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Measuring Infiltration Rates in Permeable Asphalt Pavement in Urban Landscapes

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ABSTRACT

Efficient water management of roads has become increasingly important due to the escalating challenges posed by climate change. The existing body of research focusing on permeable pavements with surface layers of asphalts, concrete, and interlocking pavers, is limited, especially with respect to the use of porous asphalt as a surface layer is. Addressing the challenges and opportunities associated with permeable asphalt pavements, such as cleaning practices and maintaining infiltration efficiency is, nonetheless, essential to improve and advance urban engineering practices. This research, therefore, explores the intricate relationship between porous asphalt pavements and the dynamic behavior of infiltration rates over time. Utilizing both quantitative and qualitative data, the study revealed a variability in infiltration rates along the tested roads, affected by variables such as, pavement porosity and surface condition resulting from variation in the pavement construction process and practice.. The study, additionally, show that continuous cleaning and maintenance have a positive effect on the infiltration capability of permeable asphalt pavements, rendering surface cleaning essential, to maintain a high infiltration performance of permeable asphalt pavements.

1. Introduction

In the face of rapid urbanization, the sustainable management of stormwater has become imperative for resilient and sustainable conscious urban development. Efficient water management is, additionally, becoming more important due to the escalating challenges posed by climate change. The Intergovernmental Panel on Climate Change (IPCC) reports have highlighted the intensification of extreme weather events, including intense storm and flooding, as a consequence of global climate shifts (IPCC, 2021; Muttuvelu and Kjems, 2021). Such occurrences necessitate innovative strategies in road pavement design to mitigate the impact of increased water runoff and enhance infrastructure resilience. One of such innovative strategies is permeable asphalt pavements, which has emerged as a promising solution to address the management challenges regarding increased precipitation.

Permeable pavements represent a shift in the way we perceive and utilize urban surfaces and can according to Meesaraganda and Kakumani (2021), and can presently be divided into three types: porous concrete pavement, porous asphalt pavement, and porous concrete block pavement. All three pavement types presents a solution for rain water management, with the third solution providing a repository for intermittent water storage during heavy rains and a subsequent slow infiltration into the subsoil (Meesaraganda and Kakumani, 2021). Usually the permeable top layer is constructed with a surface air void of minimum 16% as that has shown high infiltration and acceptable stability and durability in the pavement lifespan (Rodriguez-Hernandez et al., 2012; Muttuvelu et al., 2019; Afonso et al., 2020; Elizondo-Martinez et al., 2020). Fig. 1 shows the difference between traditional and permeable asphalt.

By allowing stormwater to infiltrate through the pavement surface into the underlying layers, permeable pavements mitigate runoff, reduce the risk of surface ponding and enhance water quality. In the US and Europe permeable pavements are primarily utilized to manage stormwater in urban areas (Bean et al., 2007). However, the integration of sustainable design principles such as permeable pavements, into urban infrastructure can potentially provide greener, more resilient, and sustainable cities (Scholz and Grabowiecki, 2007; Hansen, 2008; Beecham et al., 2012).

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Fig. 1. Left Image Shows a Surface of Traditional Asphalt, and Right Image Shows Porous Drainage Asphalt

In Denmark permeable pavements have gained increasing attention as sustainable solutions for managing stormwater in both urban and suburban areas. These pavements allow rainwater to infiltrate through their surfaces into the underlying soil layers, reducing surface runoff and alleviating pressure on traditional drainage systems. In recent years, Danish municipalities have been implementing permeable pavements in various urban settings, such as sidewalks, parking lots, and residential streets, to mitigate flooding. These are installed with grass pavers (pavers in general), porous asphalt and concrete etc.

In addition to monitoring the infiltration rate, a significant element in maintaining a consistently high rate is the regular removal of organic matter and sediment that can clog the pores of the porous surface structure especially in porous concrete and porous asphalt (Bean et al., 2007; Mullaney and Lucke, 2014). It is expected that the need for cleaning and maintenance is important wherever this type of pavement is used. In a study by Bean et al. (2007) conducted on porous concrete in Florida, it was demonstrated that the placement of permeable pavement and the maintenance thereof are crucial factors in sustaining high surface infiltration rates. This was also revealed in other research (Kuruppu et al., 2019; Winston et al., 2020) describing how one of the pivotal factors that can influence the performance of permeable asphalt pavements in stormwater management is regular maintenance and cleaning. Over time various pollutants and debris can accumulate on the pavement's surface, potentially impeding the flow of rainwater into the underlying layers. This accumulation may include sediment, leaves, litter, microplastics and hydrocarbons from vehicles (Pezzaniti et al., 2009; Drake and Bradford, 2013; Rasmussen et al., 2023). Proactive and systematic cleaning of permeable pavements is, therefore, essential to ensure proper functionality in promoting sustainable stormwater management (Hein et al., 2013; Razzaghmanesh and Beecham, 2018). The removal of surface contaminants both safeguards a pavement's permeability and plays a crucial role in upholding infiltration rates. However, the question of what the experiences are regionally and what they are when measured remain? Consequently, periodic vacuuming of the pavement, ideally one to two times a year, is recommended (Muttuvelu et al., 2022). This proactive maintenance approach ensures the optimal functionality of the permeable pavement, promoting efficient water infiltration by preventing potential issues associated with clogging (Winston et al., 2016; Browne et al., 2019; Lee et al., 2022; Yang et al., 2022; Minnesota Stormwater, 2023).

