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A Review of Porous Concrete Pavement: Compressive Strength and Clogging Investigation

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ABSTRACT

Pervious concrete pavements (PCPs) have been widely accepted as a green infrastructure solution for urban areas. Currently, pervious concrete is commonly used in permeable pavement systems such as roadways, sidewalks, driveways, parking lots, and other light-duty flatwork applications. However, the main disadvantage of this type of pavement is that it loses permeability over time due to clogging and lower compressive strength due to the pore's structures. These critical issues are the topic of this review paper. Laboratory test results relevant to the compressive strength, clogging and maintenance are discussed in detail. This review aims to present a compilation of prominent findings of studies focused on compressive strength, clogging and maintenance of PCPs. Note that PCPs with higher compressive strength must be used on roads with high traffic volumes. Subsequently, periodic maintenance is necessary to prevent sediment clogging and maximise the life of PCPs. Based on this review paper, the area of need for future research are identified.

1. Introduction

Pervious concrete pavements (PCPs) are used more frequently because of their environmentally beneficial properties. In addition, PCPs are a permeable pavement system that allows surface water to infiltrate the ground and reduce the impact of the urban heat island effect [1-7]. Various environmental advantages are attributed to PCPs, including improved runoff and infiltration of stormwater, improved skid resistance of pavement surface, improved subsurface water quality, decreased hydroplaning, heat-island effect, and traffic noise [8]. The application of PCPs in Asia becoming increasingly popular,particularly in tropical climate countries.The tropical climate referred to the average year-round temperature of 20–35 °C and relative humidity of 80 – 90% with high average of rainfall [9]. Figure 1 shows the schematic diagram of the PCPs layout.

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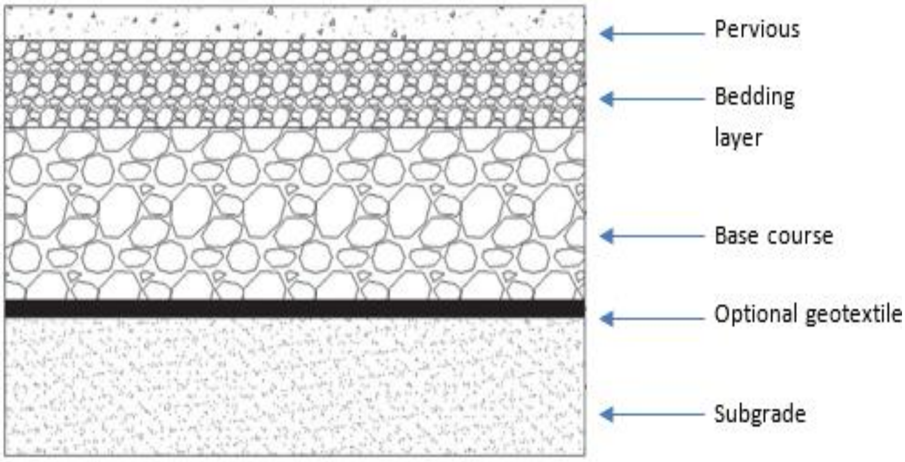

Fig. 1. Typical pervious concrete pavement [12]

Because of the pervious nature of the pavement, water accumulated on the road or pavements drains out immediately.In addition,PCPs are able to filter out certain pollutants from stormwater and runoff to infiltrate into the soil. The presence of high chemical oxygen demand (COD), biological oxygen demand (BOD), suspended and colloidal particles and dyes in industries effluent is harmful to the ground water [10]. Thus,the level of pollutant in industries effluent can be reduced with the application of PCPs . Meanwhile, Figure 2 shows the pervious concrete with coarse aggregates coated with normal cement paste and sufficient void space. The ability of these pavements to manage stormwater runoff is dependent not only on subsurface storage but also on infiltration capacity during rainfall events. Therefore, the benefits of PCPs make them ideal for use as a pavement surface in urban areas.

