Porous Concrete Paving Block: A Review of Clogging Mechanism and Durability

Yudi Pranoto[1,2][a], Nor Fazilah Hashim[1][b], Tumingan[2][c] and Joko Suryono[2][d]
[1]*Faculty of Technology and Informatics Razak, Universiti Teknologi Malaysia, Jalan Sultan Yahya Petra 54100, Kuala Lumpur, Malaysia*
[2]*Civil Engineering Department, Samarinda State Polytechnic, Jalan Ciptomangunkusumo 75131, Samarinda, East Kalimantan, Indonesia*

Keywords: Porous Concrete Paving Block, Clogging Mechanism, Durability.

Abstract: This article is to provides an overview of porous concrete paving block (PCPB) development based on recent literatures especially on clogging mechanisms, maintenance and durability. This pavement allows water to flow through the cavities in the layer, shence make a significant contribution to reducing surface runoff. Main issue is the surface infiltration rates of permeable pavements decline with time as sediment and debris clog pore spaces caused by several factors such as rainfall characteristics, soil characteristics, air temperature, drainage area, and traffic volume type. PCPB needs periodic maintenance to keep the efficiency to increase the strength and infiltration of the PCPB lot of studies has been done where various additives has been applied like fly ash, recycled aggregate, recycled asphalt, and others as a part of PCPB, but yet the optimum condition to produce it has still not been established. The performance of PCPB is determined by their compressive strength, and infiltration. In general, it is challenging to simultaneously optimize the durability, and infiltration performance of PCPB, however with continous. Modeling and advance research improve PCPB performance without significantly increasing its maintenance requirement. This article also looks into the future of PCPB with good performance, easy maintenance, and maximum infiltration.

1 INTRODUCTION

Porous concrete paving block (PCPB) is a permeable concrete type made from a mixture of cement or hydraulic adhesive, aggregate, water, and other materials without reducing the quality of the porous paving (SNI 03-0691 1996). PCPB is the upper layer of permeable concrete block pavement (semi-rigid pavement) that can absorb water from the surface into the ground. PCPB is prevalent to replace conventional infrastructures such as parks, roads with low traffic, and parking. PCPB is a type of modular permeable pavement that we often encounter in our environment. In general, Permeable pavement is divide into two types. The first is monolithic permeable pavement (porous asphalt and pervious concrete), and the second is modular permeable pavement (porous concrete paving block) (Figure 1) (Yong et al., 2013; Yu et al., 2021). The absorption concept of rainwater seep into the soil through the pores of three types of permeable pavement can be seen in Figure 2. Many previous researchers have carried out study on two types of permeable pavement (Cheng et al., 2019; Huang et al., 2016). Compared with conventional paving, PCPB has greater porosity. PCPB usually has a 15-30% porosity by volume (Kia et al., 2017).

PCPB can play an essential role in addressing dense environments such as urban areas that frequent flooding. PCPB can reduce water runoff at ground level because it can infiltrate water into the soil quickly. A recent review of permeable concrete pavement has excellent potential in delivering multiple environmental benefits in mitigating the risk

[a] https://orcid.org/0000-0003-2997-7475
[b] https://orcid.org/0000-0002-1841-4354
[c] https://orcid.org/0000-0001-9279-1521
[d] https://orcid.org/0000-0001-8281-6692

Pranoto, Y., Fazilah Hashim, N., Tumingan, . and Suryono, J.
Porous Concrete Paving Block: A Review of Clogging Mechanism and Durability.
DOI: 10.5220/0010948800003260
In *Proceedings of the 4th International Conference on Applied Science and Technology on Engineering Science (iCAST-ES 2021)*, pages 534-544
ISBN: 978-989-758-615-6; ISSN: 2975-8246

of slip-related falls, improving skid resistance, reducing traffic noise, and alleviating the burden of urban heat island (Xie et al., 2019; Euniza et al., 2014; Jusli et al., 2014). The main challenge found is the PCPB strength decreases exponentially as the void ratio increases. The strength of the porous concrete pavement still need to improve (Ramadhansyah et al. 2014).

PCPB has been studied by many researchers who are oriented towards improving mechanical properties and maintaining high porosity, primarily by using additives and new materials. For example, increasing the strength of PCPB by adding steel fibers (Kanawade, 2018; Maharana et al., 2020), coconut fibers (Limantara et al., 2018), volcanic ash (Rifa'i and Yasufuku, 2017), Polypropylene fibers (Muhammed and Varkey, 2016), fly ash (Mali and Abraham, 2016; Aman et al., 2018; Malliga and Moorthy, 2019; Qomaruddin et al., 2019; Wijaya and Ekaputri, 2014; Saputra and Arie Wardhono, 2018; nano clay and fibers (Girish et al., 2018). Using fine aggregate can increase the compressive strength of PCPB but reduce the porosity and permeability of PCPB (Sharma and Gupta, 2015; Manan et al., 2018).

In another review, research has also been carried out using recycled materials for making paving from rubber (Euniza et al., 2014; Euniza et al., 2019; Jusli et al., 2014), recycle aggregate (Abdul Ghani and Cheong, 2014; Chethana and Suhas, 2020), Recycled Asphalt Pavement aggregates (Hossiney et al., 2020). On the other hand, the use of round aggregates can reduce the strength of PCPB even though it can increase porosity (Rifqi et al., 2018).

PCPB can be used for parking, walk area, applied low traffic up to heavy traffic (Girish et al., 2018; Manan et al., 2018). A recent review of the clogging mechanism in permeable pavement has been carried out by (Razzaghmanesh and Beecham, 2018; Kia et al., 2017). Razzaghmanesh and Beecham found that porous concrete generally has the highest infiltration capacity and this is followed by permeable interlocking concrete pavement and then porous asphalt. Kia et al. found that new types of permeable concrete that can reduce storm water run off.

2 METHODS

In recent years, there are many studies conducted on PCPB, especially on developing and evaluating various types of PCPB. Still, only a few review articles summarize the latest results and future PCPB clogging and durability trends.

In this article, the latest advances regarding PCPB are discussed, considering PCPB as a promising infrastructure. This article discusses on clogging, maintenance, and durability. Advanced modeling to help optimize PCPB performance and durability also discusses in this article. More importantly, this article summarizes the latest critical findings regarding infiltration testing methods, treatment, and implementation of PCPB.