Permeable asphalt pavements can be cleaned using a hydrovac approach, which is a method utilising a high-pressure cleaner combined with a vacuum cleaner (Lane, 2005; Al-Rubaei et al., 2012; Winston et al., 2016). Using a hydrovac approach or similar, suggests minimum cleaning the surface of the pavement $1-2$ times a year, with a bar pressure of 3,000 psi being too low and a bar at 5,000 psi being considered too high, as it will wash out the binder from the surface and cause particle loss faster than expected (Lane, 2005; Al-Rubaei et al., 2012; Winston et al., 2016). In this context, Van Bochove (2000), explain that the hydrovac cleaner equipment represents the most effective method for cleaning permeable pavements, as the infiltration time almost reverts to its original state measured immediately after installation. The methods should, nonetheless, be utilized with care due to its risk of harming the top layer.

The surface infiltration of a permeable pavement can be measured over time by using simple principles from Darcy's law, in which the velocity through a porous medium is measured (Ellebjerg and Bendtsen, 2008; Ovesen et al., 2012; Atangana, 2018; Støvring and Meyer, 2021). The theory, as described by Ovesen et al. (2012), explains that there is directly proportionality between the water inlet and the pressure level and that the water inlet is directly proportional to the surface area and inversely proportional to the distance the water must travel. Other research highlight and demonstrate the utilization of permeable pavement (Ellebjerg and Bendtsen, 2008; Ovesen et al., 2012; Støvring and Meyer, 2021). However, a more comprehensive comparison of infiltration rates over time and a thorough analysis of each road is necessary to fully comprehend the process. The purpose of this research is, therefore, to investigate the complex connection between porous asphalt pavements and how their infiltration rates change dynamically over time, incorporating a qualitative and quantitative analysis of various perspectives and experiences from stakeholders within the industry, acquiring a deeper understanding of the efficiency and constraints of utilizing permeable asphalt pavements.

Data was collected from six locations with porous asphalt in Denmark, supplemented with semi-structured interviews with road owners of permeable pavements. The methodologies of the research are described in the next chapter, whilst the results from the analyses of qualitative and quantitative data are presented in section three. The empirical discussion of the results in the context of the existing body of scientific literature on permeable asphalt pavements are then presented in section five, whilst a conclusion of the research is presented in the fifth and final section of the paper.

2. Materials and Methods

2.1 Research Design

In this study, a mixed method approach was utilized (Creswell, 2021), including a small structured literature review and qualitative interviews to capture the nuanced narratives surrounding our research topic which were subsequently analyzed thematically to identify recurring themes and patterns (Fetters et al., 2013). Becker's method was, additionally employed, as a quantitative measuring approach, for infiltration rates in porous asphalt. Through combining these methods, the study harnesses the strengths of both qualitative and quantitative data and gain a holistic understanding of stormwater management, emphasizing the dynamic relationship between participant experiences and empirical measurements.

2.2 Qualitative Data Collection

To obtain an initial understanding of the concepts and processes involved in designing, using, and operating permeable pavements, qualitative interviews were conducted with six respondents from the Danish construction and infrastructure industry, using semi-structured interviews. Using semi-structured interviews does, according to Brinkmann and Tanggaard (2020), allow an in-depth understanding of the respondents including their perspectives, experiences, and opinions, in this study, with respect to stormwater management and permeable pavements.

The six respondents, participating in the semi-structured interviews, were employed either at a municipality (as road owners) or at a utility company, as shown in Table 1. The selection criteria for the respondents were based on interviewing individuals within the industry who are road owners and responsible for pavement management and new pavement projects as well as respondents from utility companies responsible for the Danish drainage system. The primary respondent selection indicator was experience with permeable pavements.

To organize the interviews, an interview protocol was developed as described by Brinkmann and Tanggaard (2020). The protocol included standardized introductory information to all participants and outlined the key questions as well as questions used as conversation starters. All interviews were video and voice recorded, and transcribed before the data was analyzed.

2.3 Quantitative Data Collection

In the pursuit of sustainable stormwater management and the evaluation of permeable pavement systems, accurate and reliable measurements of infiltration rates are fundamental.