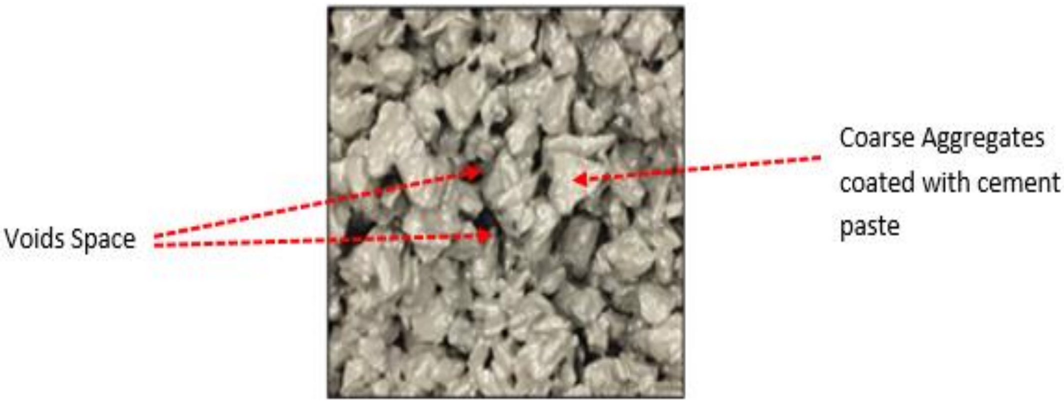

Fig. 2. Pervious concrete with coarse aggregate coated with cement pasted [13]

However, due to its porosity, the material's strength is relatively low and limits its use in high-volume traffic [11]. The material's compressive strength is only about 20-30 MPa. Furthermore, the sediment and debris accumulated on the pavement's surface will create a clogging problem [5]. This accumulation reduces surface infiltration rates, eventually leading to surface ponding. In addition, the clogging caused by sediments entering the pavement pore structure will lead to the continuous reduction of the permeability of pervious pavement until failure. Table 1 shows the normative limits value of PCPs.

Table 1
Normative limits of pervious concrete [11]

Test	Normative limits
Density	1600-2000 kg/m^3
Total Void	15-35%
Water permeability coefficient	0.14-1.2 cm/s
Compressive strength	3.5-28 MPa
Splitting – tensile strength	-
Flexural tensile strength	1-3.8 MPa

This paper is a compilation of prominent findings of studies focused on the properties of mechanical and physical performance of PCPs, such as compressive strength, clogging and maintenance. Section 2 discusses the review of the study of PCPs. Consequently, Section 2.1 until Section 2.3 explained details about the mechanical properties and durability, the clogging issues, and the maintenance measurements. Finally, Section 3 describes the conclusion. The objectives of this study was to review the compressive strength, clogging mechanism and maintenance adopted of PCPs. The outcomes of this study are to help the research community efficiently navigate the existing literature and respond promptly to new challenges and issues that arise from the rapid adoption of PCPs technology.

2. Literature Survey

A research article published from 2010 until 2022 was gathered for this literature survey by searching in the Scopus database. The search parameters were a combination of "porous or pervious or permeable concrete pavement", "clogging", and "maintenance".

An extensive collection of papers was gathered using these keywords in the initial search. Subsequently, the papers were screened for their relevance to the general theme of this review, which is the mechanical behaviour, clogging effect and maintenance measures adopted. Based on this extensive review, recent findings regarding mechanical behaviour,clogging effect and maintenance adopted has been investigated and the research gap that still needs to be studied was identified.

2.1 Compressive Strength

Pervious concrete pavements (PCPs) contain few or no fine aggregates to permit the water into its structure. During the technology development, the quality of PCPs is increasing with the improvement of their compressive strength and noise reduction. PCPs, in contrast to conventional concrete pavement, have a high percentage of voids, between 15% and 25% [14]. Figure 2 shows the position of voids spaces,coarse aggregates and cement paste in PCPs.

The void space in PCPs tends to decrease the concrete strength and durability. However, the acceptable void space is required to allow runoff water to infiltrate freely into the underneath layers. This can be achieved by controlling the fine and coarse aggregates, as well as the binders from the concrete mixtures [15].

2.1.1 PCPs modifed mixtures

There are various studies have been conducted to increase the strength of pervious concrete by modifying the concrete mixtures. The mechanical properties of PCPs was investigated by replacing cement contents by weight with styrene-butadiene rubber latex (SBRL) and the addition of recycled coarse aggregates. This study replaced SBLR with 5%, 10% and 15% cement weight. Then, 0%, 25%, 50%, 75% and 100% of recycled aggregates replaced the natural coarse aggregates. This study has found that the addition of SBRL positively affects the mechanical properties of pervious concrete. However, permeability indices have decreased slightly. The addition of 10% SBRL to pervious concrete containing 75% recycled aggregate increased the 28-day compressive, splitting, and flexural tensile strength by 70.8%, 49.4%, and 29.7%. Furthermore, the hardened voids content, water permeability, and potential for degradation were reduced by 13.3%, 11%, and 31.7%, correspondingly [16].

