Civil and Sustainable
Urban Engineering

Research Article
Volume 3(1), 2023, 70-80
https://doi.org/10.53623/csue.v3i1.236

Evaluating the Clogging Phenomenon in Pervious Concrete from January 2015 to December 2022

Ehsan Teymouri[1]*, Kwong Soon Wong[1], Masoud Rouhbakhsh[2], Mahdi Pahlevani[3], Mehdi Forouzan[4]

[1]Department of Civil and Construction Engineering, Faculty of Engineering and Science, Curtin University Malaysia, CDT 250, 98009 Miri, Sarawak, Malaysia.
[2]Research and Development Director of Mashhad Water and Wastewater Company, Mashhad, Iran.
[3]Manager of the Parkand Abad Wastewater Treatment Plant of Mashhad Water and Wastewater Company, Mashhad, Iran.
[4]Faculty of Engineering, Department of Civil Engineering, Islamic Azad University of Bandar Abbas, 685P+C7V, Bandar Abbas, Iran.

*Correspondence: ehsan.teymouri@postgrad.curtin.edu.my

SUBMITTED: 3 April 2023; REVISED: 30 April 2023; ACCEPTED: 2 May 2023

ABSTRACT: This study investigated the effects of clogging in Pervious Concrete (PC) from January 2015 to December 2022. Three different PC mixtures were used, which included coarse aggregate (4.75-9.5 mm), fine aggregate (0-20% weight of coarse aggregate), cement (340 kg/m3), and w/c ratio of 0.35. The samples were tested for compressive strength, permeability, and porosity. The best PC mixture containing 10% fine aggregate was selected for monitoring clogging over time. This mixture had a compressive strength of 24.7 MPa, permeability of 1.19 mm/s, and void content of 13.96%. A large-scale prototype of PC10 (10% of fine aggregate) measuring 3.5 m in length, 1.7 m in width, and 0.20 m in depth was constructed in Mashhad City, Iran. The in-place infiltration rate was measured on a monthly basis as the PC experienced different rainfall levels. The results showed that due to clogging, the infiltration rate was reduced by an average of 10% for the first four years of the experiments. This was followed by a substantial reduction of 20% in 2019 and 16.75% in 2020. Due to a high level of clogging, the infiltration rate was reduced by 5.02% and 2.23% in 2021 and 2022, respectively. However, the system still has the capacity to infiltrate at 1.14 mm/s. Although no maintenance was performed on the PC system, its efficiency and lifespan were substantially reduced. Nonetheless, the system can still be considered as an effective solution for stormwater management.

KEYWORDS: Pervious concrete; clogging phenomenon; infiltration rate; stormwater management

1. Introduction

Due to population growth and industrialization, cities have become denser and more populated. Parking lots, sidewalks, streets, and other infrastructure are replacing areas once covered by vegetation. This replacement increases the impact of anthropization, which is the act of transforming natural environments and open spaces to meet specific functions through human activities, especially during the urbanization process. The absence of natural surfaces and increasing anthropization have considerably disrupted the natural water cycle. The increasing impervious surfaces in urban areas have left cities with the challenge of managing increased runoff volumes, bank erosion, and flooding, eventually leading to the degradation of water sources [1-2]. Permeable pavements provide significant benefits and play a pivotal role in mitigating the detrimental impact of anthropization in urban areas. Hence, it is crucial to study the performance of pervious concrete as a viable and effective option for permeable pavement.

The Pervious Concrete (PC) system has a large number of interconnected pores, and its primary function is to allow runoff water to infiltrate through its joints [3]. This type of concrete consists of coarse aggregate, cement, water, and little to no fine materials [4-5], leading to emerging porosity between 15% and 25%, and permeability of up to 3.40 mm/s. However, the compressive strength for PC is quite low due to high void content, ranging from 3.5 to 28 MPa [6-7]. In recent years, the PC system has been widely used in parking lots, sidewalks, and green areas of cities due to its eco-friendly advantages, such as urban runoff management, flood prevention, reduction of anthropization impacts, and sound pollution by declining impervious areas. However, its application is hindered by several disadvantages, including clogging issues, poor durability, and low abrasion resistance and strength [8].