Literature review resources were collected from various journals in the development of the last ten years. This is taken through searches in the Scopus database, web of science, google scholar, and research gate. The keywords used include porous paving, clogging, infiltration, geopolymer paving, porosity, maintenance, and permeable pavement. Peer-reviewed journal papers and conference proceedings were also selected. A total of 150 relevant publications since 2011 were included in this review, using the following criteria: relevance to review points, quality and credibility, up-to-date, and indication of future trends in PCPB studies. The final result of this work is to help maintain the infiltration of PCPB performance by routine maintenance. It has had good infiltration performance over a long time and encourages the findings of new technologies to review the clogging mechanism and infiltration rate.

Figure 3 shows a flow chart of the relationship between PCPB, environment, clogging, maintenance, and durability.

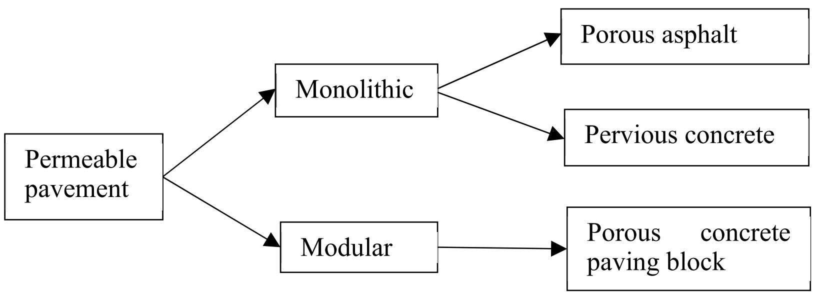

Figure 1: Permeable pavement types.

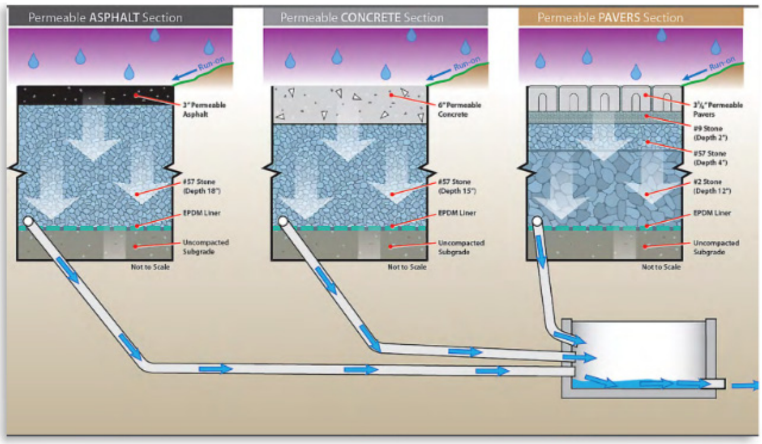

Figure 2: Conceptual diagram showing a cross-sectional profile of permeable pavement (Selbig and Buer, 2018).

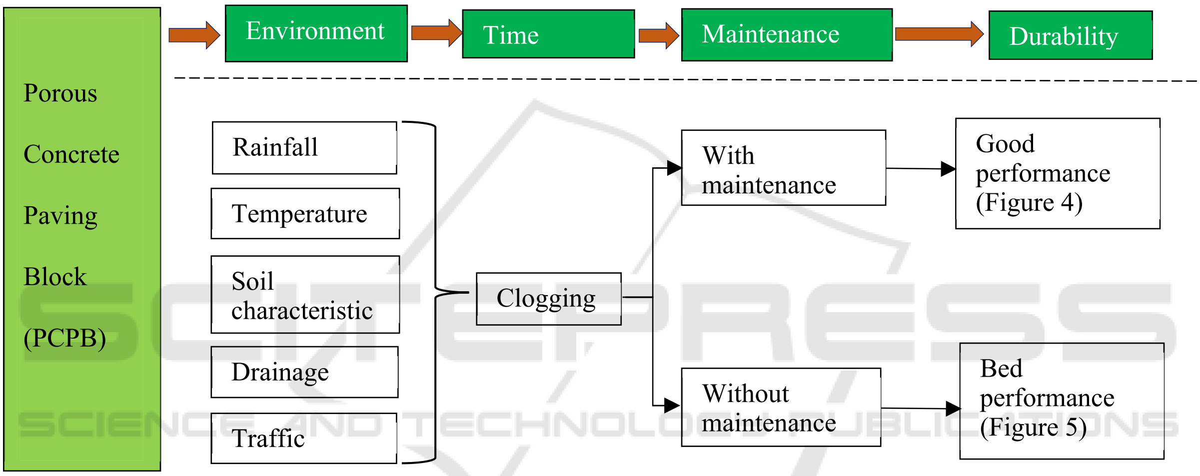

Figure 3: Relationship between PCPB and durability.

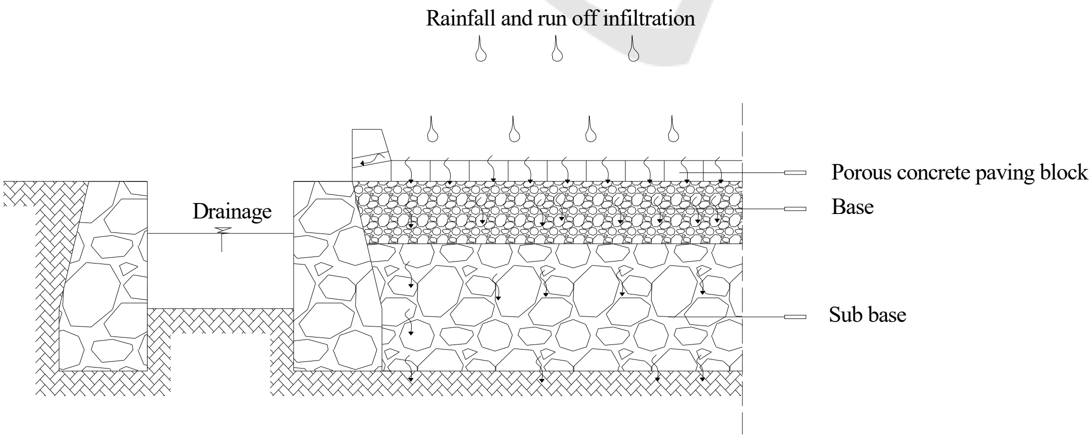

Figure 4: PCPB Performance with maintenance.