In addition, this is another study to assess a new combination of superplasticiser (SP) and Hydroxypropyl methylcellulose (HPMC) admixtures in the pervious concrete mixtures. Different paste content (15.2%, 18.3%, and 22.5%) and substitution 0%, 50%, and 100% of the natural aggregate (NA) by recycled concrete aggregate (RCA). Alternatively, the mechanical properties (compressive, flexural, and splitting-tensile strengths) were also evaluated. The incorporation of 50% RCA for paste contents of 15.2% and 18.3% increased mechanical performance without compromising permeability.

The pore structure features were extracted from pervious concrete samples through the image analysis technique to obtain pore structure parameters such as area, diameter, and size. The pore structure of the pervious concrete revealed that adding RCA increased pore connectivity and size. As a result of the findings, it appears that the use of SP and HPMC admixtures improved the interfacial transition zone of pervious concrete with RCA and enabled hydraulic-mechanical properties similar to NA concrete. Figure 3 shows the image analysis process of pervious concrete samples. Finally, the RCA-containing compositions had permeability and flexural tensile strength values that were higher than those recommended by the standards, allowing them to be used in pedestrian traffic areas [11].

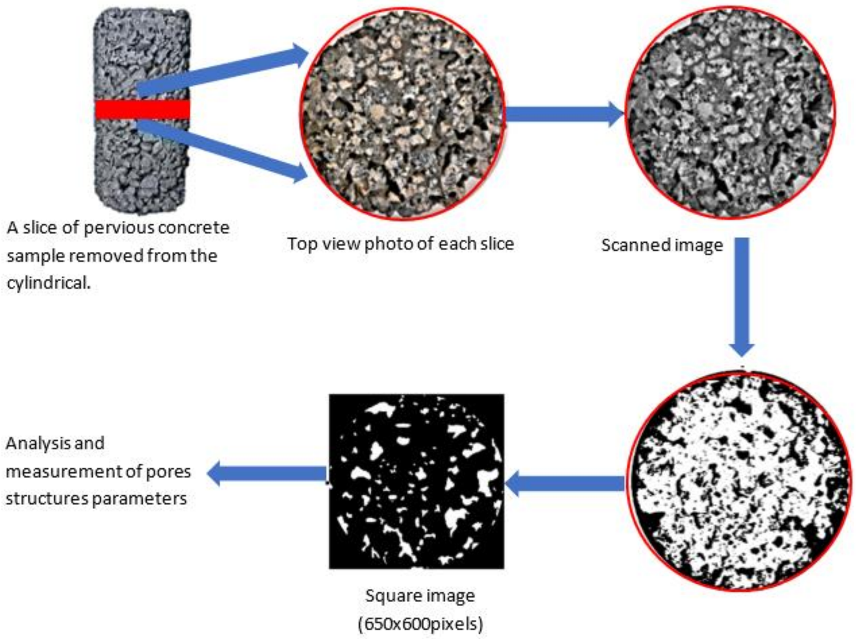

Fig. 3. Image analysis process [11]

In another study, the effect of fine aggregate and coarse aggregate quantities on the properties of pervious concrete, as well as the performance characteristics of pervious concrete in terms of permeability, compressive strength, flexural strength, and split tensile strength were investigated. The materials used are Ordinary Portland Cement (OPC) Type-I of Grade 43, fine aggregate confirming gradation (Zone II) and coarse aggregate mix of 4.75–10 mm, 10–12.5 mm, 12.5–16 mm, 16–20 mm of 15, 40, 30 and 15% of the total weight of coarse aggregate, respectively. Mixes were prepared with the water-cement ratio of 0.34 and maintaining the aggregate-cement ratio as 3.5:1.The study found that increasing the fine aggregates increases various mechanical properties such as compressive strength, flexural strength, split tensile strength, and coefficient of permeability [17].

An experimental study has been conducted to investigate the use of pervious concrete on high-traffic volume roads. The optimum mixture of pervious concrete was developed based on the Technical Specification for Concrete Road Pavements of the General Directorate of Turkish Highways. As a result, the researcher found that the pervious concrete produced with the proper aggregate/binder (A/B) ratio and aggregate size meets the required strength for concrete roads and can be used as a concrete road pavement material. The results also revealed that the (A/B) ratio and aggregate size significantly impact the strength properties of pervious concrete mixtures [18].

Furthermore, the feasibility of using incinerator bottom ashes (IBA) in pervious concrete mixture as a roadway base course was investigated. The IBA were found to have good mechanical properties compared with natural aggregates.However, increasing IBA will result in a decrease in compaction strength. It was discovered that mixtures with less than 60% IBA replacement can produce acceptable results that meet specifications [19].

In another study, the mechanical performance of high-performance PCPs with unsaturated polyester (UP) resin as the binder was investigated. The results revealed that the PCPs with 30% UP resin had optimal performance with incorporating 10%, 15%, and 20% of ethylene–vinyl acetate (EVA) as a thermoplastic material [20].