In this study, the infiltration rates were measured at six different locations with permeable pavements with the following commonalities: 10 cm porous asphalt (porous surface course and porous base course) asphalt, maximum gradation size 11 mm, density of asphalt 2 g/cm^3, estimated air void: approx. 20%. All roads are categorized under traffic class T2, which corresponds to 75 Equivalent Single Axle Loads (ESALs) per year in each direction. Furthermore, all roads are situated in Denmark, where the differences in climate across the country are relatively subtle outside of the urban heat islands. Therefore, the variation in climate has not been a significant influencing factor across county in this context. The selection of each test point was based on measuring on each side of the road (right and left), and half a meter from the curb, to ensure that the measured infiltration rates are representative of the overall pavement. Limited engagement from road owners, however, hindered acquisition of additional site information

A simple version of Darcy's Law was utilities for the measuring the infiltration rates, by placing a cylinder on top of the road and measuring the infiltration rate from one level to another level. This is in this paper described as Becker's method, as shown in Fig. 2. Using Becker's method a constant pressure head is established by maintaining a specific water level above the pavement surface. This constant pressure facilitates the measurement of infiltration rates. In essence Becker's method applies the concept of constant pressure as a practical technique for infiltration testing, while Darcy's law provides a theoretical framework for understanding fluid flow through porous media under a constant pressure gradient.

Becker's method offers several advantages, including simplicity, cost-effectiveness, and the ability to assess real-world infiltration

Table 1. Information About the Respondents

No. of respondent	Profession	Years of experience	Company	Interview Platform
1	Road/pavement engineer	10	Municipality	Microsoft Teams
2	Project Manager	20	Municipality	Microsoft Teams
3	Project Manager	20	Utility Company	Microsoft Teams
4	Supervisor	20	Municipality	Microsoft Teams
5	Water engineer	20	Utility Company	Microsoft Teams
6	Operation Manager	20	Municipality	Microsoft Teams

Fig. 2. Beckers Method Test Arrangement on Field (Water is filled up until h1 and the time in measured until h2)

rates directly on the pavement surface. However, it is essential to consider the potential influence of factors such as soil type, pavement design, and climatic conditions, which can affect the accuracy of measurements (Ellebjerg and Bendtsen, 2008; Andersen et al., 2022).

By employing Becker's method, researchers can gain valuable insights into the performance of permeable pavements over time, contributing to the ongoing development and optimization of sustainable stormwater management strategies in urban environments. The application of various statistical tests, including the normality check, paired t-test, and Shapiro-Wilk test, facilitated a comprehensive assessment of the infiltration rates across different roads.

Becker's method involves a systematic approach to measuring the infiltration rate by establishing test plots on the permeable pavement surface and is a simple falling head. The key steps in this method include:

Selection of Test Plots: Researchers carefully choose specific locations on the pavement where infiltration rates will be assessed. These locations should be representative of the overall pavement area.

Preparation: Transparent tube with a 195 mm in diameter with a plate below that helps the tube to be stable. Some putty has also been used below the tube to stabilize it further.

Water Application: Water is poured above a 20 cm line on the tube. Measuring start from the line and until water is gone from the tube.

Monitoring Water Infiltration: Researchers closely monitor and record the time it takes for the applied water to infiltrate into the pavement's underlying layers. This data is crucial for calculating the infiltration rate.

2.4 Data Analysis

The data analysis process for this study was divided into two steps. Firstly, an analysis of qualitative data from the semi-structured interviews, and secondly, a quantitative data analysis of infiltration measurements. This is shown in Fig. 3.

2.4.1 Qualitative Data Analysis

To understanding the collected interview data, a coding dictionary

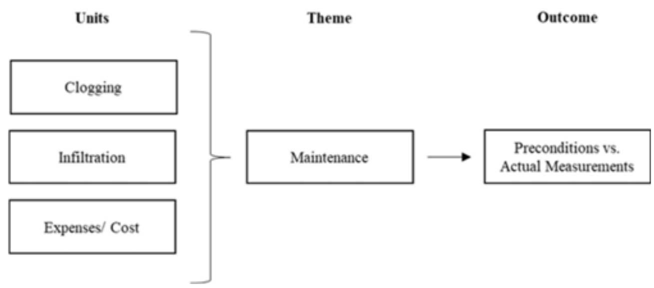

Fig. 3. The Coding Dictionary for the Research, Showing the Collection of Units, Summarised in the Theme: Maintenance which Indicates the Relationship between Units Resulting in the Outcome or Scope of the Study, Focussing Pre-Conditions vs. Actual Measurements

was developed (Brinkmann and Tanggaard, 2020), using the terms: clogging, infiltration, and expenses, which were used to categorize the transcribed interview data as shown in Fig. 2. This initial categorization revealed three common themes:: clogging, infiltration, and expenses, which were used to structure the data analysis and discussion of the findings of the research.

2.4.2 Quantitative Data Analysis

The recorded data was analysed to determine the infiltration rate, typically expressed in cm per hour, as shown in Eq. (1) (Ellebjerg and Bendtsen, 2008; Andersen et al., 2022).