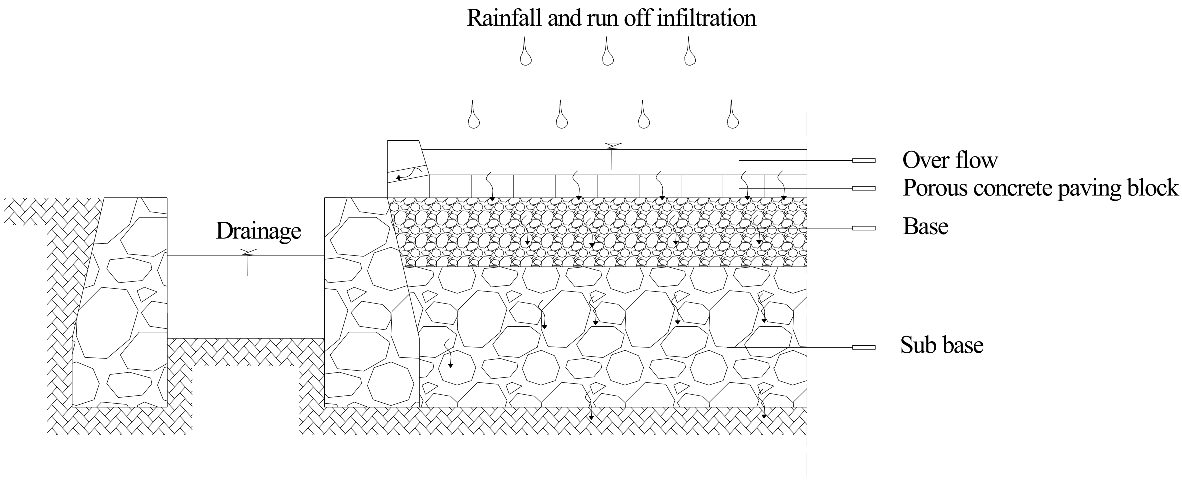

Figure 5: PCPB Performance without maintenance.

2 RESULT

2.1 Clogging Mechanism

The clogging system in porous paving is a problem that can reduce the functionality of the PCPB technology. Materials that cause clogging include sand, clay, silt that has been eroded from the surrounding area or carried by vehicles, and organic material from surrounding plants (Kia et al., 2017). PCPB will clog over time because the solid particles are stuck and accumulate. Rainwater carries these particles into the pavement layer. This particle is coupled with the pressure of passing traffic. The particles fill the space on the PCPB. Over time these particles will close the cavity in the PCPB that causes water to stagnate on the surface (Zhang et al., 2018).

The PCPB clogging has attracted the interest of many researchers, especially in the clogging mechanism and maintenance methods. The clogging problem in porous concrete has been discussed in a recent review by (Razzaghmanesh and Beecham, 2018; Razzaghmanesh and Borst, 2018; Selbig et al., 2019). They found that the highest infiltration rate occurs in areas with high rainfall, so they recommended that maintenance be carried out two until four times a year. Much research has been done on the clogging of PCPB by sand and mud that can reduce the infiltration of PCPB (Kapoor et al., 2021).

Translucent concrete made with a smaller aggregate fraction is more prone to clogging than concrete made using a large aggregate fraction. Regarding the effect of the unbound base course (UBC), it is essential to find a balance between porous concrete infiltration and the exfiltration rate of UBC, especially in the case of porous concrete made from coarse aggregates (Barišić et al. 2020). The key of the selected paper about clogging of permeable pavement show in table 1.

The table 1 shows that clogging mechanism in the permeable pavement is caused by high-intensity rain that carries particles (sand, soil, or other materials) into the porous layer. These particles penetrate the pores of the paving layer. Particles with a size of 0.6 – 2.2 mm are blocked within 2 cm of the surface layer, while particles of less than 0.3 mm can penetrate deep into the permeable pavement and accumulate over time. The highest void reduction is concentrated at the bottom of permeable pavement (40 - 90%). The reductions in total suspended solids were approximately 60 percent; clogging occurred after approximately one year.

2.1.1 Modelling and Simulation

Recently, research on permeable pavement modeling has been developed to measure the performance of porous paving. Study on clogging mechanism modeling in the permeable pavement by (Zhang et al. 2018) using fine, medium, and coarse grading sand (Figure 6). The results showed that well-graded sand was able to seep up to a depth of 30 mm on water-permeable pavements; coarse sand will settle on a shallow surface with a depth of 20 mm on the see-through pavement, and fine sand will seep to a depth of 60–100 mm on translucent pavements. Hu et al., (2021) using the same application was also used to model porous asphalt pavements clogging mechanism.

Table 1: Selected studies on clogging mechanism.

No	Author	Region of studies (year)	Data collection method	Findings / critical review
1	Kapoor et al.	India (2021)	Experimental	The decrease in infiltration rate was observed to be 30%, 50%, and 45% after the sixty cycles where sand, clay, and combination were used, respectively.
2	Coleri et al.	USA (2013)	X-ray CT image processing	Reduction air-void (40-90%). The highest reduction is concentrated at the bottom
3	Razzaghmanesh and Beecham	Australia (2018)	Previous literature	The highest infiltration rates are generally from high rainfall areas. The infiltration rates of permeable pavement sites in these areas declined dramatically with time.
4	Razzaghmanesh and Borst	USA (2018)	Experimental (embedded sensors)	The clogging progresses from the upgradient to the downgradient edge
5	Yong et al.	Australia (2013)	Experimental (3 years at the laboratory)	Clogging was found to be highly correlated with cumulative volume and flow rate
6	Zhang et al.	China (2018)	Modeling (CFD-DEM)	The well-graded sands can percolate into the depth of 30 mm, coarse sands will settle on the shallow surface within a depth of 20 mm, and fine sands will percolate into the depth of 60–100 mm in pervious pavements
7	Hu at al.	China (2021)	Modeling (CFD-DEM)	Clogging evolves through four stages: rapid clogging, slow clogging, partial recovery, and clogging stability in the pavement under rainfall.
8	Qiuxia et al.	Australia (2019)	Experimental	The heavier rainfall intensities were able to flush more sediment through the paver surface
9	Nan et al.	China (2021)	Experimental and numerical (CFD-DEM)	The particles with sizes from 0.6 to 2.2 mm are blocked within 2 cm of the surface layer, obstructing 0.3–0.6 mm particles in the wake. Particles less than 0.3 mm can penetrate deep into the permeable pavement and accumulate in the deep pores, eventually forming a deep blockage with the evolution of time
10	Shan et al.	China (2021)	Experimental and numerical (CFD-DEM)	The lateral permeability was weaker than vertical permeability for bigger clogging particles
11	Ma et al.	China (2020)	Experimental and finite element analysis	The internally retained water should not be ignored because the semi-connected voids were filled with water rapidly at the beginning of permeability tests.
12	Lucke and Beecham	Australia (2011)	Experimental	The PICP system was very effective at filtering and retaining sediment from storm water runoff but reducing permeability over time.
13	Conley et al.	USA (2020)	Experimental	Rapid initial declines of infiltration rate, primarily due to accumulation of material at the bottom of the infiltration BMP (best management practice).
14	Hafez et al.	Saudi Arabia (2020)	Modeling	Cubes and 3D crosses are the most prone to clogging because of their ability to interlock or develop face-to-face contacts that can resist torque and enhance bridging.
15	Selbig et al.	USA (2019)	Experimental	The Reductions in total suspended solids were similar for all three surfaces at approximately 60 percent. Clogging occurred after approximately one year