In summary,the compressive strength of PCPs is greatly dependent on the content and properties of aggregates and binder or cement content as shown in Table 2.

Table 2
Compressive strength of PCPs based on various aggregates and cement content

Aggregates (kg/m3)	Cement (kg/m3)	Compressive Strength (MPa)	References
1800	250	3.45	Ibrahim *et al.,* [21]
1600	200	2.80	
1800	150	1.83	
1263	554	19.89	Sumanasooriya & Neithalath [22]
1279	496	14.65	
1286	411	9.66	
1560	367	13.9	Lim *et al.,* [23]
1560	242	8.6	
1115	450	18.03	Ramadhansyah *et al.,* [24]
1450	440	14.37	
1430	400	11.82	

2.2 Pore Features and Clogging Behaviour

The hydraulic performance is crucial for PCPs. Note that the hydraulics performance can be measured by permeability or infiltration rate. The permeablity of PCPs is highly dependent on the pore features and clogging effect during its service. This section will elaborate on the effect of clogging behaviour on permeability and infiltration rate of pervious concrete pavement.

2.2.1 Permeability rate

The existence of pores were effected the permeability rate of PCPs. The contents of fine and course aggregates were affected the pores structure and permeability rate in PCPs. The permeability rate of PCPs without fine aggregates is more higher compared to with fine aggregate. The normal flow rate of permeable concrete with and without fine aggregate is 7.67 - 9 ml/s and 14.83-15.83 ml/s, respectively [25]. In a different study, Teixeira *et al.,* [27] examined the influence of sediment typology and material maintenance on the permeability of pervious concrete. Pervious concrete with varying percentages of fine aggregate was designed for the experimental programme, and the samples produced were submitted to permeability tests after sediment deposition and aspiration cleaning cycles. The findings revealed that larger particles (sand) caused permeability loss by sealing the upper layer of the samples, whereas fine sediments (clay) clogged the lower layers. These findings show that clogging is recoverable through periodic pavement maintenance and cleaning despite impacting the hydraulic performance of pervious concrete.

2.2.2 Clogging

Previous research has investigated the clog-resistant pervious concrete pavements. In this study, the combination of permeability, infiltration, and clogging testing results were analysed to provide background information for the specification and design of clog-resistant pervious concrete pavements [26]. Most of the researchers have recently shown increased interest in clogging resistance of PCPs through various initiatives. One of the initiatives is to investigate the influence of the filling and water/cement (W/C) ratios on the compressive strength and permeability of pervious concrete. A novel method using saturated slurry soil as clogging media is proposed to evaluate the clogging resistance of pervious concrete. Other than that, the clogging phenomenon was analysed by image processing, showing that the filling ratio is an important parameter in the mix design of pervious concrete and that simply lowering the W/C ratio is not always effective in preparing high-performance pervious concrete.

According to image processing analysis, large pores are beneficial to permeability. However, excessively large pores reduce permeability due to increased pore tortuosity [28]. Furthermore, the depth of the pavement and the material used in the joint and bedding aggregates were responsible for most of the sediment accumulation. Apart from that, most of the sediment was retained in the bedding and surface layers and adding a base course layer had little effect on retention. The overall rate of retention increased when mono-sized sediments were added in decreasing size order, with the coarsest sediments applied first [29]. Figure 4 shows the relationship between permeability rate and clogging cycles. Meanwhile, Figure 5 shows the difference between normal pervious concrete images and clogged pervious concrete.

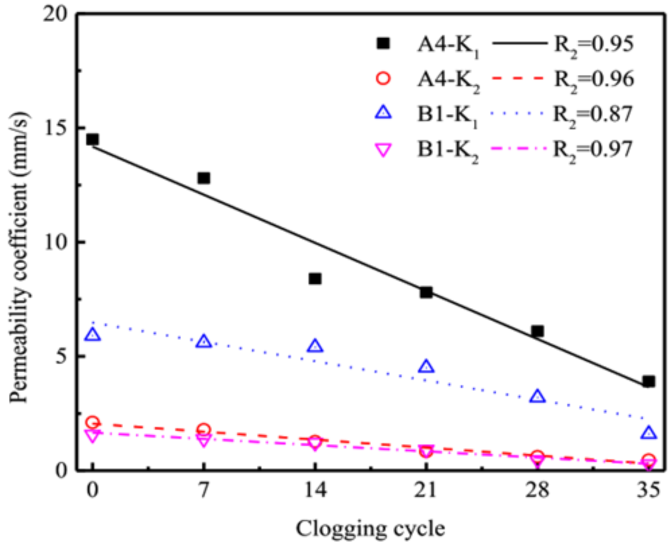

Fig. 4. Relationship between permeability and clogging cycle [28]

Fig. 5. Comparison of normal pervious concrete pavement and clogged cervious concrete pavement [28,30]

2.3 Clogging Maintenance Adopted

The main challenges for the wider application of PCPs are its low strength, high likelihood of clogging, and inconvenient maintenance [31]. Various studies have been done to find the best method of maintaining PCPs. Note that the maintenance focused on preventing the clogging effect that reduces the service life of PCPs.

