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Are Permeable Pavements a Sustainable Solution? A Qualitative Study of the Usage of Permeable Pavements

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Abstract: This paper contains an interview-based study focusing on permeable pavements as part of sustainable drainage systems. Climate change is causing pluvial flooding, according to the newest IPCC report. This mostly affects urban areas in cities due to: (1) limited capacity of existing drainage systems during heavy-intensity rainfall over a short period of time and (2) limited space for ditches in city areas. Permeable pavements are, therefore, sustainable drainage solutions which combine road infrastructure with water infrastructure. Are permeable pavements a preferable sustainable solution? To answer that question, 24 respondents were interviewed. The interview study was based on a semi-structured interview methodology. A lessons-learned experience was gathered, and the following conclusions were contrived: Firstly, official guidelines on how to construct, consult, and maintain permeable pavements are required. Secondly, more contractors should be able to offer the same product. Finally, official guidelines on the relationship between the contractors are required. These three indicators were extracted from the study.

Keywords: interview study; permeable pavements; water management; SuDS solutions; climate adaption; semi-structured interview; pluvial floodings

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1. Introduction

Climate change is causing several uncontrollable events to occur, affecting the infrastructure globally. According to the 2021 IPCC report (2021) [1], an increase in pluvial flooding and wetter areas is expected in the future. Particularly, Europe, Asia, and Africa are predicted to have an increase of 32%, 38%, and 57% more wetter areas from 2021 to 2100, whilst other regions will be more affected by an increase in warmer and colder temperatures. Recently, a heavy rainfall event occurred once per decade [1]. The 2021 IPCC report further describes how, at present, this is at a frequency of 1.2–1.3 times per decade, resulting in approx. 7% wetter areas. If global warming levels rise by 1 to 1.5 degrees Celsius or 4 degrees Celsius, wetter areas are expected to increase by 11% to 30% [1,2].

An increase in more pluvial flooding will occur in almost all regions of the world, and this flooding must be handled immediately. During the past 10 years, many regions have experienced flooding, and as a consequence, the transport infrastructure has been weakened as the existing infrastructure is not able to handle intensive and heavy rainfall [1]. Therefore, secure infrastructure is a necessity, especially in city areas where space to expand the side area for drainage as part of road construction is limited [3,4].

Permeable pavements are, in some cities, one of the solutions used as part of local drainage systems. These pavements are road constructions with two purposes: (1) to safely carry and withstand traffic loads and (2) to manage water through pavement construction without any additional utilities [5,6]

Experiences with such sustainable urban drainage systems (SuDS solutions) are generally limited and vary between to industry actors such as consultancies, contractors, and clients (road owners). How can the transport infrastructure be helped by using more local drainage systems such as permeable pavements, and what is the experience?

This paper is an interview-based study focusing on permeable pavements. The aim of this study is to present more knowledge about experience regarding permeable pavements in Denmark. The study is divided into five sections. Section 2 is a small literature review focusing on pavement design and permeable pavements, Section 3 is the methodology of the interview-based study. Section 4 presents the results from the interview. Further discussion of the results extracted from the interview is in Section 5. Lastly, a conclusion is presented in Section 6.

2. Background

As early as the 1970s, permeable pavements became of interest globally and have since then evolved with respect to design and usage. Depending on usage and location, these systems can either be constructed with a top layer of porous asphalt, porous concrete, interlocking pavers, or grid systems. The sub-base layer is a porous medium that has to work either as a reservoir or as an infiltration system that infiltrates the water through the pavement construction down to a recipient [3–5,7–14].

In Denmark, however, the use of these types of local drainage systems with asphalt as a top layer is rather new. The first permeable pavement with asphalt as a surface course was constructed in 2012 [3]. Since then, many local roads and residential streets with low traffic have been constructed with such water management systems.

The actual design of a permeable pavement depends on the area, traffic load, and the quality of the subgrade soil. A permeable pavement can either be constructed with:

- Full infiltration;
- Partial infiltration;
- No infiltration.

Full infiltration is chosen when the subgrade soil is able to infiltrate the accessed rainwater as fast as it takes the pavement construction to infiltrate the water from surface to the subgrade. Partial infiltration is a combi-solution, where the sub-base layer is used as a reservoir with overflow, with a pipe connected to a drainage system [3,4,11]. This solution is used when the subgrade soil is clay and silt based. When the permeable pavement is constructed with no infiltration, the sub-base layer is used as a reservoir. This solution is used when the subgrade soil is very silty and the infiltration rate of the subgrade is too low [4,11].

The purpose of traditional pavements are to carry the heavy traffic load easily and without any structural difficulties [15]. Water is managed through a water system that allows surface water to run via the slope of the constructed sealed top layer. Hence, the water is not intentionally let through the pavement, as with permeable pavements. How water affects the permeable sub-base is of interest, as no studies were identified in the researching of the bearing capacity in comparison to water content. Different studies have assessed the effect of water on roads, especially [8,16–20]. In these studies, it is explained that, traditionally, the lifespan of a sub-base material in a pavement depends on the traffic load, the subgrade, and whether the pavement construction is under optimal conditions. Deformation of the sub-base material will occur once a moving wheel load appears on the surface of the pavement. The deformation can be described as resilient and permanent deformation. Study [19,20] explains that a pavement construction is resilient, but it is not resilient enough to recover fully, so the material will also be deformed permanently to some degree. The degree of deformation is highly affected by the moisture content in the sub-base material and if water occurs earlier than expected theoretically [16–18,21–27]. According to several studies [17,18,26–28], adding water to a fine-grained material will increase the risk of permanent deformation and reduce the resilient properties in the material. Sub-base materials that are moistened to the optimal level will increase in strength. A further increase will, however, cause a reduction in the strength of the material. Especially discussing traditional sub-base material, previous studies [17,18,26–28] indicate that increased water content reduces the bearing capacity and the stiffness of the material. When discussing permeable pavements, this has not been evaluated yet [3].

