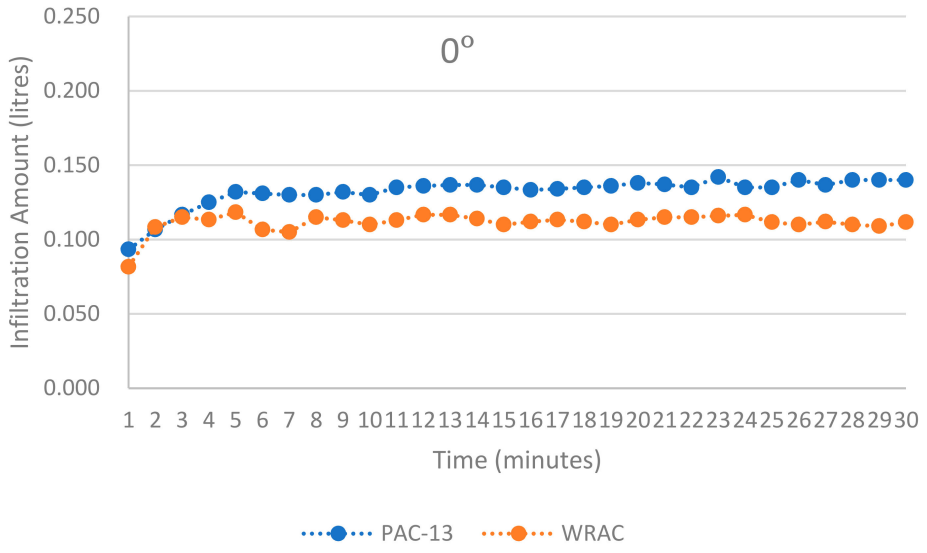



**Figure 9.** *Cont.*




**(a)**



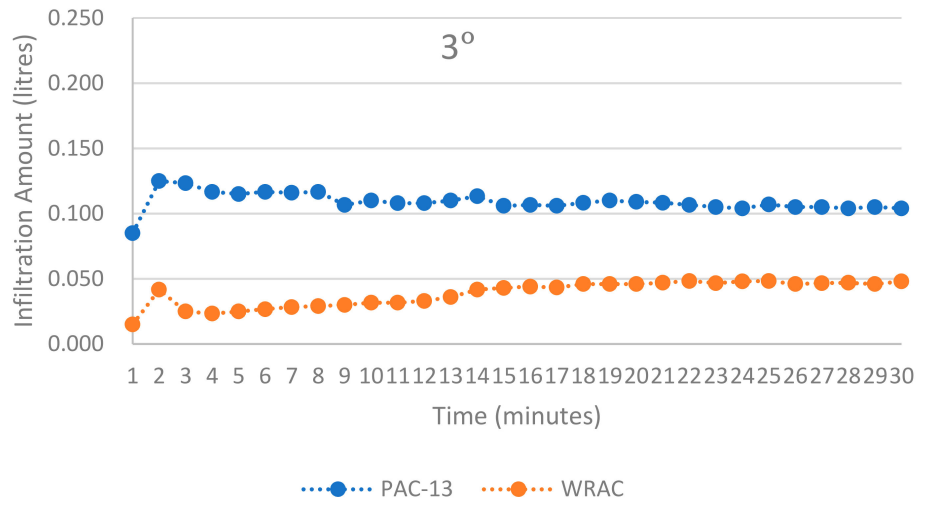
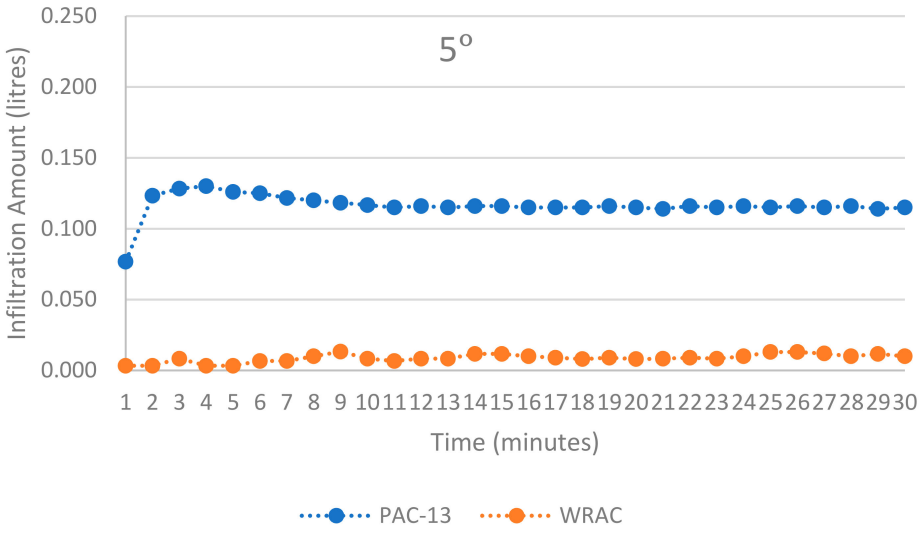
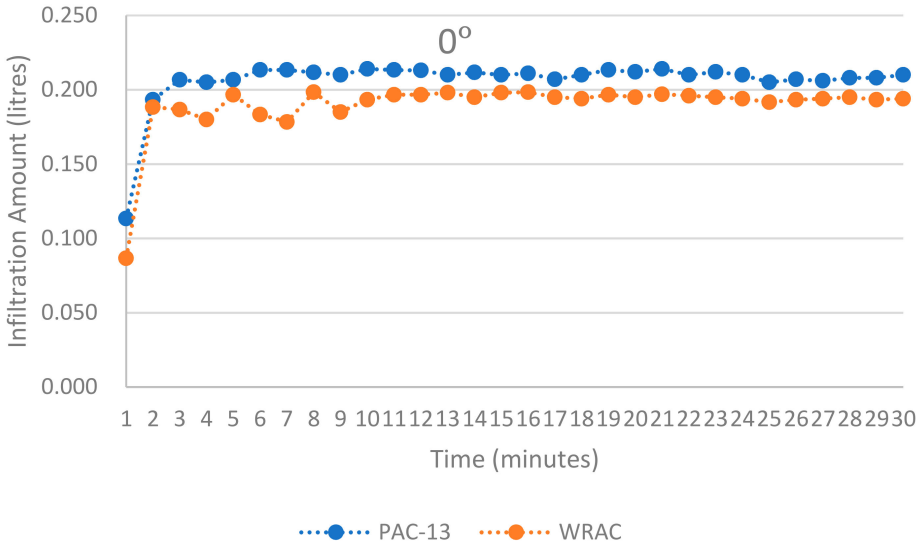