A field performance evaluation of the periodic maintenance for PCPs was carried out by Hu *et al.,* [32] to investigate the permeability of a newly constructed pervious concrete pavement. In this study, eight maintenance methods were used to test 32 samples of PCPs. Different maintenance methods, such as pressure wash, sweep and vacuum, and pressure wash and vacuum, are designed to find the best combination. As a result, the maintenance effect is similar when the pressure wash is between 5 and 20 Mpa, and the combination of pressure wash and vacuum suction has the best maintenance effect. A list of published maintenance methods to prevent the clogging effect of pervious concrete pavement is provided in Table 3.

Table 3
Summary of the reviewed studies on the Maintenance method.

No.	Maintenance Method	Results	References
1	Backwashing	The proposed novel backwashing maintenance method outperformed conventional methods, but its recovery rate was affected by clogging conditions and backwashing pore flow velocity in the PCPs layer.	Zhao *et al.,* [33]
2	Hand-held power brush and pressure washer	Surface treatment with a pressure washer and vacuum street sweeper combination significantly improved parking lot usage intensity and was deemed an important factor in restoring infiltration capacity.	Sehgal *et al.,* [34]
3	Blower	Using a blower for periodic cleaning was efficient. Monthly maintenance is the most appropriate because cleaning requires less time and fuel.	Silva *et al.,* [35]
4	Air street sweeper	Early and repeated maintenance can extend the functional life of permeable pavement, as infiltration measurements were comparable to the restorative cell even after being clogged with 25% more street sweepings.	Scott *et al.,* [36]
5	Drainage slots	Pervious concrete pavement systems with drainage slots cast into their bases would take much longer to clog than unmodified pavers.	Lucke [37]
6	Reverse flush process	The reverse flush process was found to be effective on clogging material tested, was independent of pavement porosity, and worked at the lowest pressure tested.	Shirke *et al.,* [38]
7	Power blowing, pressure washing, and vacuuming	Pressure washing and vacuuming are both equally effective as initial cleaning techniques, increasing surface infiltration rate by more than 90%. Combining vacuuming and pressure washing provides significant advantages over either method alone.	Hein *et al.,* [39]

3. Conclusion

These works were devoted to reviewing the prominent findings of studies focused on the compressive strength, clogging and maintenance of pervious concrete pavements (PCPs). It was found that the PCPs are interesting from an environmental and social viewpoint. However, the void space in pervious concrete pavement tends to decrease the concrete strength and durability. The typical mixture of pervious concrete pavement has resulted in compressive strength in the range of 3 – 28 MPa. There are various modifications of the pervious concrete mixtures have been investigated, such as replacing natural aggregate (NA) with recycled aggregate, modifying the quantities of fine and coarse aggregate, replacing cement paste with fly ash and applying the waste materials to the concrete mixture. As a result, an acceptable range of compressive strength was obtained.

Clogging issues have remained the main challenge in the application of PCPs. Note that large pores benefit permeability, but excessively large pores reduce permeability due to increased pore tortuosity. In addition, the larger pore volume (formed using a larger aggregate size) results in a significant drop in permeability due to sediment accumulation. Thus, the relationship between permeability and clogging recycling is significant in developing a better permeability rate.

Periodic cleaning is necessary to maximise the life of the paving, which should start as soon as the pavement is ready. The pavement rehabilitation performed through pressure washing indicated a significant improvement in permeability after de-clogging. Overall, regular maintenance is essential to ensure the long-term hydraulic functionality of pervious concrete pavement. The need for future research was identified in developing high-strength of PCPs which is the best PCPs mixture design to obtain the optimum pores size and compressive strength, better permeability rate, and efficient maintenance method.

In conclusion, the current challenge of PCPs applications is the clogging effects and mechanical performance that will reduce the service life of PCPs. Future research also required, especially in terms of mechanical performance of PCPs, long-term monitoring or field evaluation and maintenance on clogging effects of PCPs which will make it a promising sustainable pavements in the future.

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