Where I is the infiltration rate in cm/s, A is the cross-sectional area of the tube (d = 19.5 cm, A = 298.7 cm^2) of the sample in cm, h_1 is the initial head in cm (12 cm) and h_2 is the final head in cm (2 cm), lastly t is the time it took for the water to infiltrate (s).

$$I = \frac{(A \cdot h_1)}{t \cdot \ln\left(\frac{h_1}{h_2}\right)} \quad (1)$$

3. Results

Based on the quantitative data collection and data analysis, an evaluation of infiltration rates measured on site was made possible, whilst the qualitative data collection and analysis made it possible to explain *why* the results are as they are, in addition to

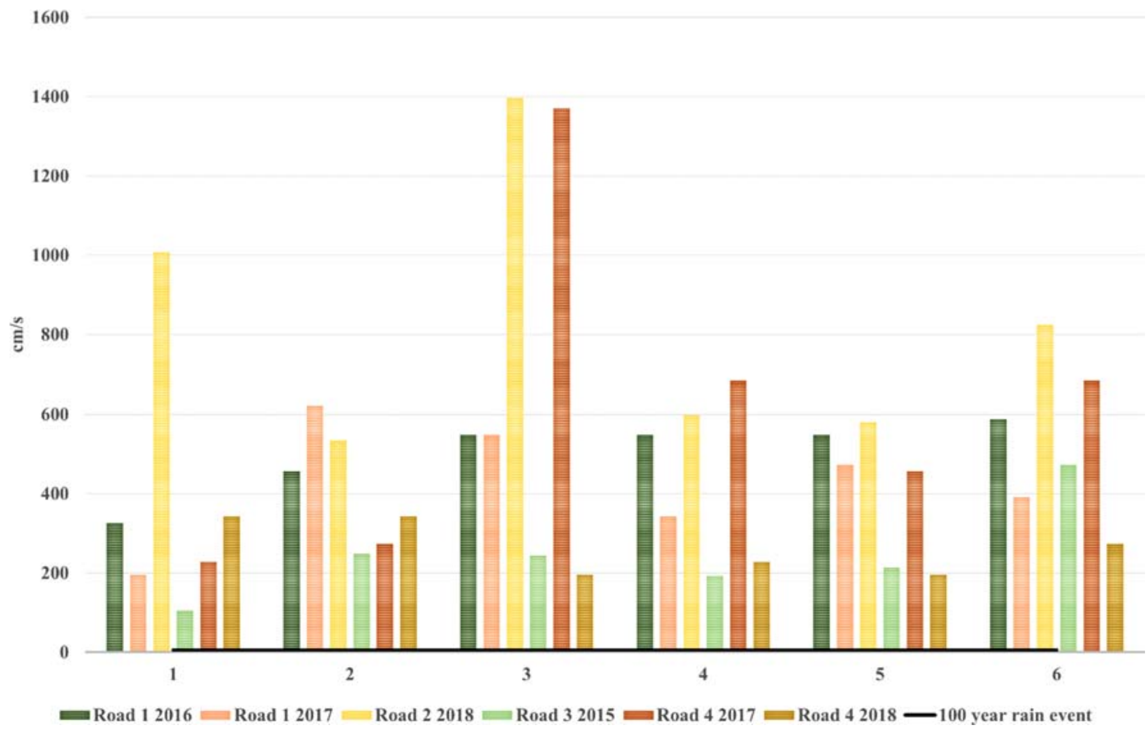

Fig. 4. Road 1 – 4 Infiltration Rates over Time in Comparison to a 100-Year Storm