**Figure 9.** *Cont.*




(**b**)



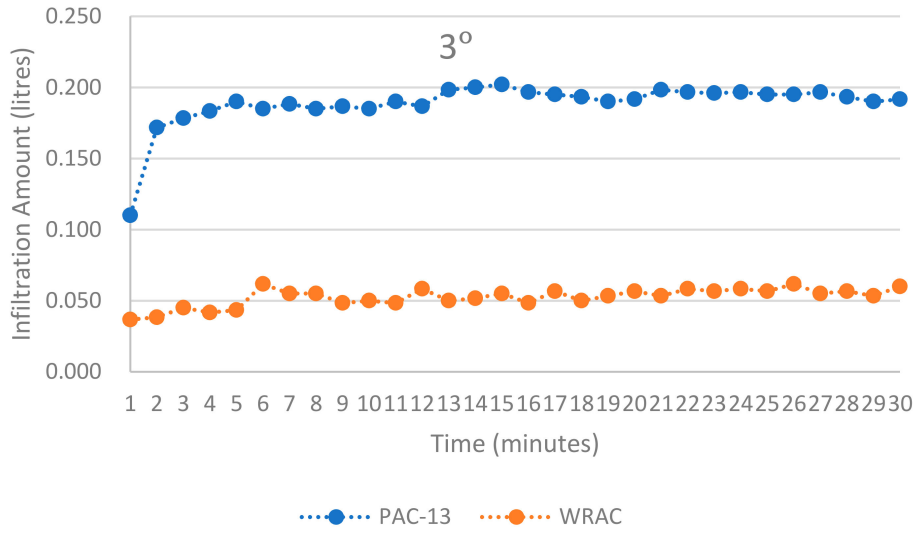
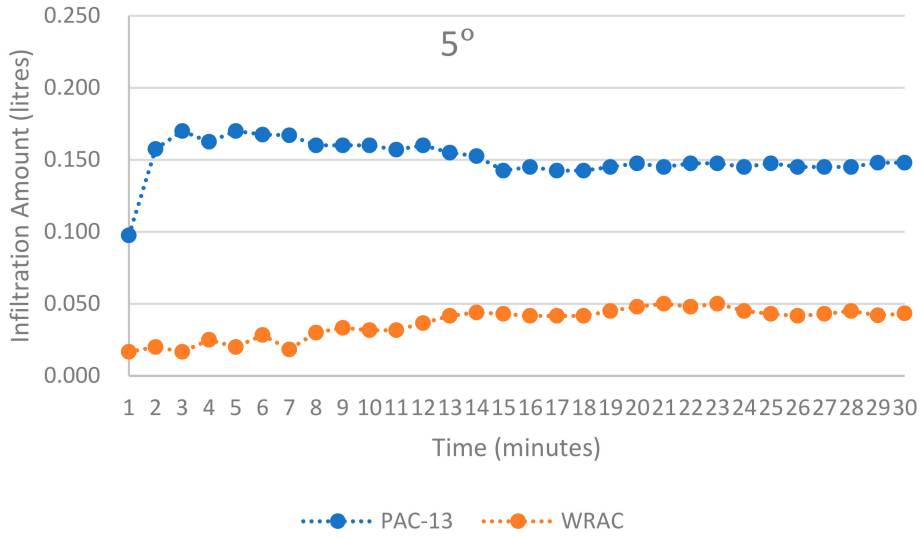