One of the advantages of the PC system is its ability to reduce the contamination of water and wastewater by capturing pollutants in its pores [9-11]. The clogging phenomenon is a serious threat to PC systems as it reduces their permeability and service life. Stormwaters carry a large number of suspended solids and have a high concentration of total suspended solids (TSS), which is the main reason for PC clogging, as the solids fill the pores of the PC and reduce its hydraulic conductivity [12-15]. PC is susceptible to clogging, and this phenomenon occurs within the first three layers of PC [16]. Gersson et al. investigated the infiltration rate of PC with natural and recycled aggregate due to clogging with three different sediments. They found that the clogging of PC with recycled aggregate was lower compared to PC with natural aggregate, and maintenance of the system every five years would make a great contribution to alleviating the clogging impact [17].

Past studies investigated the effects of sediment type on clogging potential in the laboratory, and they mentioned that coarse sand particles did not significantly reduce the permeability of PC as these large particles prevented them from entering the pores [18-19]. Cui et al. studied the effects of sediment clogging in pervious concrete pavement under storm runoff [20]. They reported that the pore clogging process included quick clogging, temporary mitigation of clogging, and progressive clogging, and the PC pavements with more porosity were more likely to encounter clogging. Zhou et al. investigated the effects of the diameter of pores on the clogging phenomenon of PC via CT scanning and image processing to evaluate the geometry of the open and closed pores [21]. They showed that the size of the pore is directly related to the clogging degree, and it is possible to alleviate the effects of clogging by considering a suitable mixture design.

There are several ways to alleviate the effects of clogging, such as vacuum sweeping and pressure washing, and the second is more effective [22]. Kayhanian et al. evaluated the PC clogging in a parking lot using the falling head method and NCAT device [23], and Deo et al. developed a falling head permeability cell to assess the contribution of pores towards clogging [24]. In 2014, a series of tests were performed to evaluate the mechanical and physical properties of PC. Three different mixture designs, based on ACI 211 3/R [25], were mixed and evaluated for compressive strength according to BS 1881 [26], porosity based on ASTM C1754

[27], and permeability based on ACI 522 [28]. The best sample which had reasonable compressive strength, porosity, and permeability was selected to construct a PC pavement as shown in Fig.1 for investigating the clogging phenomenon.

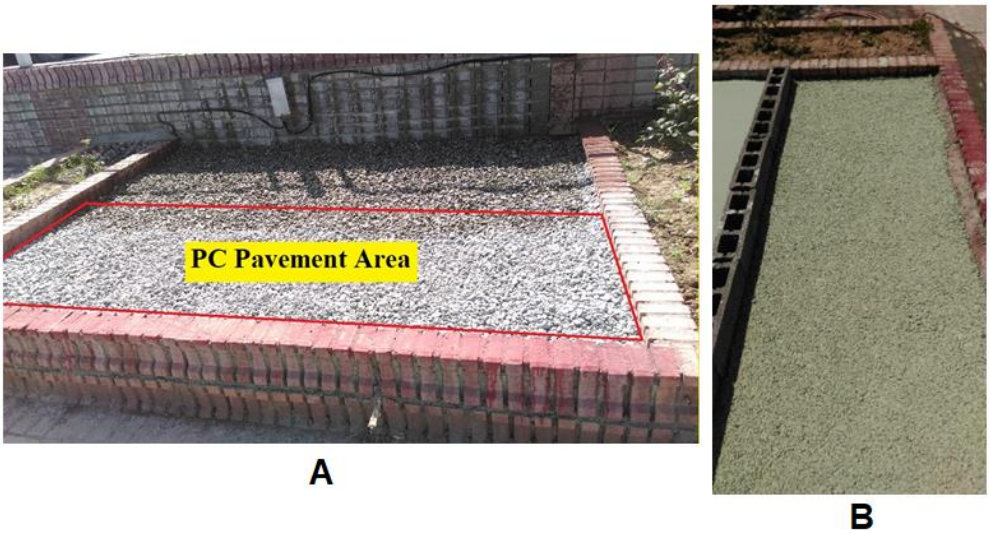

Figure 1. A layer with 0.20 m thick coarse aggregate beneath the PC pavement (A) and constructed PC pavement (B).