According to the Danish pavement standards [15], the pavement design is always constructed with a frost protection layer between the subgrade and the sub-base material if the subgrade is considered as clay and/or silty. A principle sketch of traditional pavement following Danish standards is shown in Figure 1. If the pavement is constructed without a frost protection layer, the pavement will have a high risk of permanent deformation due to permafrost. Table 1 is shown below, where the total thickness of the pavement design is presented according to traffic level and frost suspectibility. As per Danish standard, the thickness of the pavement increases when the soil subgrade is very susceptible to frost and when there is a high traffic volume. As shown, the pavement construction should be minimum 900 mm if the soil subgrade is very susceptible, whilst there are no requirements needed when the soil subgrade is not susceptible. If the soil subgrade is not susceptible, the only leading factor for pavement thickness is the stiffness of the subgrade and the number of heavy vehicles.

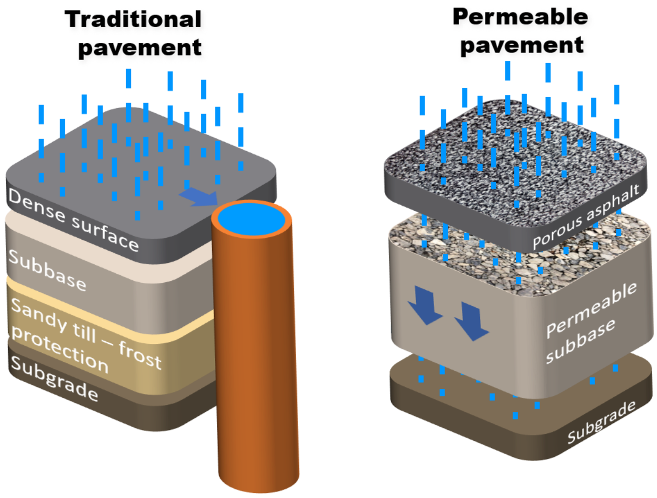

Figure 1. Principle sketch of a permeable pavement.

Table 1. Danish standards for pavement thickness when the soil subgrade is not susceptible to frost, susceptible to frost (clay-silt), or very susceptible to frost (very silty) [15].

	Not Susceptible	Susceptible	Very Susceptible
No traffic to low	-	400 mm	500 mm
Low traffic to medium	-	500 mm	700 mm
Medium traffic	-	600 mm	800 mm
High traffic	-	700 mm	900 mm

An issue related to water in roads, as in studies in [8], is seasonal variation and specifically frost heave and spring thaw. When an unbound material with a moisture content is exposed to freezing temperatures, the water in the unbound material will start forming ice crystals. If the unbound material is sensitive to water, the ice crystals will continue to grow until ice lenses are formed. Because of the ice crystals' growth, the water expands, and this will lead to heaving of the road construction. The ice lenses will eventually melt, and the road construction will deform in spring. This will lead to a major reduction in bearing capacity and stiffness [3,15,16,29,30].

Through a water management perspective, water must be handled and considered throughout the full pavement lifecycle, from design through operation, and especially during the various phases of construction [15]. This is especially of interest when already constructed pipes and drainage systems are too small. A spatial analysis of base course thickness of a permeable pavement in different areas of Australia was performed in [31]. The study identified a close relationship between soil classification, base course thickness, and rainfall intensity. For more clay-classified soil subgrades, it is expected that a slower infiltration will occur, and hence a thicker base course thickness is needed [15,29]. This is relatable to Denmark, as the soil subgrade in Denmark is very different depending on the region and even in-between areas of the same region.

In Denmark, the oldest existing drainage systems are constructed as combined systems, where sewage water and storm water are shared in the same pipe. The most frequent issue with these combined systems is that their capacity is too small to manage extreme rainfall events, and therefore, they can be overwhelmed by heavy precipitation, causing pluvial flooding. One way to solve this problem is to separate the combined systems so sewage pipes and storm water pipes are separated [1,3]. Each municipality in Denmark handles the expenses for all public roads. However, each homeowner has to pay between 1.500 and 15.000 € for the separation of their sewage and drainage systems [32]. The water from the pipes is then transported and connected to separate artificial man-made lakes or reservoirs where the excess water is kept. The most important function for such reservoirs and the artificial man-made lakes is storage or a functionality as a retarding basin. For smaller properties, rainwater is often also drained locally on the private property using gravel percolation or soakaway crates. Many municipalities have been actively engaged in transforming the existing drainage system from combined to separate, but the main issue in this regard is the economic and sustainability aspect of it. In some situations, it is too expensive to separate the sewage and stormwater pipes and reservoirs. Instead, many municipalities look into SuDS solutions, such as permeable pavements called "semi-separate solutions". Nonetheless, this type of climate adaptation solution arouses an interest in clients (e.g., municipalities and supply companies). A hybrid solution, in theory, can handle both the water and transport infrastructure in one element. However, according to some studies, a lot of issues regarding clogging in the surface of a permeable pavement has been reported [5,6,10,11]. The clogging in the surface is especially observed in pavements with porous asphalt, where there air voids are clogged with dirt. According to [4], permeable pavements needs maintenance at least twice a year to be able to hold up its infiltration rate, and according to study [33], which was conducted on porous concrete, it was concluded that periodic cleaning is necessary to maximize the life of the surface. In principle, this type of clogging is natural and thus also problematic to avoid. The challenge is therefore the maintenance of the drainage capacity. Permeable pavements are self-cleaning when the permitted speed is more than 70 km/h. Firstly, a speed of 70 km/h on a residential road/city street with low heavy traffic is unsafe in terms of traffic safety, and secondly, the self-cleaning effect is not effective enough to completely clean the clogged pores in the asphalt pavement, even at 70 km/h. This results in the water not being able to seep down through the pavement and thus having a greatly reduced lifespan [4,5,7,10,34]. This study aims to obtain knowledge about the existing experiences of permeable pavements and whether they are a sustainable solution or not. To acquire this knowledge, this paper includes results from semi-structured interviews and a data analysis of the information acquired from the respondents through said interviews.

3. Research Methodology

This study is based on literature found through a small literature review and qualitative semi-structured interviews as a means of acquiring empirical data regarding permeable pavements in the Danish construction and infrastructure industry, hence the research methodology. In addition to presenting the methods utilised in collecting scientific literature and empirical data, the chapter presents how the empirical data were analysed through identifying meaning units and essential non-redundant themes in the collected interview data in order to answer the problem-statement of the study.