**Figure 9.** *Cont.*




(**c**)

**Figure 9.** (**a**). Infiltration rates through porous asphalt specimens for light rain. (**b**). Infiltration rates through porous asphalt specimens for moderate rain. (**c**). Infiltration rates through porous asphalt specimens for heavy rain.

Overall, the measured runoff and infiltration rates indicate that PAC-13 specimens have excellent runoff retention and infiltration capacities at all three slopes. The WRAC specimens also showed comparably good infiltration rates at 0° slopes, but these decreased at higher slopes. The high infiltration rates at 0° slopes can occur because the permeability of the WRAC specimens at k = 0.107 cm/s is higher than even the heavy rainfall rate (133 mm/h ≡ 0.0054 cm/s). However, this high permeability rate will not be available at slopes of 3° and 5°. As for the dense-graded asphalt specimens, these generated higher runoff rates in most tests due to their very low porosity and permeability. The relationship between these two properties is important to understand. There have been several studies that have investigated the relationship between porosity and permeability in porous concrete [27], but this is less so for porous asphalt [28]. Figure 10 shows the relationship for the three asphalt mixes used in this study compared to the modelled relationship presented by Praticò and Moro [28].

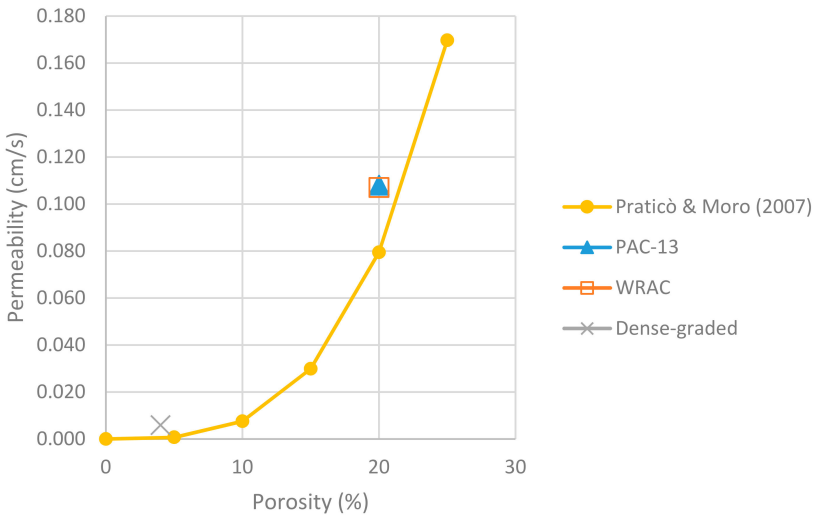



**Figure 10.** Relationship between porosity and permeability for asphalt concrete mixes (adapted from [28]).

From Figure 10, it can be seen that the modelled curve from Praticò and Moro [28] generally provides a reasonable estimate of the porosity-permeability relationship for the three asphalt types (PAC-13, WRAC and dense-graded) used in this study. Praticò and Moro also suggested that effective porosity may be a more suitable property than air void content when considering the relationship with permeability. They defined effective porosity as the porosity that only takes into account the voids that can be filled with water from the external surface. This would include both the connected and semi-connected voids, but not the disconnected or sealed voids shown in Figure 6. However, their modelling results did not provide sufficient evidence to clearly identify effective porosity as a superior property to air void content.