2. Materials and Methods

Portland Cement Type II was used in this study based on the requirements of ASTM C150 [29] to construct the PC mixture. The specimens for compressive strength tests were cast in 150 mm cube molds and cured for 28 days in a water tank before testing. The compressive strength of 150 mm PC cubes were determined as per BS 1881 standard [26], and displayed in Fig. 2 (left). Meanwhile, the porosity of PC specimens, as depicted in Fig. 2 (right), was assessed using water displacement method, which is based on Archimedes' principle of buoyancy and ASTM C1754 [27]. The 100 mm PC cube specimens were oven-dried for 24 hours at 105 °C. The immersed weights of PC specimens were measured and its porosity were calculated using Equation 1. All the tests were conducted based on the necessary Standards and each data point represents the average value of three specimens.

Figure 2. Compressive strength of PC samples based on BS 1881 (left), and measuring porosity of PC samples (right).

$$A_t = \left(1 - \left(\frac{W_2 - W_1}{\rho_w V}\right)\right) 100\% \tag{1}$$

where, A_t is the porosity (%), V is the volume (cm^3), ρ_w is the water density (g/cm^3), W_1 and W_2 are the specimen’s weight in water and dry weight (g).

To evaluate the clogging phenomenon on the PC pavement, first, a layer of coarse aggregate (9.5-12.5 mm) was laid at the site with a depth of 0.20 m. The surface of the coarse aggregate was wetted before pouring the top layer with PC10, with a thickness of 0.10 m for better cohesion. After pouring the PC10, the surface was smoothed and cured for 28 days by covering it with plastic to prevent the water from evaporating from the paste, as depicted in Fig. 3.

Figure 3. Curing process of PC.

Covering the surface of the PC with plastic instead of spraying water on a daily basis would prevent the water of the paste generated from cement hydration from evaporating, ensuring that the curing process would be effective. From January 2015 to December 2022, the in-place permeability of the PC was measured on a monthly basis. The PC experienced various precipitation events, as illustrated in Fig. 4.

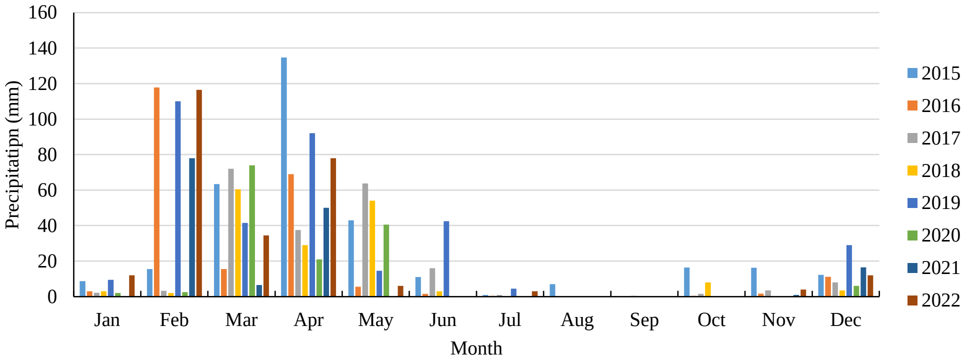

Figure 4. Precipitation events in Mashhad from January 2015 to December 2022.

To measure the infiltration rate of the PC and investigate the clogging phenomenon, the method outlined in ASTM C1701 [30] was used, as shown in Fig. 5. According to the standard, to prevent water leakage, the ring was secured to the pavement with foam. The surface of the PC was cleaned of solids and debris and then pre-wetted by pouring approximately 3.6 kg of water into the ring at a rate sufficient to maintain a head between the marked lines at a distance of 10 and 15 mm from the bottom (Fig. 6), until all 3.6 kg of water was used. For the actual test, 18 kg of water was used. The time measurement started as soon as the water touched the PC surface and was stopped when free water was no longer present on the PC. The infiltration rate was calculated based on Equation 3. To measure the permeability of the PC in laboratory conditions and the in-place infiltration rate, the following tests were conducted:

ACI 522 (2006) provides a falling head method for measuring PC permeability in laboratory conditions and uses Equation 1 [27], while ASTM C1701 provides a standard for measuring in-place PC infiltration and uses Equation 2 [30].

$$K = \frac{aL}{At}\ln\left(\frac{h_1}{h_2}\right) \tag{2}$$

where a is the cross-sectional area of the device in mm^2, L is the length of PC specimen in mm, A is the cross-sectional area of the PC specimen in mm^2, t is the time elapsed in sec, h_1 is the initial head of water in mm, and h_2 is the final head of water in mm.

$$I = \frac{KM}{D^2 t} \tag{3}$$

where I is the infiltration rate in $mm.h^{-1}$, K = 4,583,666,000 $mm^3\ kg^{-1}$, M is the mass of infiltrated water in kg, D is the inside diameter of infiltration ring in mm, and t is the time required for measured amount of water to infiltrate in sec.