3.1. Literature Collection

A small literature review was performed before the qualitative semi-structured interview. This was done to obtain a small overview regarding permeable pavements. Scopus and Google Scholar databases were used to find papers regarding permeable pavements and basic theory of traditional pavements. This resulted in approx. 15.000 records, of which 36 studies where screened and used in this paper.

3.2. Empirical Data Collection

The empirical data collection was divided into two parts. Firstly, by conducting the 24 semi-structured interviews, and secondly, through transcription of the interviews.

3.2.1. Selection of Respondents

Twenty-four respondents were selected for this interview, as they have been working with permeable pavements directly in either the role of client, contractor, or consultant. This was chosen to obtain a balanced understanding of how permeable pavements function in Denmark between the three categories. The selection criteria were therefore based on:

- Obtaining a balanced interview between clients, contractors, and consultants;
- Interviewing different companies in different regions of Denmark to observe any differences;
- Interviewing people with different years of experience to observe any variation in the respondents.

The experiences from the 24 respondents were therefore unique to gather for this study, as these are seen as professionals in regards of permeable pavements in Denmark. The respondents' expertise and experience are described further in Table 2.

In all, 24 respondents from the Danish construction and infrastructure industry participated in the empirical data collection, divided into three groups of eight respondents, which were (1) the clients, (2) consultants, and (3) contractors, representing the key stakeholders in the industry with respect to permeable pavements.

All respondents, as shown in Tables 2 and 3, were professionals with experience in owning, maintaining, or constructing permeable pavements.

3.2.2. Interview Process

The semi-structured interviews were guided by [35], utilising the conversation as a means of collecting information in a narrative format. To structure the interviews, an interview protocol was developed, which specified the introductory information which was given to all respondents, as well as the questions which were used as a conversation-starter in all interview sessions:

- Can you please introduce yourself?
- Have you been working with permeable pavements?
- In which way have you been working with permeable pavements?
- Where do you think permeable pavements should be used?
- Are there any issues and/or positive aspects to using permeable pavements?

Use of semi-structured interviews has the benefits of providing a formal and structured outline for the interview, whilst also allowing the interviewer to ask spontaneously arising questions in response to the respondent's answers [35].

The interviews were conducted in the time period from 1 December 2021 through 10 March 2022. All interviews were conducted through Microsoft Teams, which made it possible to video-record all interviews, or using the phone, in which case the interview was sound recorded.

All recordings were transcribed as recommended by [35] as it provided a great foundation for the thematical analysis, which allowed the person transcribing the recordings to attain a deeper understanding of the interview data.

Table 2. No. of respondents, gender, expertise, and experience.

No. of Respondents	Gender	Expertise	Experience, Years
1	Female	Road/pavement engineer	+10
2	Female	Project Manager in climate adaption projects	+20
3	Male	Project Manager, construction engineering, working with drainage	+20
4	Male	Road-owner of permeable pavements	+20
5	Male	Construction engineer, pavement maintenance	+20
6	Male	Material science and pavement design	+20
7	Male	Water engineering	+20
8	Female	Construction engineering, pavement maintenance	+20
9	Female	Lab. Manager, asphalt and porous asphalt	+20
10	Male	Lab. Manager, construction engineer	+20
11	Male	Specialist in permeable pavements	+20
12	Male	Specialist in permeable pavements	+20
13	Male	Foreman, porous asphalt layout	+20
14	Male	Foreman, layout of permeable pavement	+20
15	Male	Hydraulic engineering, water management	+20
16	Male	Foreman, layout of permeable pavement	+20
17	Male	Pavement specialist	+20
18	Male	Climate adaption projects, water management	+20
19	Female	Climate adaption projects, permeable pavement specialist	+20
20	Male	Road Engineer, inspection of permeable pavements	+10
21	Female	Road Engineer, inspection of permeable pavements	+10
22	Male	Landscape architect, permeable pavements	+20
23	Female	Project Manager in climate adaption projects	+20
24	Male	Pavement design	+20

Table 3. No. of respondents, profession, company, and interview platform.

No. Respondent	Profession	Company	Interview Platform
1	Road/pavement, engineer	Municipality	Teams
2	Project Manager	Municipality	Teams
3	Project Manager	Utility Company	Teams
4	Department Manager	Private company	Teams
5	Supervisor	Municipality	Phone
6	Chief Consultant	Danish Road Directorate	Teams
7	Engineer	Utility Company	Teams
8	Operation Manager	Municipality	Teams
9	Lab. Manager	Construction, asphalt	Teams
10	Lab. Manager	Construction, All materials	Teams
11	Sales Chief	Construction, All materials	Teams
12	Sales Chief	Construction, All materials	Teams
13	Foreman	Construction, asphalt	Phone
14	Owner and foreman	Construction, only construction	Teams
15	Chief Advisor	Construction, asphalt	Teams
16	Foreman	Construction, sub-base	Teams
17	Head of Section & Project Manager	Consultant	Teams
18	Development manager	Consultant	Teams
19	Market Chief	Consultant	Teams
20	Road Engineer	Consultant	Teams
21	Road Engineer	Consultant	Teams
22	Researcher	University	Teams
23	Head of Section & Project Manager	Consultant	Teams
24	Senior Engineer	Consultant	Teams

3.3. Data Analysis

In order to analyse and interpret the empirical data, a thematical analysis was utilised, as described by [36], following the five steps below:

1. Reading of the transcripts to obtain an overall understanding of the interview content;
2. Natural meaning unit selection, based on the respondent's comments;
3. Thematisation of collected meaning found in the selected meaning units;
4. "Interrogating" the meaning units with respect to the purpose of the study;
5. Completion of the description of the essential and nonredundant statements of the data.

This process was followed to ensure a structured meaning condensation process, which allowed an extensive explication of the interview data. This was achieved through breaking down the interview-transcription text into smaller units to understand both what was said by the respondents directly, as well as facilitate a reliable interpretation of meaning [36].

Based on the first readthrough of the interview transcriptions, ten meaning units were generated, which were then collected in the three themes: (1) issues of permeable pavements, (2) benefits of using permeable pavements, and (3) supplier versus local government desires, as shown in Figure 2.