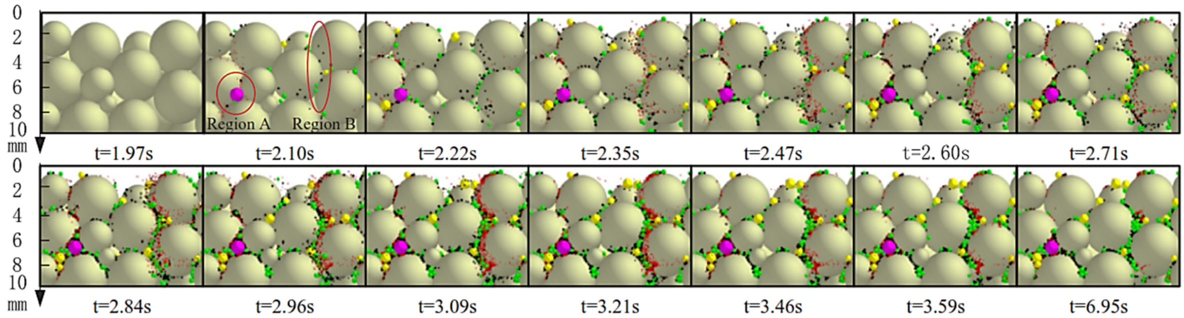

Figure 6: Clogging mechanism (Zhang et al., 2018).

Clogging also occurs due to the shape of the particles that enter the porous layer. Hafez et al., 2021, made modeling of particle shapes into four, namely cube, sphere, 2D cross, 3D cross (figure 7). 3D cubes and crosses are the most prone to clogging due to their ability to lock or develop face-to-face contact, which can withstand torsion and improve bridges.

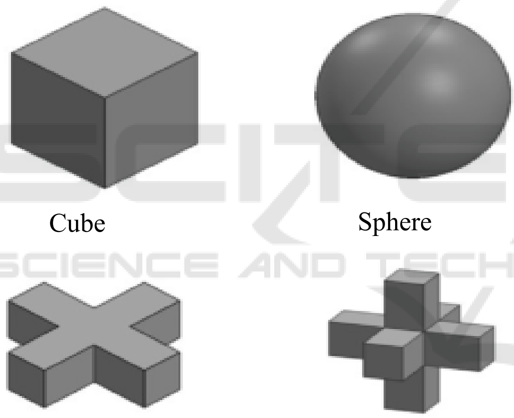

Figure 7: Particles shapes models (Hafez et al. 2021).

2.1.2 Maintenance

Maintenance of porous paving is essential. Usually, the main problem with porous paving is the clogging in the cavity, so that the function of porous paving is lost. These clogging are caused by dust and mud or sand carried by motorized vehicles or by humans themselves (Boogaard et al., 2014). Paves with small cavities are more likely to suffer damage than large diameters ((Barišić et al., 2020). Several studies have shown that the depth of blockage only occurs on the surface. Therefore, it is necessary to treat the surface layer that can restore PCPB performance to its original state. Apart from that area with high rainfall, the infiltration rate has decreased significantly, even since the two years since installation. Therefore, routine maintenance is required two to four times a year (Razzaghmanesh and Borst, 2018; Razzaghmanesh and Beecham, 2018). Lin et al., 2016, suggest that maintenance be carried out within two years after installation using a vacuum cleaner (Lin et al., 2016).

Several PCPB treatment methods have been developed, such as lifting the top 2 cm, mechanical road sweeping, air sweeping, suctioning, high-pressure water jetting, and grinding porous asphalt (Winston et al., 2016). Of some methods, up to 2.5 cm of lift almost restores the asphalt pavement to its new condition for 21-year-old asphalt pavement. However, people prefer maintenance using a suction device rather than a mechanical sweeper. A study recommends that maintenance using a high-pressure vacuum cleaner followed by a high suction vacuum is the most effective treatment for permeable pavements (Selbig et al., 2019). The key of selected paper about maintenance of permeable pavement show in Table 2.

It can be seen that the maintenance of permeable pavement should be carried out routinely two to four times a year. Maintenance can be carried out using a high vacuum cleaner, which is the most effective method compared to mechanical sweeping and high-pressure water flow. The other method is by lifting the top 2 cm can restore the pavement as new condition.

2.2 Durability

One of the critical things in making a PCPB mixture is how to increase the compressive strength of PCPB without reducing its porosity. In several decades PCPB has developed rapidly, especially regarding mixed design and fabrication. They found that a mixture with PCPB with a homogeneous material will produce low compressive strength, so it is advisable to use various materials. It also increase a little sand that can increase the compressive strength

Table 2: Summary of key studies on maintenance of permeable pavement.