Figure 5. Measuring the infiltration rate of PC based on ASTM C 1701 [24].

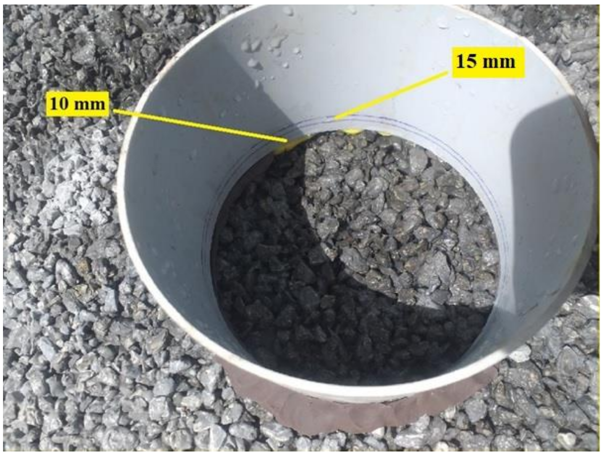

Figure 6. Marked lines in a distance of 10 and 15 mm to keep the level of water

3. Results and Discussion

To select the appropriate PC mixture for investigating clogging, three different samples were tested for compressive strength, porosity, and permeability. These samples included an aggregate size of 4.75-9.5 mm and different portions of fine aggregate (0-20% of the weight of coarse aggregate). The mix proportions and results are presented in Table 1. After analyzing the results, PC10 was chosen as the best mixture design to be examined in real conditions due to its acceptable range of porosity and permeability and high compressive strength. A large-scale prototype of PC10 with a length of 3.50 m, width of 1.70 m, and depth of 0.20 m was constructed on a layer of coarse aggregate with a thickness of 0.20 m in Mashhad city, Iran, as shown in Fig. 1. Monthly measurements of the in-place infiltration rate of PC were conducted to investigate the clogging phenomenon of PC under precipitation.

Table 1. Mix proportions, mechanical and physical results of PC.

Mix code	Aggregate content (kg/m^3)	Cement Content (kg/m^3)	Fine aggregate content	Water content (kg)	Compressive Strength (MPa)	Porosity (%)	Permeability (mm/s)
PC0	1700	340	0	119	17.5	20.47	1.36
PC10	1700	340	170	119	24.7	13.96	1.19
PC20	1700	340	340	119	43.6	4.86	0.94

Figure 7 shows the in-place infiltration rate of PC10 on a monthly basis from Jan 2015 to Dec 2022. It is worth noting that no maintenance such as sweeping or pressure washing was performed on the PC surface, and the infiltration rate of PC decreased slightly each month. As seen in Fig. 4, the highest precipitation occurred from February to May of each year, and during these months, a significant reduction in the permeability of PC was observed. However, a slight decrease in permeability was also observed during dry months, indicating that PC permeability continues to decrease over time, with a more pronounced effect during rainy months. The slope of the infiltration rate line reduced significantly in the seventh and eighth years, approaching the horizontal axis, indicating that the PC pavement had become significantly clogged in the last two years of observation, and the effects of rainfall on filling the pores were not significant. However, maintenance of the surface of PC by washing and sweeping can substantially increase the lifespan of the system.