In the thematical analysis process, measures were taken to ensure objectivity and an unbiased selection of meaning units through multiple people in step one and two, whilst step three was carried out by the principal investigator of this study initially, after which the results of the thematisation were discussed with peers in order to explore alternative collected meanings and themes. Steps four and five were additionally conducted in collaboration between the principal investigator of the study and two other researchers.

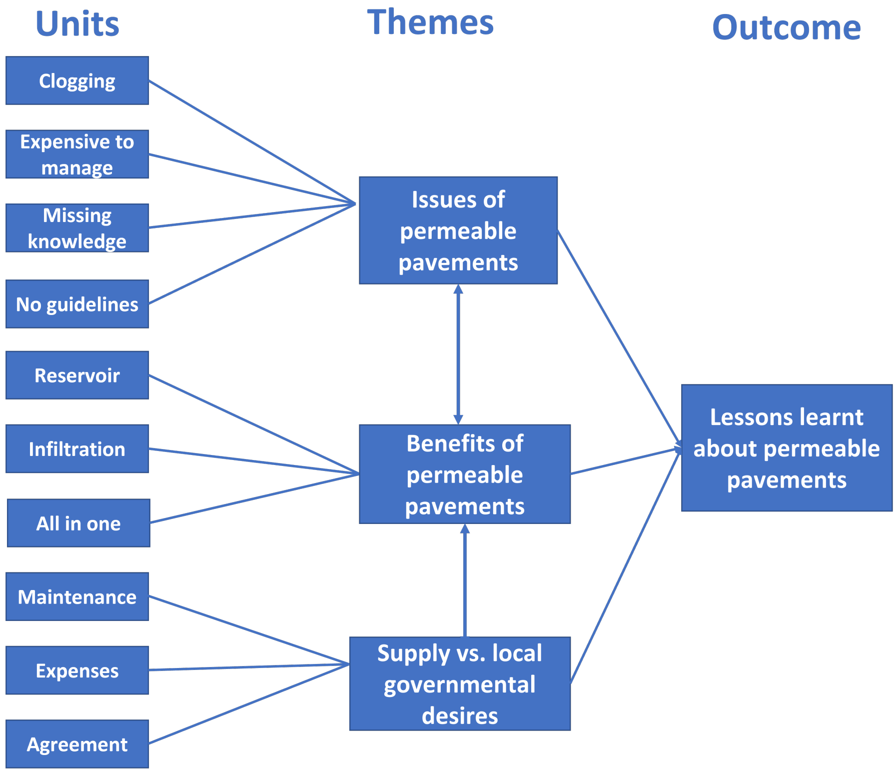

Figure 2. Coding Dictionary used for data analysis.

4. Results

In order to evaluate the response from the interviews, this section is divided into four different topics: (1) experience with permeable pavements, (2) permeable pavement issues, (3) permeable pavement benefits, and (4) road-owner vs. supply company.

4.1. Experiences with Permeable Pavements

Permeable pavements are, as mentioned earlier, used as an SuDS solution in several European countries. In Denmark, these solutions are rather novel, with the first permeable pavement constructed in 2012 on a trafficked road near Billund Airport in Denmark. Since then, approx. 40 places with porous asphalt as the top layer and a permeable sub-base have been constructed all around Denmark; some of these are shown in Figure 3. The mapped overview shown in Figure 3 is gathered from the interviewed contractors in Denmark.

As mentioned in Section 3, 24 respondents have been interviewed for this paper. When asking the respondents which experiences they have gathered in the past 10 years with respect to the usage of permeable pavements, the answers were very different. Respondent 1, the road owner of a permeable pavement construction, explains that *"it is not everywhere* *you can use permeable pavements. It has succeeded here due to its design and the location of the road.*" The road is a blind alley and a residential area where no heavy vehicles are present.

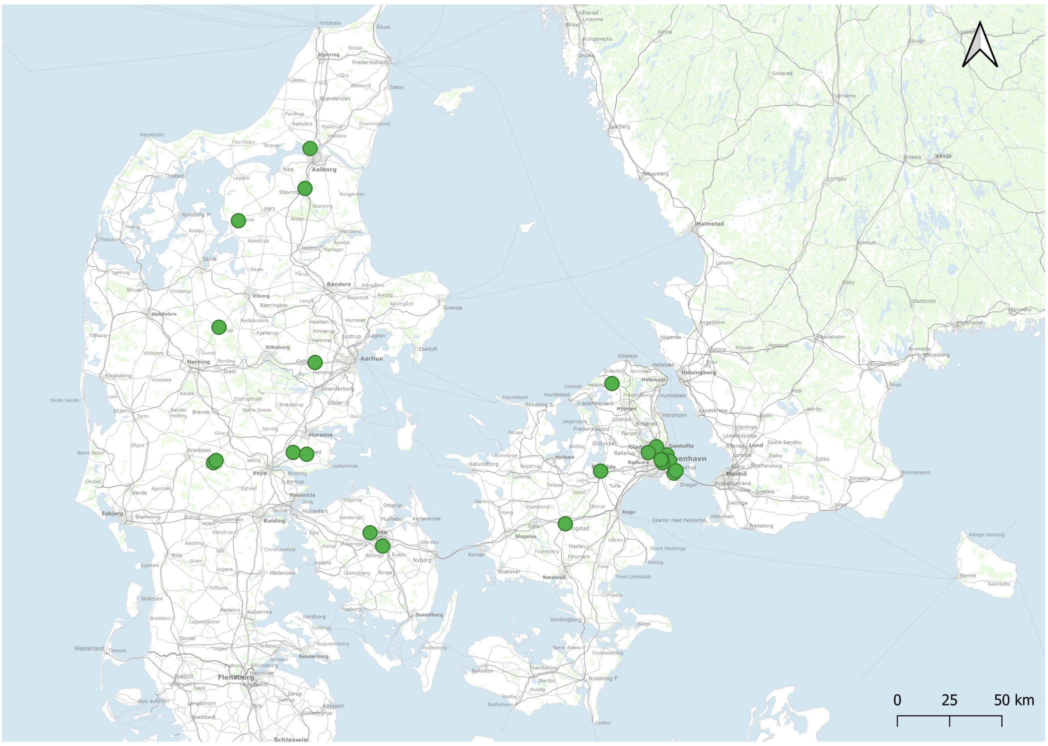

Figure 3. Mapped overview of places with asphalt toplayer, permeable pavements in Denmark.