No	Author	Region of studies (year)	Data collection method	Findings/critical review
1	Sehgal et al.	Canada (2018)	Experimental	Regular maintenance is essential to ensure long-term hydraulic functionality of Permeable Interlocking Concrete Pavements
2	James et al.	Ontario (2018)	Field test	Rapidly cleaned-out PICPs (RCPP) need routine cleanouts.
3	Atoyebi et al.	Nigeria (2020)	Experimental	The optimum curing method was the ponding method, as it resulted in the highest compressive strength.
4	Winston et al.	USA and Sweden (2016)	Experimental	Milling to a depth of 2.5 cm nearly restored SIR for a 21-year old porous asphalt pavement to like-new conditions
5	Danz et al.	USA (2020)	Experimental	The practices maintenance for permeable pavement using a high-pressure wash followed by a high-suction vacuum.

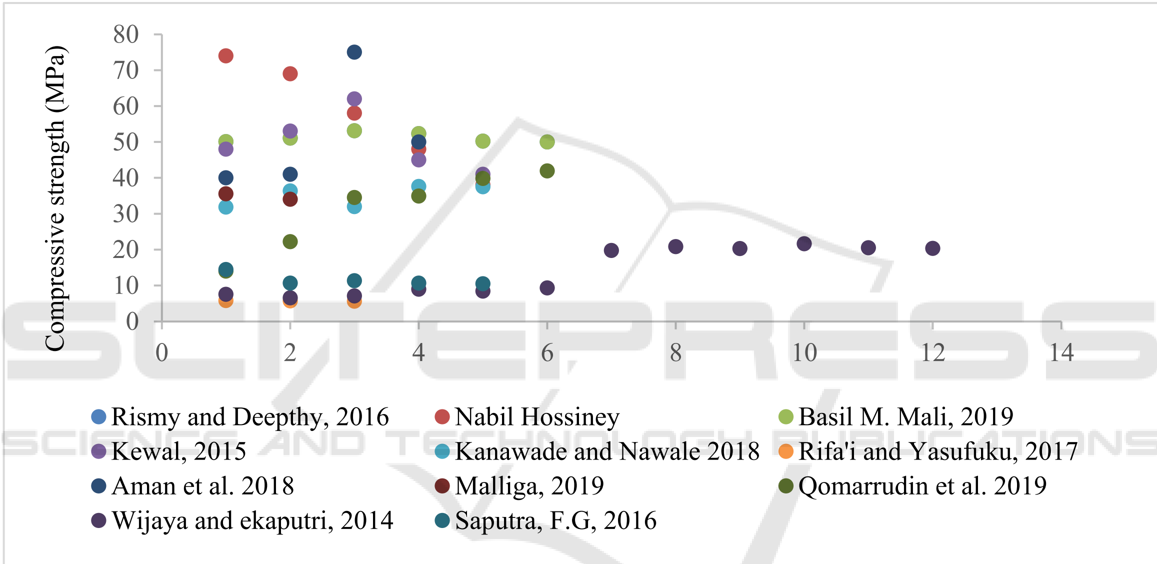

Figure 8: Performance of PCPB from several studies.

significantly but will reduce the porosity of the paving. Many studies have been conducted using added ingredients such as superplasticizers (Pandei et al. 2019). The key of selected papers about the performance of permeable pavement show in table 3.

The quality of PCPB is greatly influenced by the condition of the material, manufacture method, and maintenance. Porous paving made by the mechanical method will produce better PCPB and more consistent quality because mechanically using measured pressure and vibration. In addition to quality by mechanical means can produce more PCPB. By using a sack immediately after the paving has been printed, good maintenance will maintain the porous paving quality.

Figure 8 shows that in the last decade, PCPB has experienced significant developments. There are very varied compressive strengths from the reference obtained, but there are studies that can produce high-quality PCPB with high compressive strength values (> 50 MPa). This result is excellent in the development of PCPB, but on the other hand, there are still results with minimal compressive strength. This result indicates that there is no standard to produce PCPB with high compressive strength for various regions.

3 CONCLUSIONS AND FUTURE TRENDS

PCPB can help reduce standing water on the surface due to rainwater through its pores. The problem that

Table 3: Selected studies on durability of PCPB.

No	Author	Region of studies (year)	Data collection method	Findings/critical review
1	Limantara et al.	Indonesia (2018)	Experimental	The percentage of fibers and coconut shells combined in a mixed paving design tends to decrease the compressive strength
2	Liu et al.	Australia (2020)	Experimental	The results indicated that above 10% of DWTS (drinking water treatment sludge), the replacement was detrimental to such properties of the CPB (concrete paving block)
3	Euniza et al.	Malaysia (2019)	Experimental	The porosity of DRCPB (double-layer rubberized concrete paving blocks) increased multiple when RG (rubber granules) content increases from 0 to 40 %.
4	Euniza et al.	Malaysia (2014)	Experimental	The percentage of waste tire rubber content for DL-RCPB affects the density, porosity, and compressive strength.
5	Abd Halim et al.	Malaysia (2018)	Experimental	Porous concrete paving blocks with different sizes of coarse aggregate cause a great reduction in the water volume during the permeability test
6	Patil et al.	India (2019)	Experimental	The variation in the compressive strength by oven curing is 20% higher than the ambient curing, with limited variation in flexural strength
7	Rifqi et al.	Indonesia (2018)	Experimental	Circle stone aggregate is not recommended for porous paving.
8	Kanawade	India (2018)	Experimental	The compressive strength of paver blocks with 2.5 % of fiber gives maximum strength is 37.57MPa.
9	Abdul Ghani and Cheong	Malaysia (2014)	Experimental	The recycled aggregates are suitable to be used as the primary material in previous pavers.
10	Rifa'i and Yasufuku	Indonesia (2017)	Experimental	The optimum mixture of the porous paving block is the mixture with 30% volcanic ash.
11	Hidayah et al.	Malaysia (2014)	Experimental	There was a reduction in the strength of PCPB when coarse aggregate at different sizes was used but an increase in skid resistance.
12	Jusli et al.	Malaysia (2015)	Experimental	The compressive strength was reduced when the percentage of waste tire rubber was increased.
13	Muhammed and Varkey	India (2016)	Experimental	The inclusion of polypropylene fibers in Geopolymer concrete shows a considerable increase in compressive, abrasion resistance & flexural strength.
14	Mali and Abraham	India (2016)	Experimental	Geopolymer concrete can be effectively used for the manufacture of precast concrete paver blocks.
15	Aman et al.	Indonesia (2018)	Experimental	Curing temperature and liquid to solid ratio (L / S) significantly affect compressive strength.
16	Chethana and Suhas	India (2020)	Experimental	The long curing time of the fly-ash-based GPC paver, the higher is the compressive strength.
17	Malliga and Moorthy	India (2019)	Experimental	Fly ash and GGBS can use for geopolymer concrete paver block.
18	Maharana et al.	India (2020)	Experimental	Fiber can use for paver blocks in heavy traffic.
19	Sharma and Gupta	India (2015)	Experimental	The Compressive strength of geopolymer paver block was found to be decreasing with the replacement of foundry sand
20	Qomaruddin et al.	Indonesia (2019)	Experimental	The compressive strength test of geopolymer paving with a mixed carbide waste and fly ash (10 %: 90%) produced 34.6 MPa, and 39.8 MPa.
21	Jonbi and Fulazzaky	Indonesia (2020)	Experimental	The optimum performance of GPB predicted for the NaOH / Na2SiO ratio range of 0.4 to 0.67 increases by using a high enough concentration of NaOH.
22	Lzrescu et al.	Romania (2020)	Experimental	The alkali-activated geopolymer paving blocks have excellent mechanical properties, by reference to OPC paving blocks, making them suitable for practical applications
23	Manan et al.	Pakistan (2018)	Experimental	The compressive strength of pervious concrete indicated a higher reduction of the sand reduces compressive strength and almost 50% compressive strength decreased by 100% sand from the design mix.
24	Wijaya and Ekaputri	Indonesia (2014)	Experimental	PCPB from coal ash with 6 hours of steam has optimum results, with an average compressive strength of 20.8 MPa.
25	Saputra and Arie Wardhono	Indonesia (2018)	Experimental	The best PCPB with 10 % added fly ash.