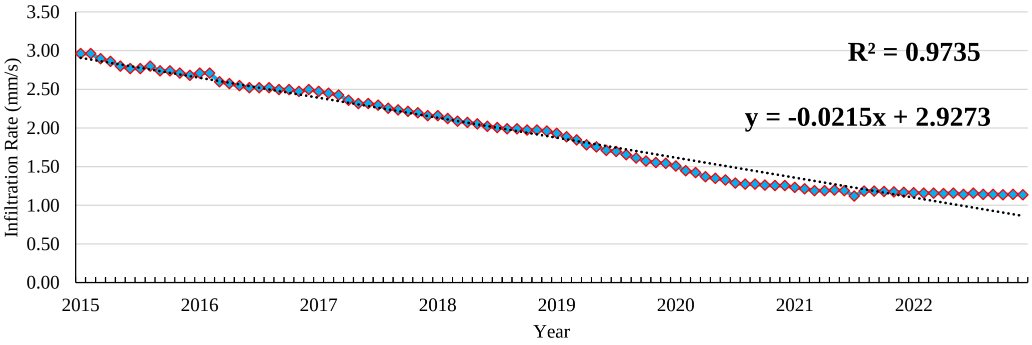

Figure 7. Infiltration rate of PC10 from Jan 2015 to Dec 2022 on a monthly basis.

Table 2 presents the detailed values of PC infiltration rate. In the first four years of the PC's lifespan, the average permeability reduction was about 10% per year, but this reduction increased considerably from 2019 to 2020. By the end of 2020, the PC permeability had decreased by 57.63%, while the infiltration rate of 1.14 mm/s was still acceptable for managing stormwaters [31-34]. In 2021 and 2022, the PC pavement experienced a minimum reduction in infiltration rate of 5.04% and 2.23%, respectively. This minimum reduction in PC permeability in the last two years of the experiments indicates that the pores of PC have become significantly clogged, and the permeability has reached its minimum value.

Table 2. Permeability of PC10 and effects of clogging.

Month - Year	2015	2016	2017	2018	2019	2020	2021	2022
Jan	2.961	2.709	2.4723	2.158	1.9291	1.5067	1.2301	1.1627
Feb	2.961	2.709	2.4485	2.122	1.8862	1.4468	1.212	1.1574
Mar	2.8937	2.5984	2.4252	2.087	1.8452	1.4226	1.189	1.1574
Apr	2.861	2.5722	2.3578	2.0703	1.7807	1.369	1.189	1.1522
May	2.7983	2.5464	2.3149	2.0536	1.7561	1.3473	1.1955	1.1574
Jun	2.7679	2.5212	2.3149	2.021	1.709	1.3262	1.189	1.1419
Jul	2.7679	2.5212	2.2941	2.0051	1.6976	1.2861	1.1201	1.1574
Aug	2.7983	2.5212	2.2535	1.9894	1.6535	1.2732	1.1844	1.1419
Sep	2.7391	2.4965	2.2337	1.9894	1.6116	1.2732	1.1844	1.1419
Oct	2.7381	2.4965	2.2143	1.974	1.5719	1.2606	1.1789	1.1368
Nov	2.709	2.4723	2.1952	1.974	1.5527	1.2544	1.1734	1.1419
Dec	2.6805	2.4965	2.158	1.9588	1.5433	1.2544	1.1681	1.1368
Infiltration Reduction (%)	9.47	7.84	12.71	9.23	20.0	16.75	5.04	2.23

Figure 8 depicts the surface of the PC in December 2022. It is obvious that debris, sand, clay, and solids have filled the pores of the PC system, and its service life has reduced substantially. Although no maintenance was done to the PC during the experiment, the system still has the ability to infiltrate stormwater at a permeability of 1.14 mm/s. It is anticipated that the clogging phenomenon of the constructed PC would follow Equation (4), which indicates the infiltration rate of the PC pavement, where Y is the infiltration rate (mm/s), and X is the number of months after constructing the PC pavement. Equation (4) is more precise for the first four years of operation. Also, the regression of the model is 0.9735, which presents the accuracy of the prediction.