### 3.3. Effect of Slope

From Figures 8 and 9, it can be seen that after 10 min of rainfall, the runoff and infiltration rates have both stabilized. To examine the effect of slope in more detail, the average value of the runoff and infiltration rates between 10 and 30 min after rainfall commenced was calculated for each rainfall intensity and for each slope. These average values are plotted in Figure 11.

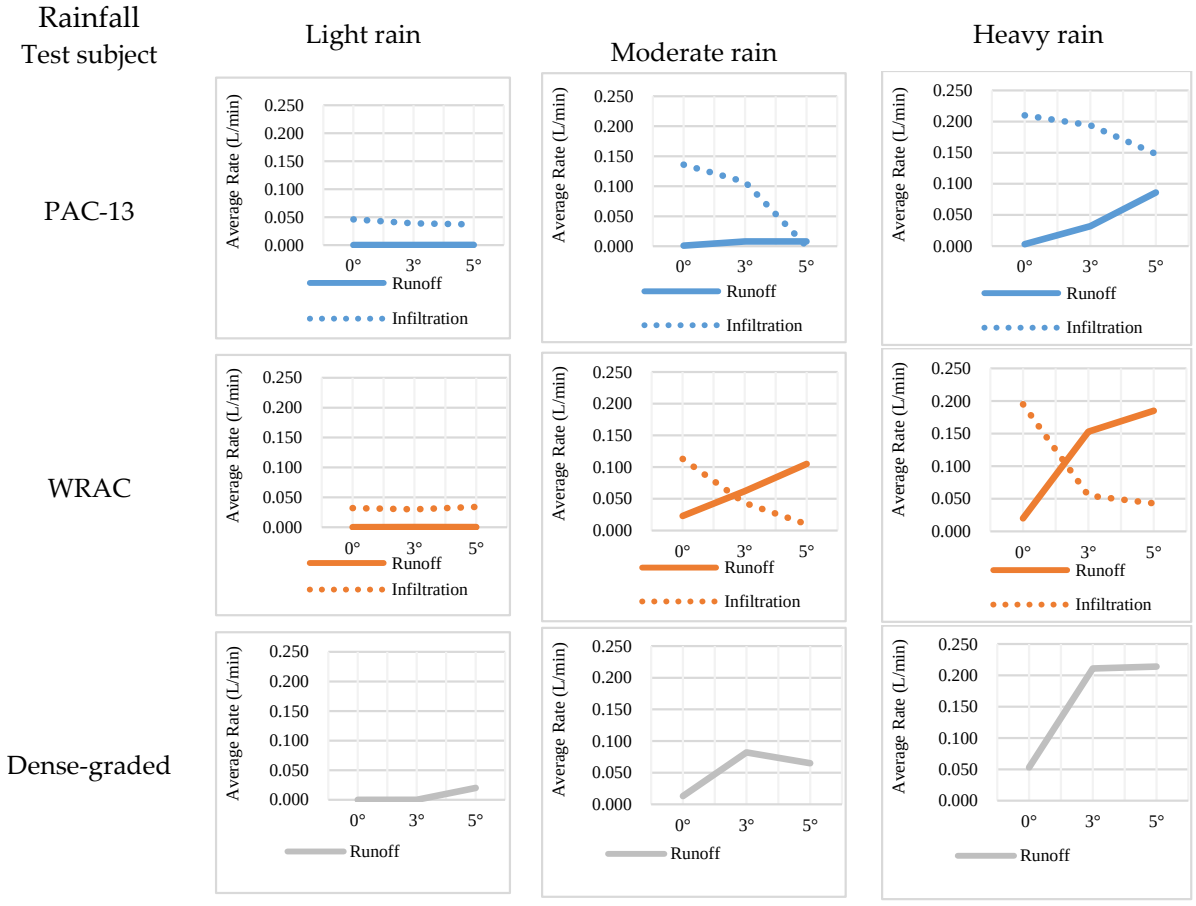



**Figure 11.** Average runoff and infiltration rates.

It can be seen from Figure 11 that increasing slope has more effect on runoff at higher rainfall intensities for all three types of asphalt, but it has less effect on PAC-13 specimens than on the other two asphalt types. A similar trend is observed for infiltration through the two porous asphalt types, in that for light rain, there is not much change in slope for either the PAC-13 or WRAC specimens. However, for moderate and heavy rainfalls, infiltration decreased noticeably with increasing slope. This decrease is steeper for WRAC than for PAC-13, particularly at the highest rainfall intensity (173 mm/h). For example, for PAC-13

with heavy rain, the infiltration rates for the 3° and 5° slopes only decreased to 90% and 70%, respectively, of the value observed at the 0° slope. However, for WRAC with heavy rain, the infiltration rates for the 3° and 5° slopes decreased to 30% and 20%, respectively, of the value observed at the 0° slope. These effects of slope are likely due to the higher availability of connected pore spaces in the PAC-13 specimens compared to the WRAC specimens, as illustrated in Figure 6.

## 4. Conclusions

The infiltration and runoff behaviour for three types of asphalt (PAC-13, WRAC and dense-graded) pavements were compared experimentally for three different applied rainfall rates and at three pavement slopes. It was found that for light rainfall, all three asphalt types were able to detain runoff for longer periods at lower slopes, largely because of the high infiltration capacity of the two porous asphalt specimens (PAC-13 and WRAC) and the wetting and ponding capacity of the dense-graded specimens. However, as the pavement slope increased, this capacity reduced, particularly for the relatively impermeable dense-graded asphalt. The WRAC specimens were able to detain potential runoff at both 0° and 3° slopes, due partly to the capacity of the water-retentive slurry that allows WRAC specimens to absorb infiltrated water and partly to its different flow pathways. The PAC-13 specimens have more connected voids, while in the WRAC specimens, some of the connected voids will have been altered to semi-connected voids with the inclusion of the water-retentive slurry. The dense-graded