arises is that the owned pores are often clogged over time so that the infiltration is reduced. There is a standard test to measure the infiltration rate. However, researchers consider that the testing system is still complicated, so some researchers are trying to measure the new infiltration rate, which is fast and cheap. PCPB blockages are caused by environmental conditions such as rainfall, soil characteristics, air temperature, drainage area, and traffic volume types. In areas with high rainfall, PCPB will quickly experience blockages even within two years after installation. The particles with small sizes will quickly cause PCPB to be clogged than particles with large sizes. Likewise, the type and shape of the particles also affect the rate at which blockages occur.

To prevent PCPB blockage, some researchers recommend performing treatment after two years of insertion. Treatment can be done by lifting the top 2 cm, mechanical street sweeping, regenerative air street sweeping, vacuum street sweeping, and high-pressure water jets. However, this treatment method only helps reduce clogging problems but cannot restore the PCPB in expected performance. There are many studies to improve the performance of PCPB by improving physical properties by adding/replacing some with other materials that aim to keep the high porosity of PCPB and high compressive strength and ease to maintain. However, the correct method has not been found yet, thus opening opportunities for researchers to conduct better further research.

In recent years there has been an increasing interest in PCPB. This work provides a detailed overview of PCPB benefits as well as performance in terms of mix design, fabrication and maintenance. This is supported by the latest research studies on PCPB models, materials, mixtures and characteristics. PCPB technically has the potential to replace existing infrastructure in sustainable development. Table 3 describes the most recent research that has been carried out and the resulting findings.

ACKNOWLEDGEMENTS

The authors of this paper would like to thank University Teknologi Malaysia (UTM) and Samarinda State Polytechnic (POLNES) for the support and sponsor under UTM Encouragement Research Grants, Vot No. Q.K130000.2656.18J25, each of which enabled this paper to be written. The authors also thank the POLNES permeable pavement research group.

REFERENCES

Abd Halim, N. H. et al. 2018. "Permeability and Strength of Porous Concrete Paving Blocks at Different Sizes Coarse Aggregate." *Journal of Physics: Conference Series* 1049(1).

Abdul Ghani, A. N., and P. C. Cheong. 2014. "Porous Pavers: Effects of the Recycled Aggregate Size on Drainage Properties." *MATEC Web of Conferences* 17(September).

Aman, A. Awaluddin, A. Ahmad, and M. Olivia. 2018. "Parametric Study on the Compressive Strength Geopolymer Paving Block." *IOP Conference Series: Materials Science and Engineering* 345(1).

Atoyebi, O. D. et al. 2020. "Effect of Curing Methods on the Strength of Interlocking Paving Blocks." *Cogent Engineering* 7(1).

Barišić, Ivana, Ivanka Netinger Grubeša, Tihomir Dokšanović, and Matija Zvonarić. 2020. "Influence of Clogging and Unbound Base Layer Properties on Pervious Concrete Drainage Characteristics." *Materials* 13(11): 1–13.

Boogaard, Floris, Terry Lucke, Nick van de Giesen, and Frans van de Ven. 2014. "Evaluating the Infiltration Performance of Eight Dutch Permeable Pavements Using a New Full-Scale Infiltration Testing Method." *Water (Switzerland)* 6(7): 2070–83.

Cheng, Yung Yun et al. 2019. "Field Testing of Porous Pavement Performance on Runoff and Temperature Control in Taipei City." *Water (Switzerland)* 11(12).

Chethana, and Suhas. 2020. "A Study on Geopolymer Concrete Paver Block with Recycle Aggregate." *International Research Journal of Engineering and Technology (IRJET)* 07(10): 1850–53.

Coleri, Erdem et al. 2013. "Clogging Evaluation of Open Graded Friction Course Pavements Tested under Rainfall and Heavy Vehicle Simulators." *Journal of Environmental Management* 129(August): 164–72.

Conley, Gary, Nicole Beck, Catherine A. Riihimaki, and Michelle Tanner. 2020. "Quantifying Clogging Patterns of Infiltration Systems to Improve Urban Stormwater Pollution Reduction Estimates." *Water Research X* 7: 100049. https://doi.org/10.1016/j.wroa.2020.100049.

Danz, Mari E., William R. Selbig, and Nicholas H. Buer. 2020. "Assessment of Restorative Maintenance Practices on the Infiltration Capacity of Permeable Pavement.Pdf." *water* 12(1563): 1–16.

Euniza, J. et al. 2019. "Porosity and Density Characteristic of Double-Layer Concrete Paving Blocks Incorporating Rubber Granules." *IOP Conference Series: Earth and Environmental Science* 244(1).

Euniza, J et al. 2014. "A Review of Double Layer Rubberized Concrete Paving Blocks." *5th international conference for Engineering and sustinability* (June): 1–5.