After working with three designs of permeable pavement with porous asphalt as the top layer, respondent 2 has gathered the following experience: "*If we knew what we knew today after all these experiences, we would never have used or constructed permeable pavements with porous asphalt as the top layer.*" These pavements were constructed at the beginning of 2016 and late 2017, so they are merely 5–6 years old. Already a lot of damage appears on the pavement. These types of pavements appear to be unsuitable for use in the city centre, where transit traffic is heavy. Even on residential roads, substantial damage has occurred, indicating a significant difference to the experience gathered from respondent 1.

Respondent 14 explains the difficulties of laying out the porous asphalt due to its sticky consistency and, construction-wise, being focused on not compressing it but still keeping it loose to keep up the air-void in the surface.

Looking at it from the consultants' perspective, respondent 19 explained that the use of permeable pavements really depends on the topography, subsoil, and traffic load in the area. Respondent 1 is the road-owner of a permeable pavement that is a great example of how it can function well when the terrain is flat and there are no heavy vehicles, except for municipal waste vehicles coming once a week.

Compared to another work, where permeable pavements were used at a busy intersection in Greater Copenhagen, here the pavement construction had settled and was in bad shape after only 4–5 years of construction. This experience made the consultant realise that heavy, channelized traffic load is critical for the lifetime of the permeable pavement. It also indicates that a better solution could have been proposed to the client before the construction if there were any official guidelines on how to advise and calculate the lifespan of a permeable pavement.

The experiences are rather different among the respondents. Therefore, it would be of interest to extract all the issues, benefits, and the relationship between the supply companies and the municipalities to determine what is actually needed or what solutions should be prioritised when using permeable pavements.

4.2. Permeable Pavement Issues

Permeable pavements are, in fact, a pavement design where the surface layer allows the water to infiltrate and the permeable sub-base material allows the water to transport it further into the pavement.

In Table 4, issues from different respondents have been extracted from the interviews. As it appears, a larger variety of different issues regarding permeable pavement are presented in the interview data, indicating that all parties shared similar opinions, especially regarding clogging in the surface asphalt layer and the surface asphalt being in bad shape already after only 5 years, the limited possibilities of being able to use permeable pavements in other places than residential areas, missing official guidelines and tender documents for each material in a permeable pavement, not being able to ensure the compaction level of the sub-base material, and lastly, that the CO_2 emissions might not only become higher in the future due to the import of gravel and rocks, which is a necessity for construction, but also because of the need to reconstruct the surface layer as it is worn out already after a few years. In the following, some of the interviews with the respondents are extracted, presented, and discussed.

Respondent 2 is the road owner of three small roads with permeable pavement. The respondent clearly stated that they are no longer interested in using the porous asphalt course as the top layer or using permeable pavements as part of a sustainable solution to climate adaptation as a result of cracked and worn roads already after 5–6 years. This was an overall issue noted by most of the respondents.

Traditionally, a pavement design is designed with an intended lifespan of 20 years [15]. When using permeable pavements, which in fact is a more expensive material than traditional solutions, the lifespan should also be minimum 20 years.

Many municipalities are aware of this and are, therefore, very conservative about using permeable pavements as a SuDS solution. Respondent 5 stated that they do not believe this solution is sound, neither financially nor in terms of CO_2-emission, and that they prefer to use other SuDS solutions instead. Talking about CO_2-emission, Denmark is running out of gravel in the near future—within 10 years—and is in need of imports from Norway for larger infrastructure projects. This will increase CO_2 emissions in Denmark due to infrastructure projects, thereby making the solution less sustainable in a full lifecycle perspective.

As part of not living up to its 20-year lifespan, many interview respondents claimed that they lack knowledge regarding the bearing capacity of the permeable sub-base material and how it changes over time when it is exposed to water infiltration throughout its lifespan. In Denmark, traditional sub-base materials are usually well-graded gravel. The permeable sub-base material is sorted sub-base material and therefore constructed with a high percentage of air void (up to 30%). Hence, it is expected to have a lower bearing capacity due to its openly graded structure [19,20].

All respondents had at least one opinion in common. The knowledge about the materials' properties and the requirements for them during construction are not visible nor described in any official guidelines. For instance, respondent 8 has experience with a pavement that has settled over time, but with no knowledge about why this has happened. The respondent, however, suspected that it is due to the properties of the permeable sub-base material over time. It is rather difficult to determine the specific reason, as there is no real reference to the beginning stage of the constructed pavement nor any detailed knowledge about the properties of the materials that are used.

This leads to the discussion about missing: (1) tender documents with requirements for the products (e.g., permeable sub-base material), (2) knowledge about how to measure the degree of compaction, and (3) material specification of the permeable sub-base material. The Danish Road Directorate was also interviewed in this paper. In Denmark, the Danish Road Directorate publishes standards for highways and other roads that are state-owned. For instance, official guidance and standards for standard materials are used and modified for each project, even in smaller municipalities.

Table 4. Issues of using permeable pavements in the sector.

No. of Respondents	Respondent Type	Issue
21	6 Clients, 7 Contractors, 8 Consultants	Surface asphalt layer is clogging over a short period of time
4	3 Clients, 1 Consultant	Expensive to clean the surface after clogging, or cleaning as recommended—once a year
17	7 Clients, 2 Contractor, 8 Consultants	There is only one certified contractor of these materials for a permeable sub-base
4	2 Contractors, 2 Consultants	Would be easier to offer the product if there were general requirements set for it, hence more contractors about the bit
14	6 Clients, 2 Contractors, 6 Consultants	The surface asphalt layer already looks cracked and worn after only 5–6 years
3	1 Client, 1 Contractor, 1 Consultant	The surface asphalt layer is clogged with cigarette shutters and other dirt over time. This cannot be removed even after cleaning
9	3 Clients, 2 Contractors, 4 Consultants	There are no knowledge about how the bearing capacity of the sub-base material changes over time due to water infiltration and frost
24	8 Clients, 8 Contractors, 8 Consultants	Can only be used in residential areas
24	8 Clients, 8 Contractors, 8 Consultants	There is no official guidance on tender documents for the contractors, like for traditional pavements
24	8 Clients, 8 Contractors, 8 Consultants	There are no official guidance on how to calculate or dimension these permeable pavements
8	2 Clients, 4 Contractor, 2 Consultants	There are no specifications for a permeable sub-base
12	4 Clients, 4 Contractor, 4 Consultants	It is difficult to determine the degree of compaction of the permeable sub-base material
10	4 Clients, 6 Contractor	Heavy vehicles, traditional compaction machines are not allowed to drive on permeable sub-base materials
6	3 Clients, 3 Consultants	The surface is not only impermeable when clogged, but sometimes also seen as part of the contractors job
6	6 Clients	It is difficult when other excavators excavate in the permeable pavements and reconstruct the road with traditional materials afterwards
24	8 Clients, 8 Contractors, 8 Consultants	CO_2 emissions might be high, as Denmark needs to import gravel from Norway in the future
6	2 Clients, 1 Contractor, 5 Consultants	Heard from others' experiences that these solutions are not economically beneficial.