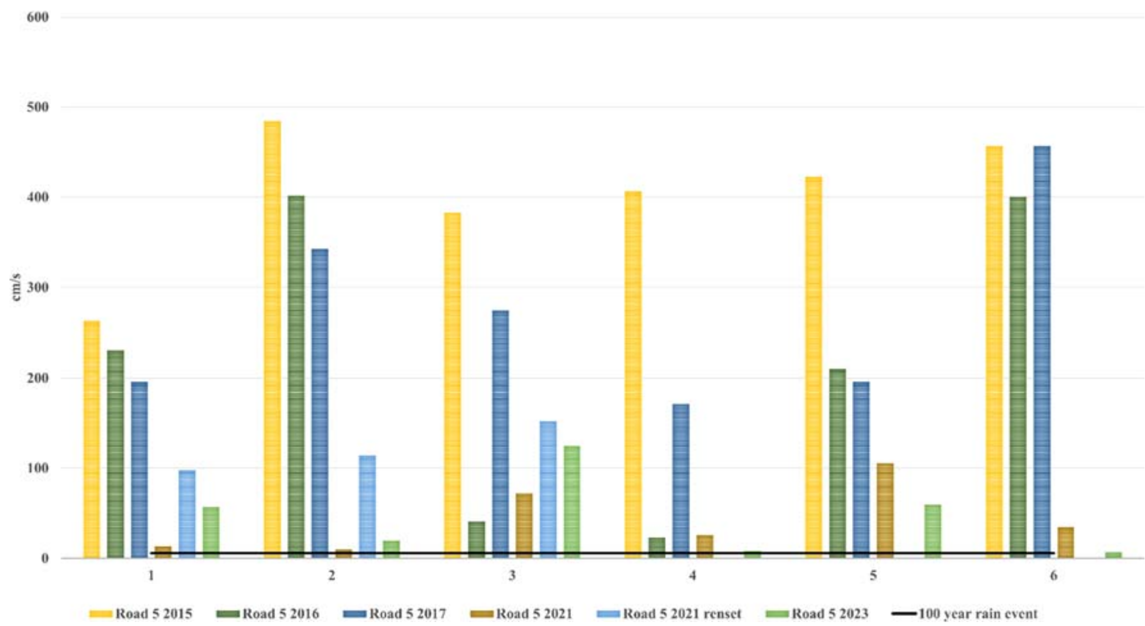

Fig. 5. Road 5 Infiltration Rates over Time in Comparison to a 100-Year Storm

understanding the narrative surrounding the designing, construction, and operation of permeable asphalt pavements.

3.1 Quantitative Results

The measured infiltration rates were compared against a benchmark representing a 100-year's storm event, which is illustrated as a constant linear line in Fig. 4 through Fig. 6. The 100-year storm event is used as a benchmark as it provides a standardized reference point for assessing the severity of rainfall events and designing infrastructure to withstand extreme weather conditions. These measurements pertain to 6 different roads, each denoted from road 1 to 6, with road 6 still serving as the focal point for continuous testing. All measurements were collected continuously, allowing for the selection of a subset of measurements from the various roads, which were applied for further analysis. In Table 2, the average infiltration rates and standard deviations for each road is shown.

A normality assessment test using Shapiro-Wilk test was

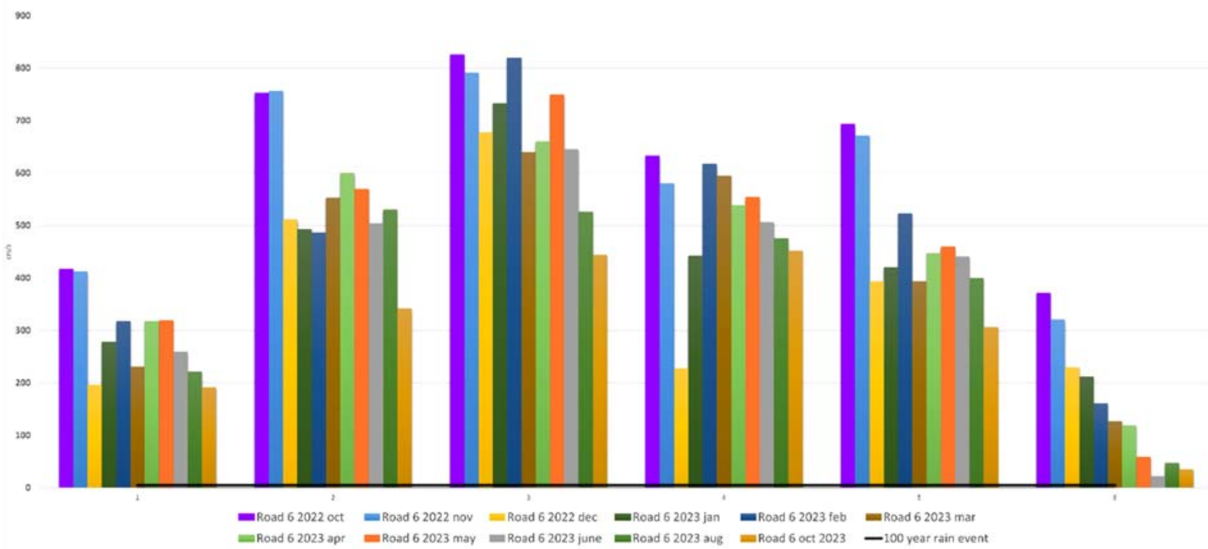

Fig. 6. Road 6 Infiltration Rates over Time in Comparison to a 100 Year Storm Event

Table 2. All Measured Values Together with Average and Standard Distribution of Road 1 Through 6

	Road 1		Road 2	Road 3	Road 4		Road 5						
	2016	2017	2018	2015	2017	2018	2014	2015	2016	2017	2021 (not cleaned)	2021 (cleaned)	2023
1	326	196	1007	105	228	343	427	263	231	196	13	98	57
2	457	623	535	249	274	343	319	484	402	343	10		20
3	548	548	1398	245	1370	196	598	383	41	274	72	114	125
4	548	343	598	193	685	228	578	407	23	171	25		8
5	548	472	581	214	457	196	835	423	210	196	105	152	60
6	599	391	825	472	685	274	685	457	401	457	34		7
Average	502	429	825	105	617	263	574	431	218	273	43	121	46
Standard Deviation	97	153	334	122	417	68	183	40	165	110	38	8	45