$$Y = -0.0215X + 2.9273 \tag{4}$$

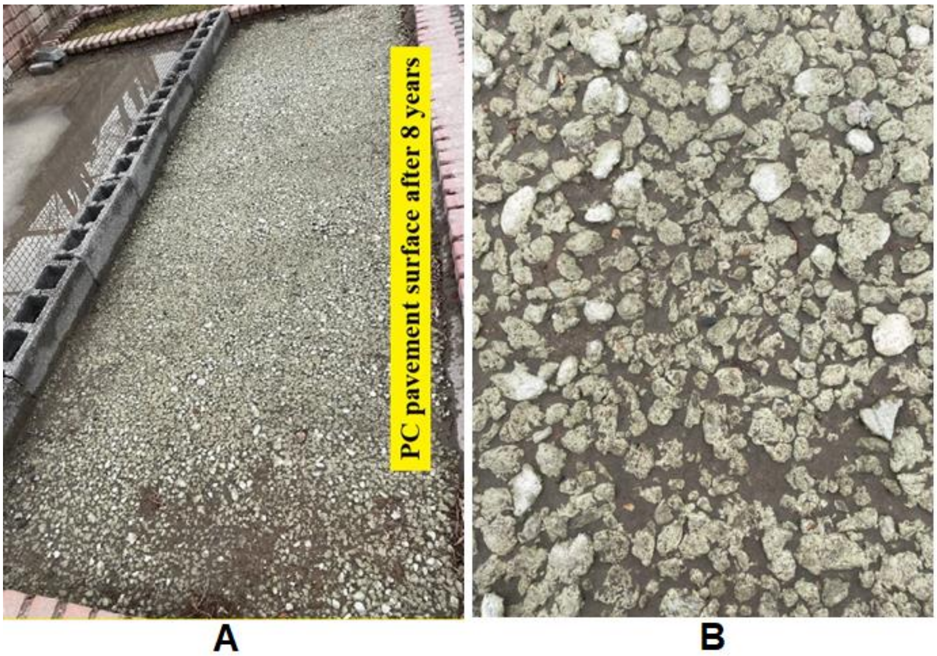

Figure 8. PC10 after 8 years of experiencing different rainfalls (A) and clogged surface of PC10 after 8 years (B).

4. Conclusions

This study aimed to investigate the effects of clogging on pervious concrete over an eight-year service period from January 2015 to December 2022. A large-scale PC pavement measuring 3.50 m in length, 1.70 m in width, and 0.20 m in depth was constructed in the city of Mashhad, Iran. The PC system was subjected to varying amounts of rainfall over the eight years, causing the pores of the pavement to fill with solids, debris, and sand. The results of the experiment indicated that the PC pavement is a viable solution for managing stormwater runoff and preventing floods. At the beginning, the infiltration rate of the PC was 2.96 mm/s, which reduced by an average of 10% in the first four years, reaching 1.96 mm/s in December 2018. Subsequently, the infiltration rate of the PC reduced considerably, with an annual reduction of 20% and 16.75% observed in 2019 and 2020, respectively, leading to a permeability of 1.25 mm/s in December 2020. From December 2020 onwards, the infiltration rate of the PC reduced slightly, with only a 5.04% and 2.23% reduction observed in 2021 and 2022, respectively. This suggests that the pores of the PC pavement are clogged enough, but at the end of the experiment, the permeability of the system was 1.14 mm/s, indicating that it still has the capacity to infiltrate.

Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

[1] Wanielista, M.; Chopra, M.; Spence, J.; Ballock, C. (2007). Hydraulic performance assessment of pervious concrete pavements for stormwater management credit. Storm Water Management Academy, University of Central Florida, USA.

[2] Teymouri, E.; Wong, K.S.; Pauzi, N.N.M. (2023). Iron slag pervious concrete for reducing urban runoff contamination. *Journal of Building Engineering*, *70*, 106221. https://doi.org/10.1016/j.jobe.2023.106221

[3] Karami, H.; Teymouri, E.; Mousavi, S.F.; Farzin, S. (2018). Experimental Investigation of the Effect of Adding LECA and Pumice on Some Physical Properties of Porous Concrete: Some Physical Properties of Porous Concrete. *Engineering Journal*, *22*, 205–213. https://doi.org/10.4186/ej.2018.22.1.205.

[4] Tennis, P.D.; Leming, M.L.; Akers, D.J. (2004). Pervious concrete pavements (No. PCA Serial No. 2828). Portland Cement Association, Skokie, and National Ready Mixed Concrete Associated, Silver Spring.

[5] Chindaprasirt, P.; Shigemitsu, H.; Thanudkij, C.; Mishima, N.; Yukihisa, Y. (2008). Cement paste characteristics and porous concrete properties. *Construction and Building Materials*, *22*, 894–901. https://doi.org/10.1016/j.conbuildmat.2006.12.007.