Permeable pavements are not a solution directly for state-owned roads, as these roads are highly trafficked, and highways and other state-owned roads are constructed in an area where there is enough space for ditches in the side area, which, in fact, are much more efficient when it comes to water management. Permeable pavements have, therefore, rarely been a topic of interest for the Road Directorate. It can therefore be discussed if official guidance from the Road Directorate could help solve the issues mentioned in Section 4. Respondent 6 agreed with the preceding and explained that, unlike municipalities, they do not rely on SuDS solutions because they have room for ditches at side areas. However, he agreed that official guidelines for SuDS solutions, specifically permeable pavements, should be developed in the near future. The majority of the interviewed respondents agreed on the three mentioned points, especially from the interviewed group of contractors and consultancies. Respondents 17–24 explained the difficulties of advising the client when it comes to permeable pavements, as there are no requirements or guidance documents to take inspiration from or to legally follow, as is the case with traditional pavements and road designs. Respondent 18 said: *It is difficult to advise clients and give them a solution that we know can obtain a lifespan of 20 years.* The contractors, respondents 9 and 10, also added the difficulty of selling permeable pavement as a solution when there are no official specifications regarding its use giving exact "promises" to the client regarding capability and durability. They both expressed the fact that this is a bigger issue if a future with permeable pavements is likely.

Another issue that was discussed and mentioned throughout the interviews was clogged pores on the surface. Water still infiltrates through the pavement, but the pores are visually clogged with dirt from cigarette shutters, gum, etc. Respondent 6 elaborated: *. . . these pores are very difficult to get cleaned, as the vacuum cleaners that are used for cleaning permeable pavements are not strong enough to remove these more physical and heavy items that are just stuck in the pores. Then you need a real person to go and remove them. That takes a lot of time, and time is equal to money. Also it seems like visually the dirt does not effect the infiltration rate at all but it gives a unpleasent look in the city center. . . .* This leads to a general discussion of the expenses used for cleaning permeable pavements, together with the hassle of keeping the road-users informed that they cannot unload gravel, sand, or the likes of it on the pavement, as this will clog the pores fully, which is an uncontrollable factor, as noted by respondents 11, 12, and 17.

4.3. Permeable Pavement Benefits

As shown in Table 5, the benefits of using permeable pavements are few. As discussed in Section 4.2, a lot of experience still indicates the fact that there is a need for general guidance and specifications to be able to use permeable pavements as a SuDS solution. The benefits of using permeable pavements are few, but the few seem to outweigh the disadvantages, at least to some degree. The majority of the interviewed respondents agreed on the convenience of using the pavement construction as both a drainage system as well as a transport path. As respondent 24 explained: *. . . you can construct a storage capacity beneath the terrain in a cheap way by using permeable pavements if you are going to dig up the original pavement construction anyway. Or, if you are already constructing a new parking lot, it can only be "quite cheap" if you are reconstructing the whole existing pavement construction*.

Respondents 23, 18, and 8 all explained that many projects in different municipalities are rebuilding the existing road or milling the existing asphalt to build a new one. Here, the solution will not be beneficial, but once the road owner reconstructs the existing from a pavement design perspective, constructing a new area where both drainage systems and roads are needed can be a cheaper solution from a water management perspective.

Respondent 7 additionally explained that permeable pavements are usable in areas where the existing drainage system is already overloaded and will overflow once high-intensity rainfall events occur. Permeable pavement will create a solution to the problem at the location, whereas reconstructing the existing pipe to a bigger pipe will only move the problem further away in the subsurface utilities unless every pipe system is changed. Respondent 4 further added that, even though permeable pavements are not a proper solution for every road type, there is still a need to investigate how to manage stormwater and flooding.

Table 5. Issues of using permeable pavements in the sector.

No. of Respondents	Respondent Type	Benefit
19	6 Clients, 8 Contractors, 5 Consultants	Water infiltrates easily once the surface course is cleaned
24	8 Clients, 8 Contractors, 8 Consultants	An easy solution to combine a detention basin and road to handle cloudbursts
14	5 Clients, 4 Contractor, 5 Consultants	More convenient to use a semi-separated solution instead widening the existing pipeline
5	3 Contractors, 2 Consultants	When first constructed, the pavement has a high infiltration rate, higher than what is needed during cloudbursts and heavy precipitation
3	1 Client, 1 Contractor, 1 Consultant	Even though it looks clogged in the surface, the surface is still able to infiltrate water
24	8 Clients, 8 Contractors, 8 Consultants	Can easily be used in a cities or areas where there is no room for basin etc.
24	8 Clients, 8 Contractors, 8 Consultants	It is used as a reservoir with large capacity
24	8 Clients, 8 Contractors, 8 Consultants	Using the permeable sub-base as a reservoir and pairing it with traditional asphalt layer

Respondents 1 and 3 were the clients of a permeable pavement project, as mentioned in Section 4.1. All parties have performed infiltration tests, where they placed a 100 mm tall plexiglass cylinder on top of the permeable pavement and measured the surface infiltration rate in mm/s. The measurements were taken once a year at the same exact location, starting in 2014 through to 2021. The results are shown in Figure 4 and are gathered from respondent 3. The permeable pavement is divided into lanes, so the left lane is cleaned once a year with a vacuum cleaner, whilst the right lane is cleaned with a sweeper. These methods are also used for traditional pavements. These are illustrated with blue and red regressions in Figure 4, together with error bars that indicate the variation between each measurement. The constant green line indicates 10 mm within 15 min of rain, which can be categorized as a cloudburst.