	Road 6												
	2022			2023									
	October	November	December	January	February	March	April	May	June	July	August	September	October-cleaned
1	418	413	196	278	318	231	318	320	259		222	204	191
2	753	757	512	493	486	554	600	570	504		530	365	342
3	826	792	678	733	819	640	660	750	645		526	595	444
4	633	581	228	443	618	595	538	555	506		475	486	452
5	694	672	393	421	524	394	448	459	441		400	421	306
6	372	321	230	212	161	127	119	59	22		47	117	35
Average	616	589	373	430	488	423	447	452	396		367	365	295
Standard Deviation	183	189	192	183	230	209	201	239	222		194	178	160

conducted for all the data, revealing that the data conforms to a normal distribution. This conformity enables the application of additional statistical tests of the results.

3.1.1 Infiltration

One noticeable trend was the substantial variation in standard deviation from the average over the years. Particularly in the case of road 5, shown in Fig. 5. Following a pavement cleaning in 2021, this variation diminishes and aligns more closely with the average value. Equally intriguing is the fact that when initially established, the average infiltration rate was notably higher. However, nine years later, it plummeted from an average of 574 cm/

s to 46 cm/s, representing an approximate decline in infiltration rates of 92% throughout this period. The infiltration rate on both sides of road 5 road, with one side having been cleaned and the other one not having been cleaned, revealed a clearly observable and measurable discrepancy in infiltration rates, with the cleaned side of the road performing significantly better than the side of the road which was not cleaned.. As shown in Table 2, the average value is 43 mm/s when uncleaned while 121 mm/s when cleaned. This reveal that cleaning the permeable surface is equal to maintaining the infiltration rate. When comparing the measurements of the 6 roads, the null hypothesis in the performed Shapiro-Wilk test, revealed no difference between the groups, whilst the alternative hypothesis stated that there is a difference ($P = 0.02$). With a p-value of 0.02, the null hypothesis was rejected, and it was concluded that at least one road is significantly different from the others in terms of infiltration rates. Especially road 1, road 3 and road 4 differed from road 2 and road 6.

This highlights a concerning aspect of laying permeable porous asphalt, as the statistical analysis indicates irregularities ($p < 0.5$) among the various roads. Notably, roads 2 and 3 exhibited no statistical consistency in infiltration rate, see Fig. 6. This discrepancy is further evident in Fig. 6 and Table 1, where both the mean and standard deviation significantly deviate from the overall averages and variances observed in all the roads. The statistical analysis underscored the challenges associated with the construction of porous asphalt pavements.

3.1.2 Clogging

When examining roads 5 and 6 individually, both roads showed high p-values ($p = 0.16$ and $p = 0.09$) when comparing the results before and after cleaning the permeable porous surface. This implies a positive impact on infiltration when the permeable asphalt is cleaned.

Based on these two roads, cleaning the permeable pavement with a high-pressure cleaner is yielding positive results. However, the need for assessing the correlation between infiltration rates before cleaning and after cleaning must be emphasized. Based solely on roads 5 and 6, it is not possible to definitively determine the necessity and the full extent of the infiltration efficiency of the roads.

Fig. 7. Road 6 in December 2022, Where Ice Had Clogged the Pores (left) (The difference between a traditional pavement and a permeable pavement surface is shown on the right-hand picture. Photo was taken on 15.12.2022.)

Another critical point revealed in the analysis of measurement data as shown in Figs. 4, 5 and 6, is that even after an extended period without cleaning the road, an average infiltration rate higher than that of a 100-year storm event as observed in all 6 roads. However, certain sections of the road experienced lower infiltration performance. This can be attributed to the initial conditions of the construction of the road, with asphalt not having been uniformly distributed across the entire road, which is the fact of road 6. Hence, the initial expectation of having a porosity of 20% might not be applicable on the whole surface length. The monthly infiltration rates for road 6 is visualized in Fig. 6, offering a more detailed insight into the infiltration rate and the durability of the road.

The average infiltration rate in December 2022 was, significantly lower than in the other months, as shown in Table 2. A paired t-test revealed a p-value of 0.0303, leading to the conclusion, that the winter season affected the surface infiltration of the permeable pavement on road 6. A paired t-test was, additionally, performed to compare the data between November-December 2022 as shown in Fig. 7.

3.2 Qualitative Results

3.2.1 Infiltration

A notable limitation of the porous asphalt road, according to one of the respondents, is that the surface is not always uniform along the entire length of the road. "*Some section of the road may be either clogged or less porous than the rest of the road or pavement, resulting in stormwater accumulating and forming of puddles on the surface of such areas, impeding infiltration*".

Road slope might in some instances, nonetheless, rectify such a scenario and help the water shift from an area in which it has accumulated to another area, facilitating the infiltration of the water on a different location of the road or pavement. According to one of the respondents, this might also be a situation that calls for some areas needing more cleaning of the surface area, as well as other maintenance.