specimens will possess mostly disconnected or sealed voids, as illustrated by their very low permeability values. The water retention capacity of the WRAC specimens was demonstrated by the much longer times than for PAC-13 before infiltrated water appeared for both light and moderate rainfalls. This delay is likely to be due to water absorbance with the water-retentive slurry, which is only included in the WRAC specimens. For heavy rainfall, this effect is reduced, presumably due to the faster rate of infiltration.

In terms of the rate of runoff, the two porous asphalt specimens (PAC-13 and WRAC) performed well and generated very low flow rates (<0.003 L/min) even at a slope of 5°. The dense-graded asphalt specimens were the only ones to produce sustained runoff, but only at the 5° slope. For moderate rain, the dense-graded asphalt and WRAC specimens produced runoff for all three slopes, but the PAC-13 specimens again generated very little runoff (<0.015 L/min) even at the 5° slope. At the heavy rainfall rate, the dense-graded asphalt specimens produced the highest runoff rates for all three slopes, while the WRAC specimens produced the second-highest runoff rates. In terms of infiltration, the PAC-13 specimens had higher infiltration rates than the WRAC specimens, although this difference decreased with increasing slope.

Overall, the measured runoff and infiltration rates indicate that the PAC-13 specimens demonstrated excellent runoff retention and infiltration rates at all three slopes. The WRAC specimens also showed comparably good infiltration rates at 0° slopes, but infiltration rates decreased at higher slopes. The dense-graded asphalt specimens generated higher runoff rates in most tests due to their very low porosity and permeability. Increasing slope had more effect on runoff at higher rainfall intensities for all three types of asphalt, but it had less effect on PAC-13 specimens than on the other two asphalt types.

It can be concluded that WRAC is an innovative type of porous asphalt that has similar infiltration performance to traditional PAC-13 porous asphalt for horizontal pavement surfaces. However, PAC-13 has superior performance for sloping pavements.

A limitation of this experimental investigation was the use of new asphalt specimens and clean water. In field situations, asphalt surfaces are subject to regular sediment loads conveyed in urban stormwater, and this can lead to partial clogging of the pavement. An extension to this research, therefore, would be to either include various sediment concentrations in the applied rainfall or spread sediment across the asphalt specimens prior to the application of the rainfall.

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