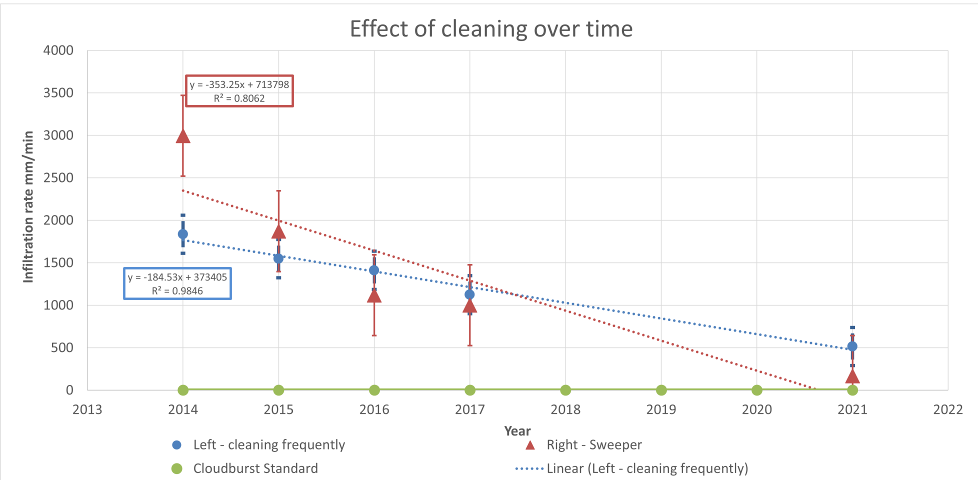

Figure 4. Received measured data a permeable pavement, where drainage functions well.

As shown in Figure 4, it is clear to see that the permeable pavement is constructed with a lot more ability with respect to water management than what is actually needed during cloudbursts. The effect of either sweeping the pavement with a traditional sweeper or cleaning with a vacuum cleaner results in a limited difference, and the respondents concluded that the cleaning process with a vacuum cleaner is not needed in the early stages of the pavement's lifecycle.

4.4. Road-Owner vs. Supply Company

The reoccurring theme during these interviews is the relationship between being a road owner and a supply company. According to the contractors and consultancies, both parties are seen as clients when it comes to constructing a pavement design that could benefit both traffic and water management. Whom is permeable pavement really most beneficial towards? The answer is simple: it is the supply companies, but who pays for the pavement design?

The municipalities pay for the construction, and for the most part, also the maintenance of the permeable pavements. Due to this settlement, many municipalities are not keen on using permeable pavement as a solution. Respondents 2 and 5 addressed this as a difficult issue, by stating that they are not interested in using permeable pavements due to the expenses. However, if the supply company cared to at least pay for the maintenance, it would be a better deal.

Respondent 1, the road owner, explained the following: *We have agreed with the supply company that we take care of the maintenance of the surface course and the curbs, while the supply company takes action to clean the surface course of the permeable pavement in regards to obtain a high infiltration rate, so it can still function and drain as desired*.

Another road-owner, Respondent 8, pays for the vacuum cleaning themselves as the supply company, and the road-owner could not agree on several things. Respondent 3 explained that it was important that the supply company is part of the conversation when choosing to use permeable pavements as a SuDS solution in a certain area. Especially, the supply company has the responsibility to (1) register information about the specific pipes, reservoirs, etc., in a database where all required data for subsurface utility engineering are registered, and (2) it is in the interest of the supply company to find a solution for water management when the existing pipes are not capable of handling the high-intensity rainfall events. It is important to specify that the excavators need knowledge about what they should be aware of when excavating and what material they should use when constructing the pavement again. The interviewed consultants, specifically respondents 20, 21, and 22, explained that the factor of "who is responsible for what" is a big issue, and there should be more official and general rules about it in the future. Respondent 22 additionally expressed: *"... we cannot deny that roads and water systems in the future should be handled together, so there is a general official need to have newer rules and newer guidance of who does what"*.

This clearly illustrates that there is a need for more communication about the maintenance of permeable pavements. As indicated in the statements presented above, permeable pavements are a combined solution to both water management and regular roads. The results of the semi-structured interviews are summarized in Table 6 and in the following section:

1. Giving the client the assurance that permeable pavements can be used as SuDS solutions;
2. The client is not aware of how to construct or what requirements to define for permeable pavements in tender documents;
3. The specifications for all materials in permeable pavements are issued in official documents, including calculating the lifespan of permeable pavements;
4. All contractors being able to offer the same products fulfills the given official guidelines;
5. Between the municipality and the supply company—who manages what?
6. Guidelines for maintenance;
7. Limited usage of permeable pavements due to clogging and worn off top layer.

Table 6. Empirical results.

No.	No. of Respondents	Respondent Type	Conclusion
1	8	2 Clients, 1 Contractors, 5 Consultants	Giving the client the assurance that permeable pavements can be used as SuDS solutions.
2	8	8 Clients	The client is not aware of how to construct or what requirements to define for permeable pavements in tender documents.
3	24	8 Clients, 8 Contractors, 8 Consultants	The specifications for all materials in permeable pavements are issued in official documents, including calculating the lifespan of permeable pavements.
4	17	7 Clients, 2 Contractors, 8 Consultants	All contractors being able to offer the same products fulfills the given official guidelines.
5	8	6 Client, 2 Consultant	Between the municipality and the supply company. Who manages what?
6	24	8 Clients, 8 Contractors, 8 Consultants	Guidelines for maintenance.
7	11	8 Clients, 3 Consultants	Limited usage of permeable pavements due to clogging and worn off top layer.

As extracted from the interview, these seven points clearly indicate the need for official guidelines regarding both material properties, construction methods, and maintenance to ensure a higher demand for permeable pavements from clients. This will be further discussed in the following sections.

5. Discussion

Permeable pavements are, in theory, a great solution for water management. In reality, they still cause a lot of issues, despite the benefits.