3.2.2 Clogging

Through qualitative data analysis, it was revealed that most of the respondents were informed that porous asphalt pavements must be cleaned twice a year, for the pavement to work properly. However, most of the respondents emphasized that not all types of clogging materials or debris have the same effect on the porous asphalt, regarding clogging of the porous surface.

One respondent noted, "*We find that clogged pores caused by leaves or similar debris have a lesser impact on the long-term infiltration rate, compared to the clogging effect caused by sand or other smaller particles in the pores*".

Another respondent added, "*I do not believe that the clogged items are affecting the infiltration rate, as water does not pool on the road, but infiltrates rapidly. However, the visual look is not* *pretty*".

To address both aesthetic and infiltration-based issues, additional maintenance might be an obvious solution. However, in this regard the respondents noted that, cleaning pavement 2 – 3 times a year, can end up revealing cracks in the surface of the porous asphalt, as the binder can be washed away during maintenance. This can result in the loss and the surface making it necessary to change it after five years. As part of the maintenance the respondents, additionally, described how clogging can be a result the lack of being able to clean the road surface, e.g., due to parked cars along the road.

3.2.3 Expenses/cost

One of the most important elements of the design, construction, and operation of permeable pavements was according to the respondents, the cost of the pavement, in addition to the expenses of maintaining it. One respondent noted, *"Cleaning the permeable pavement twice a year is super expensive, and it does not seem like we even need to clean, as rainwater is always penetrating through the surface"*. This indicates that there is not necessarily a consensus between the prescribed maintenance requirements of porous asphalt pavements and roads and the perceived experience of needs for maintenance amongst the owner of permeable pavements and the designers and operators of permeable pavements.

One respondent described how their municipality made an agreement with the utility company, which were to pay for all expenses associated with rainwater management, whilst all expenses regarding resilience and construction was paid for by the municipality. However, no common standard agreement for how to divide expenses and cost between the owner of the road or pavement and those constructing and operating it is currently available in the Danish industry.

As noted by another respondent, a division of cost is important asking the questions: "*it is expensive to clean – and who pays for it? Is it us* (the municipality rd.) *or the utility company, or do we share?*"

Another respondent further described how the cost of cleaning the porous asphalt can cost up to 1,000 € pr 1,000 m^2 per pavement, which can become extremely costly if the owner has many such roads.

4. Discussion

In the exploration of permeable pavements and their efficiency managing water infiltration, it is evident that there are several critical factors in play. Permeable asphalt pavements present both opportunities and challenges for both planners and owners of such pavements. As revealed through both quantitative and qualitative analysis, a diverse range of expectations and experiences regarding permeable asphalt pavements, were highlighted, particularly in the context of cleaning, clogging, and infiltration rates. However, when infiltration rates are measured, the respondents described how their process include measuring which might skew the qualitative evaluation of the pavement's performance, as the respondent's opinion in this regard is not necessarily based on objective measurable data. This issue is also addressed by Muttuvelu et al. (2022), presenting an interview-based study involving various stakeholders such as contractors, consultancies, and clients (utility companies and municipalities) concluding that there are no official requirements for the installation of permeable asphalt pavements. This lack of standardized guidelines underscore the challenges and inconsistencies often associated with the use of permeable asphalt pavements.

4.1 Variability across Road Length

According to the qualitative data presented in this study; infiltration rates exhibit considerable variability along the length of permeable asphalt pavements. A variability which can be attributed to the inherent heterogeneity of the pavement's structure. Whilst some sections demonstrate a rapid infiltration of water; others may experience delays or face difficulties in water absorption.

Examining the infiltration rates shown in Figs. 4, 5, and 6, it is evident that the qualitative data aligned with the observed variations in infiltration rates along the length of the road, as shown in Table 2, in which the mean and variance are shown. This practical observation raises significant concerns, as it indicates a frequent discrepancy between the actual infiltration rates and the expected 20% porosity in the surface course (Muttuvelu et al., 2019; Muttuvelu and Kjems, 2021).

The paired t-tests, furthermore, indicate that each contractor laid the porous asphalt differently or applied varying compression outcomes. Based on this result, it is recommended that core samples along the pavement is extracted, and volumetric data is assessed in a laboratory setting, in future research to determine the porosity. This approach can allow for the calculation of density and porosity, ensuring that the porous asphalt meets the necessary requirements. Ultimately, this calls for the establishment of uniform national requirements for all permeable pavements that contractors can adhere to, making this pavement type more practical and efficient in fulfilling its intended purpose. For efficient management of permeable pavements, uniform infiltration across the entire road length is essential. This consistency is vital for determining the appropriate cleaning processes and for ensuring a sustained infiltration rate over time. The challenges arises when water accumulates intermittently due to incorrect layout and compression in the surface course, hindering long-term infiltration, as highlighted by respondent 6. It is conceivable that the lack of uniformity of the six roads, is the result of the pavements being constructed by different contractors, presuming with varying degrees of experience with respect to constructing practices for porous asphalt.