Girish, M. G., Kiran K. Shetty, and A. Rao Raja. 2018. "Self-Consolidating Paving Grade Geopolymer Concrete." *IOP Conference Series: Materials Science and Engineering* 431(9).

Hafez, Ahmed et al. 2021. "The Effect of Particle Shape on Discharge and Clogging." *Scientific Reports* 11(1): 1–12. https://doi.org/10.1038/s41598-021-82744-w.

Hossiney, Nabil et al. 2020. "Geopolymer Concrete Paving Blocks Made with Recycled Asphalt Pavement (RAP) Aggregates towards Sustainable Urban Mobility Development." *Cogent Engineering* 7(1).

Hu, Jianying, Tao Ma, and Kang Ma. 2021. "DEM-CFD Simulation on Clogging and Degradation of Air Voids in Double-Layer Porous Asphalt Pavement under Rainfall." *Journal of Hydrology* 595(February): 126028. https://doi.org/10.1016/j.jhydrol.2021.126028.

Huang, Jian, Caterina Valeo, Jianxun He, and Angus Chu. 2016. "Three Types of Permeable Pavements in Cold Climates: Hydraulic and Environmental Performance." *Journal of Environmental Engineering* 142(6): 04016025.

James, William, Harald Von Langsdorff, and Michael McIntyre. 2018. "Permeable Pavers Designed for Rapid Renewal by Considering Sweeper Mechanics: Initial Field Tests." *Journal of Water Management Modeling* 2018(Ada 2010): 1–13.

Jonbi, Jonbi, and Mohamad Ali Fulazzaky. 2020. "Modeling the Water Absorption and Compressive Strength of Geopolymer Paving Block: An Empirical Approach." *Measurement: Journal of the International Measurement Confederation* 158: 107695. https://doi.org/10.1016/j.measurement.2020.107695.

Jusli, Euniza et al. 2014. "Effect of Using Waste Tyre Rubber on the Properties of Double Layer Rubberized Concrete Paving Blocks." *Jurnal Teknologi* 71(3): 1–5.

Jusli, Euniza, Hasanan Nor, and Ramadhansyah Putra Jaya. 2015. "Low Noise and Properties of Double Layer Concrete Paving Block." *Springer Science (ICGSCE)* (June): 291–99.

Kanawade, Bhimaji Dashrath. 2018. "Strength and Durability of Concrete Paver Block." *Advances in Civil & Structural Engineering* 2(3): 0–11.

Kapoor, Kanish, Mudasir Nazeer, Gowhar Afzal, and S P Singh. 2021. "Experimental Study of Pervious Concrete and Artificial Clogging." *Sustainable Environment and Infrastructure* (January): 29–39.

Kia, Alalea, Hong S. Wong, and Christopher R. Cheeseman. 2017. "Clogging in Permeable Concrete: A Review." *Journal of Environmental Management* 193: 221–33. http://dx.doi.org/10.1016/j.jenvman.2017.02.018.

Limantara, A. D. et al. 2018a. "Optimization of Standard Mix Design of Porous Paving Coconut Fiber and Shell for the Parking Area." *AIP Conference Proceedings* 2020(October 2018).

A. D. Limantara, S. Winarto, E. Gardjito, et al., 2018b. "Optimization of Standard Mix Design of Porous Paving Coconut Fiber and Shell for the Parking Area." *AIP Conference Proceedings* 2020(October).

Lin, Wuguang et al. 2016. "Development of Permeability Test Method for Porous Concrete Block Pavement Materials Considering Clogging." *Construction and Building Materials* 118: 20–26. http://dx.doi.org/10.1016/j.conbuildmat.2016.03.107.

Liu, Yue et al. 2020. "Utilization of Drinking Water Treatment Sludge in Concrete Paving Blocks: Microstructural Analysis, Durability and Leaching Properties." *Journal of Environmental Management* 262(March): 110352. https://doi.org/10.1016/j.jenvman.2020.110352.

Lucke, Terry, and Simon Beecham. 2011. "Field Investigation of Clogging in a Permeable Pavement System." *Building Research and Information* 39(6): 603–15.

Lzrescu, A. et al. 2020. "Experimental Investigation on the Development of Geopolymer Paving Blocks by Using Romanian Local Raw Materials." *IOP Conference Series: Materials Science and Engineering* 877(1).

Ma, Yaolu, Xianhua Chen, Yanfen Geng, and Xinlan Zhang. 2020. "Effect of Clogging on the Permeability of Porous Asphalt Pavement." *Advances in Materials Science and Engineering* 2020.

Maharana, Gitanjali, Biswajit Jena, and Sagarika Panda. 2020. "A Study On Mechanical And Durability Properties Of Interlocking Fly Ash Based Concrete Paver Block Using Different Types Chopped Fibers." *Journal of Xi'an University of Architecture & Technology* XII(V): 6–9.

Mali, Basil M, and Renjan Abraham. 2016. "Study on Geopolymer Concrete Used for Paving Blocks." *International Journal of Innovative Research in Advanced Engineering* 09(3): 2349–2763.

Malliga, P, and J Ashthava Moorthy. 2019. "Paver Blocksby Using Fly Ash and GGBS (Geopolymer Concrete)." *International Journal of Engineering Research & Technology (IJERT)* 7(11): 1–4.

Manan, Aneel et al. 2018. "Experimental Investigation of Compressive Strength and Infiltration Rate of Pervious Concrete by Fully Reduction of Sand." *Civil Engineering Journal* 4(4): 724.

Muhammed, Rismy, and Deepthy Varkey. 2016. "Experimental Investigation on Properties of Geopolimer Concrete Paver Block with the Inclusion of Polypropylene Fibers." *International Journal of Scientific & Engineering Research* 7(10): 10–15.

Nan, Xuan et al. 2021. "Clogging Mechanism of Pervious Concrete: From Experiments to CFD-DEM Simulations." *Construction and Building Materials* 270: 1–11.

Nur Hidayah, A. H., Md Nor Hasanan, and P. J. Ramadhansyah. 2014. "Porous Concrete Paving Blocks Using Coarse Aggregate." *Applied Mechanics and Materials* 554: 111–15.