The respondents spoke freely about their experience with permeable pavements, and the majority of the respondents agreed that permeable pavements are, in general, a good solution, as water penetrates through the surface easily. There is, however, still room for improvement. As discussed throughout this paper, in theory, permeable pavements function as a great solution due to the merging of handling water through the pavement construction, similar to a symbiosis. However, there are a lot of specific functional aspects that make clients hesitant to invest in a SuDS solution and that kept the respondents from seeing the solution as being beneficial in an all regards.

Referring back to Section 4 and Table 6, in which, seven bullets were extracted from the interview data, the following is a discussion for each bullet:

(1) How can the client be assured to use permeable pavements as a SUDS solution and (2) how can the client become aware of to how to construct and what requirements to define for permeable pavements?

Traditionally, water is not allowed to enter the sub-base materials in regards to shortened lifespan [3,19,20], as discussed in Section 2. Using permeable pavements definitely contradicts with the traditional pavement method and is unusual to all the interviewed respondents categorized as clients, contractors, and consultancies. Some of the respondents indicated a more conservative attitude and compared the permeable pavement to the traditional pavement design. As discussed earlier and in other studies, water and moisture has a risk of resulting in a greater loss of bearing capacity, thus causing permanent deformation [10,18,23,27–29]. What should be kept in mind is the fact that permeable pavement is constructed for water management; hence, nearly all fines are discarded from the permeable sub-base material to function as a reservoir and still keep up with the bearing capacity. It is therefore of interest and importance that the bearing capacity of a permeable sub-base material under varying water level is identified to be able to ensure how big of a loss in bearing capacity is applicable in this situation.

As discussed in Section 2, Danish pavement systems are constructed based on frost protection; hence, a minimum thickness for each traffic group is important [15]. Frost protection is based on the water that evolves from the subgrade of clay or silt, which holds the water and creates air voids [17,18,26]. With respect to permeable pavements, this aspect changes the fact the pavement system should be constructed only based on frost protection, as water is intentionally let through the pavement and all the materials in the pavement design are exposed to water. Therefore, further experiences and guidelines, as well as requirements, are important to specify to be able to construct a permeable pavement that can withhold the traffic load and also function as a water management system.

The discussion above indicates that only some of the needs that should be looked into to be able to give clients the assurance that permeable pavements are a sustainable solution and hence also requirements to define.

Points (3) and (4) concluded that there is a need for specifications regarding construction, operation and maintenance, and official documents and that all contractors offering the same product might be what is needed to actually be able to give the client the assurance that these pavements are a SuDS solution. Specification and official documents are, as previously described in this paper, necessary to be able to provide the client with what is expected and also for the client to know what to expect when investing in a SuDS solution. One of the problems discussed during the interviews focused mainly on missing official guidelines, calculation guidelines, and especially tender documents for this type of pavement construction. To urge the clients and the industry to use these types of SuDS solutions, this calls for fixed industry-wide guidelines. This, as well, applies to the building industry. According to [37], tender documents in the building industry are rather lacking. In fact, tender documents are in general lacking in the construction industry, which is surprising, as tender documents are rather important documents for the contractor to be able to construct what the client wants and what the consultant has advised.

(5) In this study, it was found that the relationship between the supply company and the road owner is quite an important topic to take into account. Especially as water and roads are expected to be more dependent on each other, a more general approach or standard should be made as a standard agreement between the municipality and the supply company. This will help out with the discussion between the two about who manages what.

(6) Guidelines for maintenance are rather difficult to formulate, as the experience of permeable pavements are project-dependent and depend on the surrounding area and traffic. However, the maintenance can become of minor consideration if the permeable pavement is constructed with a sealed top layer and a permeable sub-base.

(7) One of the issues regarding the permeable pavement surface that cannot be solved with official guidelines is the clogged, cracked, and visually poor looking surface of the porous asphalt top layer. This was discussed in Section 4.2 as one of the problems, which is also mentioned in several studies [4,7,14,34]. Some of the clients were worried as they are experiencing issues with the top layer as the construction of the pavement is finished, and as the study [33] states for concrete porous surface top layers, it is necessary to perform periodic cleaning to obtain the best results. However, this does not solve the specific problem based on these interview, where the problem is not water management directly, but the appearance and condition of the pavement a couple of years after the construction phase has concluded. The top layer can be clogged with dirt that looks unappealing but still functions for drainage. The clogged area can typically not be cleaned with a vacuum cleaner, as this does not remove enough of the dirt accumulated in the surface. One way to solve the issue is by constructing a sealed top layer instead of a porous medium and then building in drain grates with sand traps that can be emptied once in a while. The sub-base layer should be constructed with a permeable sub-base, so the pavement construction is still used as a reservoir. This would eliminate the issue of clogging in the asphalt pores and the expense of cleaning and similar maintenance.

6. Conclusions

Permeable pavements are known to be sustainable urban drainage solutions. However, is it a efficient solution?

The interviews reflected on many topics, revealing that the issues of permeable pavement usage and maintenance and operation are strong and many. In general, there is a long way to go for the client to be interested in permeable pavements with asphalt as a surface layer and to finalize the deal.

Based on the empirical results, presented in this paper, permeable pavements are clearly not the most efficient solution to climate adaptation, when looking at it from both an economic and a sustainable (resource) perspective. Permeable pavement needs maintenance, as also found in this empirical study, which revealed that the pavement surface already needs some sort of reconstruction after 6–7 years of the pavement's lifespan, which is too soon according to clients when compared to traditional pavement.

As pointed out in the bullet points below, there are several needs to be satisfied by different actors in the industry before this specific SuDS solution will increase in demand and be useful in the future. As discussed in Section 4.2, the respondents clearly stated that there is a need for knowledge about the materials that are used so that this can be part of official guidance of construction, operation, and requirements for permeable pavements, answering questions such as: What is it that we buy from the contractor? or Is the material fulfilling the requirements set for it? Questions which are imminent to obtain answers to for the contractor, consultant, and client to be able to design, build, and operate permeable pavements.

- There is a need for official guidance and official tender documents on how to construct, how to consult, and what to expect for the intended performance of the road.
- There is not enough information about the specific materials that are used in permeable pavements.
- It should be considered whether a porous top layer is a solution that should be recommended in the future.
- There is a need for official or general guidance between the road owner and the supply company when using SuDS solutions.

The question remaining is: who will take the first step?

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