[6] Huang, B.; Wu, H.; Shu, X.; Burdette, E.G. (2010). Laboratory evaluation of permeability and strength of polymer-modified pervious concrete. *Construction and Building Materials*, *24*, 818–823. https://doi.org/10.1016/j.conbuildmat.2009.10.025.

[7] James, W.; Von Langsdorff, H. (2003). The use of permeable concrete block pavement in controlling environmental stressors in urban areas. 7th international conference on concrete block paving, Sun City, South Africa, pp. 12–15.

[8] Wu, H.; Zhuo, L.; Beibei, S.; Jian, Y. (2016). Experimental investigation on freeze–thaw durability of Portland cement pervious concrete (PCPC). *Construction and Building Materials*, *117*, 63–71. https://doi.org/10.1016/j.conbuildmat.2016.04.130.

[9] Teymouri, E.; Mousavi, S.F.; Karami, H.; Farzin, S.; Kheirabad, M.H. (2020). Municipal Wastewater pretreatment using porous concrete containing fine-grained mineral adsorbents. *Journal of Water Process Engineering*, *36*, 101346. https://doi.org/10.1016/j.jwpe.2020.101346.

[10] Javaheri-Tehrani, M.; Mousavi, S.F.; Abedi-Koupai, J.; Karami, H. (2020). Treatment of domestic wastewater using the combination of porous concrete and phytoremediation for irrigation. *Paddy Water Environment*, *18*, 729–742. https://doi.org/10.1007/s10333-020-00814-7.

[11] Teymouri, E.; Mousavi, S.F.; Karami, H.; Farzin, S.; Kheirabad, M.H. (2020). Reducing urban runoff pollution using porous concrete containing mineral adsorbents. *Journal of Environmental Treatment Techniques*, *8*, 429–436.

[12] Tan, S.A.; Fwa, T.F.; Han, C.T. (2003). Clogging evaluation of permeable bases. *Journal of Transportation Engineering*, *129*, 309–315. https://doi.org/10.1061/(ASCE)0733-947X(2003)129:3(309).

[13] Yong, C.F.; Deletic, A.; Fletcher, T.D.; Grace, M.R. (2008). September. The clogging behaviour and treatment efficiency of a range of porous pavements. Proceedings of the 11th International Conference on Urban Drainage, Edinburgh, Scotland, UK, pp. 1–10.

[14] Zhou, H.; Li, H.; Abdelhady, A.; Liang, X.; Wang, H.; Yang, B. (2019). Experimental investigation on the effect of pore characteristics on clogging risk of pervious concrete based on CT scanning. *Construction and Building Materials*, *212*, 130–139. https://doi.org/10.1016/j.conbuildmat.2019.03.310.

[15] Sandoval, G.F.; Galobardes, I.; Campos, A.; Toralles, B.M. (2020). Assessing the phenomenon of clogging of pervious concrete (Pc): Experimental test and model proposition. *Journal of Building Engineering*, *29*, 101203. https://doi.org/10.1016/j.jobe.2020.101203.

[16] Scholz, M.; Grabowiecki, P. (2007). Review of permeable pavement systems. *Building and Environment*, *42*, 3830–3836. https://doi.org/10.1016/j.buildenv.2006.11.016

[17] Sandoval, G.F.; Galobardes, I.; De Moura, A.C.; Toralles, B.M. (2020). Hydraulic behavior variation of pervious concrete due to clogging. *Case Studies in Construction Materials*, *13*, e00354. https://doi.org/10.1016/j.cscm.2020.e00354.

[18] Coughlin, J.P.; Campbell, C.D.; Mays, D.C. (2012). Infiltration and clogging by sand and clay in a pervious concrete pavement system. *Journal of Hydrologic Engineering, 17*, 68–73. https://doi.org/10.1061/(ASCE)HE.1943-5584.0000424.

[19] Schaefer, V.; Kevern, J. (2011). An integrated study of pervious concrete mixture design for wearing course applications. Cui, X.; Zhang, J.; Huang, D.; Tang, W.; Wang, L.; Hou, F. (2019). Experimental simulation of rapid clogging process of pervious concrete pavement caused by storm water runoff. *International Journal of Pavement Engineering, 20*, 24–32. https://doi.org/10.1080/10298436.2016.1246889.