Pandei, Romario W., Steve W. M. Supit, Jemmy Rangan, and Arthur Karwur. 2019. "Studi Eksperimen Pengaruh Pemanfaatan Superplasticizer Terhadap Kuat Tekan Dan Permeabilitas Beton Berpori (Pervious Concrete)." *Jurnal Poli-Teknologi* 18(1): 45–52.

Patil, Shabarish, Vineethraj Math, Rajatkumar Vaidya, and Ishwargouda Patil. 2019. "Experimental Study on Suitability of Geopolymer Concrete Paver on Medium Traffic Condition Highway." *International Journal of Advanced Science and Engineering* 5(3): 975–81.

Qiuxia, Yang, Simon Beecham, Jixue Liu, and David Pezzaniti. 2019. “The Influence of Rainfall Intensity and Duration on Sediment Pathways and Subsequent Clogging in Permeable Pavements.” *Journal of Environmental Management journal* 246: 730–36.

Qomaruddin, Mochammad et al. 2019. “Compressive Strength Analysis on Geopolymer Paving by Using Waste Substitution of Carbide Waste and Fly Ash.” *Journal of Physics: Conference Series* 1424(1).

Ramadhansyah, Putra Jaya, Mohd Yusak Mohd Ibrahim, Hainin Mohd Rosli, and Wan Ibrahim Mohd Haziman. 2014. “A Review of Porous Concrete Pavement: Applications and Engineering Properties.” *Applied Mechanics and Materials* 554(June): 37–41.

Razzaghmanesh, Mostafa, and Simon Beecham. 2018. “A Review of Permeable Pavement Clogging Investigations and Recommended Maintenance Regimes.” *Water (Switzerland)* 10(3).

Razzaghmanesh, Mostafa, and Michael Borst. 2018. “Investigation Clogging Dynamic of Permeable Pavement Systems Using Embedded Sensors.” *Journal of Hydrology* 557: 887–96. https://doi.org/10.1016/j.jhydrol.2018.01.012.

Rifa’i, Ahmad, and Noriyuki Yasufuku. 2017. “Utilization of Bantak and Merapi Volcanic Ash for Porous Paving Block as Drainage Control in the Prambanan Temple Yard.” *International Journal of GEOMATE* 12(31): 141–46.

Rifqi, Mirza Ghulam, M. Shofi’ul Amin, and Yuris Indra Lesmana. 2018a. “Karakteristik Paving Berongga Menggunakan Material Batu Kali Bulat Berbasis Ramah Lingkungan.” *Potensi : Jurnal Sipil Politeknik* 20(1).

Rifqi, M. G., Amin, M. S., & Lesmana, Y. I., 2018b. “Karakteristik Paving Berongga Menggunakan Material Batu Kali Bulat Berbasis Ramah Lingkungan.” *Potensi : Jurnal Sipil Politeknik* 20(1): 28–32.

Saputra, Firman Ganda, and Arie Wardhono. 2018. “Pemanfaatan Abu Terbang Limbah Batu Bara Terhadap Kuat Tekan Dan Tingkat Porositas Paving Stone Berpori.” *Jurnal Rekayasa Teknik Sipil* 1(1): 186–94.

Sehgal, Kirti, Jennifer Drake, Tim Van Seters, and William Kyle Vander Linden. 2018. “Improving Restorative Maintenance Practices for Mature Permeable Interlocking Concrete Pavements.” *Water (Switzerland)* 10(11): 9–13.

Selbig, William R., and Nicolas Buer. 2018. U.S. Geological Survey Scientific Investigations Report 2018–5037 *Hydraulic, Water-Quality, and Temperature Performance of Three Types of Permeable Pavement under High Sediment Loading Conditions*. https://pubs.er.usgs.gov/publication/sir20185037.

Selbig, William R., Nicolas Buer, and Mari E. Danz. 2019. “Stormwater-Quality Performance of Lined Permeable Pavement Systems.” *Journal of Environmental Management* 251(August): 109510. https://doi.org/10.1016/j.jenvman.2019.109510.

Shan, Jingsong, Shanshan Feng, Feng Li, and Shuyin Wu. 2021. “Lateral Permeability of Pervious Asphalt Mixtures and the Influence of Clogging.” *Construction and Building Materials journal* 273: 1–10.

Sharma, Sanjay K., and Himmi Gupta. 2015. “Development of Paver Block By Using Foundry Sand Based Geopolymer Concrete.” *Journal of Today’S Ideas - Tomorrow’S Technologies* 3(2): 129–44.

SNI 03-0691. 1996. Badan Standar Nasional Indonesia *Bata Beton (Paving Block)*.

Wang, Hanxi, Lianxi Sheng, and Jianling Xu. 2021. “Clogging Mechanisms of Constructed Wetlands: A Critical Review.” *Journal of Cleaner Production* 295(March): 126455. https://doi.org/10.1016/j.jclepro.2021.126455.

Wijaya, Yulia Putri, and Januarti Jaya Ekaputri. 2014. “Paving Geopolimer Dari Coal Ash Limbah Pabrik.” *Jurusan Teknik Sipil FTSP ITS, Surabaya* (June): 33–42.

Winston, Ryan J, Ahmed M Al-Rubaei, Godecke T Blecken, and William F Hunt. 2016. “Maintenance for Preservation and Recovery of Permeable Pavement Hydraulics: Effects of Vacuum Cleaning, High Pressure Washing, Street Sweeping, and Milling Entretien Pour La Préservation et Le Rétablissement Des Caractéristiques Hydrauliques de Chaussées.” *NOVATECH*: 1–6.

Xie, Ning, Michelle Akin, and Xianming Shi. 2019. “Permeable Concrete Pavements: A Review of Environmental Benefits and Durability.” *Journal of Cleaner Production* 210: 1605–21. https://doi.org/10.1016/j.jclepro.2018.11.134.

Yong, C. F., D. T. McCarthy, and A. Deletic. 2013. “Predicting Physical Clogging of Porous and Permeable Pavements.” *Journal of Hydrology* 481: 48–55. http://dx.doi.org/10.1016/j.jhydrol.2012.12.009.

Yu, Zhiji et al. 2021. “Performance of Permeable Pavement Systems on Stormwater Permeability and Pollutant Removal.” *Environmental Science and Pollution Research* (2006).

Zhang, Jiong et al. 2018. “Numerical Study on Pore Clogging Mechanism in Pervious Pavements.” *Journal of Hydrology* 565(August): 589–98.