As also revealed in the interviews, two respondents claimed that smaller items, such as leaves and cigarette studs, which congest the pores, do not appear to significantly affect the infiltration rate. However, from an aesthetic perspective, their presence is considered unattractive. Other research has shown similar results (Støvring et al., 2018), in which an finalized permeable pavement was observed over time, leading to the conclusion that the underlaying soil affected the surface pavement, whereas leaves and cigarette studs did not fall under the category of advanced sedimentation process. This also refers to other explaining that sediments, rubber from tires etc. also clogs the pores (Rasmussen et al., 2023).

4.2 Pre-Cleaning and Post-Cleaning Comparisons

An interesting observation with respect to the impact of cleaning methods, focusing on high-pressure cleaning, on infiltration rates, was revealed in the statistical analysis (t-test). It showed a positive outcome resulting from cleaning, with a discernible improvement in infiltration efficiency of $p > 0.5$. However, to draw more conclusive insights, further research is warranted to examine the precise correlation between pre-cleaning and post-cleaning infiltration rates and a more concentrated study based on this should be followed up. This has implications for maintenance practices which can enhance the functionality of permeable pavements. This is in line with research by Støvring et al. (2018) emphasizing the importance of cleaning permeable pavements to sustain an infiltration rate that is high enough for future storms (Støvring et al., 2018; Lee et al., 2022; Yang et al., 2022; Minnesota Stormwater, 2023).

Variables such as pavement porosity, surface condition, and environmental factors play significant roles in determining the success of water infiltration. Urban engineers must carefully consider these factors in their designs and maintenance plans to maximize the utility of permeable pavements, leading to the question: *how can infiltration efficiency be sustained?* Several studies (Støvring et al., 2018; Lee et al., 2022; Yang et al., 2022; City of Melbourne, 2023; Minnesota Stormwater, 2023), additionally, present suggestions and advices for an improved cleaning process to sustain infiltration efficiency.

As shown in the analysis of qualitative data, presented previously in this paper, the interviewed respondents all mention the need for cleaning permeable asphalt pavements twice a year. The respondents, furthermore, define the economical aspect of maintenance as a burden. In Denmark the cost of for cleaning one road is approximately 1,000 € pr. 1,000 m^2. Though, the price is dependent on design and area. Other literature focusing on permeable asphalt pavements does not comment on the cleaning process cost, but only on the efficiency of the cleaning, rendering cost comparison with another research impossible. However, the discussion of the cost involved in cleaning the surface infiltration of the permeable pavement is of great importance for municipalities and other road owners. Especially because the operation costs' can be a deciding factor in selecting new road designs, as well as being a deciding factor regarding maintenance frequency, and thereby pavement efficiency.

Finally, the dynamics of infiltration rates within permeable pavements constitute a critical dimension of their performance. Addressing the variability along the road length, improving pre- and post-cleaning outcomes and sustaining infiltration efficiency are key challenges and opportunities in the realm of urban engineering.

5. Conclusions

The exploration of permeable asphalt pavements and their efficiency in managing water infiltration has brought to light a range of critical factors that influence their performance. The findings from both quantitative and qualitative analyses underscore the complexity and variability associated with permeable asphalt pavements, particularly concerning cleaning, clogging, and infiltration rates. The lack of standardized guidelines for the installation of permeable asphalt pavements, as highlighted by in the existing research, contributes to challenges and inconsistencies in their usage. The observed variability in infiltration rates along the length of the road, influenced by the pavement's inherent heterogeneity, raises concerns about the discrepancy between actual infiltration rates and expected porosity.

Variables such as pavement porosity, surface condition, and environmental factors play pivotal roles in determining water infiltration success. Urban engineers must carefully consider these factors in both design and maintenance plans. The sustainability of infiltration efficiency remains a key question, addressed by various studies offering suggestions and advice for an improved cleaning process.

The significance of uniform infiltration across the entire road length as emphasized in chapter 4 with practical recommendations such as extracting core pavement samples for laboratory assessment. Establishing national requirements for permeable pavements is crucial for ensuring uniformity in construction practices, thereby enhancing the practicality and efficiency of these pavements in fulfilling their intended purpose.

The impact of cleaning methods, specifically high-pressure vacuum cleaning, on infiltration rates is evident from statistical analysis, indicating a positive outcome. However, further research is needed to precisely correlate pre-cleaning and post-cleaning infiltration rates, informing maintenance practices that can enhance the functionality of permeable pavements.

The economic aspect of cleaning permeable asphalt pavements, as stated by the interview respondents, adds a practical dimension to the discussion, as the cost involved in cleaning surfaces is a significant consideration for municipalities and road owners. A consideration impacting decision-making on new road designs, maintenance frequency planning, and thereby overall pavement efficiency.

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