[20] Cui, X.; Zhang, J.; Huang, D.; Tang, W.; Wang, L.; Hou, F. (2019). Experimental simulation of rapid clogging process of pervious concrete pavement caused by storm water runoff. *International Journal of Pavement Engineering, 20*, 24–32. https://doi.org/10.1080/10298436.2016.1246889.

[21] Zhou, H.; Li, H.; Abdelhady, A.; Liang, X.; Wang, H.; Yang, B. (2019). Experimental investigation on the effect of pore characteristics on clogging risk of pervious concrete based on CT scanning. *Construction and Building Materials. 212*, 130–139. https://doi.org/10.1016/j.conbuildmat.2019.03.310.

[22] Chopra, M.B.; Stuart, E.; Wanielista, M.P. (2010). Pervious pavement systems in Florida—Research results. In Low Impact Development 2010: Redefining Water in the City; Struck, S., Lichten, K., Eds.; ACSE: San Fransisco, USA, pp. 193–206. https://doi.org/10.1061/41099(367)18.

[23] Kayhanian, M.; Anderson, D.; Harvey, J.T.; Jones, D.; Muhunthan, B. (2012). Permeability measurement and scan imaging to assess clogging of pervious concrete pavements in parking lots. *Journal of Environmental Management, 95*, 114–123. https://doi.org/10.1016/j.jenvman.2011.09.021.

[24] Deo, O.; Sumanasooriya, M.; Neithalath, N. (2010). Permeability reduction in pervious concretes due to clogging: experiments and modeling. *Journal of Materials in Civil Engineering, 22*, 741–751. https://doi.org/10.1061/(ASCE)MT.1943-5533.0000079.

[25] Pervious concrete, ACI522R-06 Report, ACI Committee 522. (accessed on 1 March 2023) Available online: https://www.concrete.org/Portals/0/Files/PDF/Previews/52206_2pager.pdf.

[26] Testing Concrete Method for making test cubes from fresh concrete (1983), British Standard 1881, Part 108. (accessed on 1 March 2023) Available online: https://www.thenbs.com/PublicationIndex/documents/details?Pub=BSI&DocID=247358.

[27] ASTM Standard C1754/C1754M (2012) Standard Test Method for Density and Void Content of Hardened Pervious Concrete. Annual Book of ASTM Standards, Vol. 09.49, ASTM International, West Conshohocken.

[28] Guide for Selecting Proportions for No slump Concrete, ACI 211.3R Report. (accessed on 1 March 2023) Available online: https://www.studocu.com/row/document/university-of-engineering-and-technology-taxila/engineering-mechanics/aci-2113r-02-r09-guide-for-selecting-proportions-for-no-slump-concrete-my-civil/7098439.

[29] ASTM Standard C150/C150M (2012). Standard specification for Portland cement. Annual Book of ASTM Standards, Vol. 09.49, ASTM International, West Conshohocken.

[30] ASTM Standard C1701/C1701M (2017). Test method for infiltration rate of in-place pervious concrete. https://doi.org/10.1520/C1701_C1701M-17A.

[31] Kevern, J.T.; Schaefer, V.R.; Wang, K.; Suleiman, M.T. (2008). Pervious concrete mixture proportions for improved freeze-thaw durability. *Journal of ASTM International, 5*, 1–12. http://doi.org/10.1520/JAI101320.

[32] Kia, A.; Wong, H.S.; Cheeseman, C.R. (2017). Clogging in permeable concrete: A review. *Journal of Environmental Management, 193*, 221–233. https://doi.org/10.1016/j.jenvman.2017.02.018.

[33] Mousavi, S.F.; Karami, H.; Farzin, S.; Teymouri, E. (2018). Effects of adding mineral adsorbents to porous concrete for enhancing the quality performance of urban runoff systems. *World Journal of Engineering*, *15*, 489–497. https://doi.org/10.1108/WJE-10-2017-0314.

[34] Teymouri, E.; Mousavi, S.F.; Karami, H.; Farzin, S.; Javaheri-Tehrani, M. (2016). Experimental investigation of the effect of different additives on characteristics of porous concrete, applicable in urban runoff system. *Journal of Transportation Infrastructure Engineering*, *2*, 51–64. https://doi.org/10.22075/JTIE.2016.464.