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Field performance monitoring of pervious concrete pavements

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ABSTRACT

Pervious concrete pavements (PCP) have been successfully constructed in low-to-medium volume roads attributed to their sustainability benefits. Several studies have investigated the hydrological performance of PCPs, but limited attention has been given to the structural and environmental aspects. Thus, the objective of this study was to monitor the structural, hydrological and environmental performance of two PCP parking lots built using in-situ and ready-mix methods. Structural distresses were classified based on the distress identification manual, while the infiltration tests were performed every three months for three years to quantify the clogging rate. Joints/edges formed the weakest zones, while inefficient maintenance caused 98% clogging within 18 months. Further, in-situ mixing was 17% cheaper and 0.74% carbon-intensive than ready-mix technology. Overall, this research is envisioned to pave way for the development of guidelines that classify distresses and severity levels specific to PCPs, which also cover adequate maintenance recommendations for field implementation.

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KEYWORDS
Pervious concrete pavements; real-time field performance; structural distresses; functional deficiencies

1. Introduction

The rapid transformation of natural ground into transportation infrastructure has rendered imbalance in the ecosystem and has caused severe problems such as flash floods, runoff generation, soil erosion, urban heat islands, excessive hydraulic load on drainage systems, and noise generation (Wang et al., 2021, 2020). More so, the accumulation of water on the pavement poses health threats to local species, forces the users to take alternate routes, and affects the pavement surface condition (Harvey et al., 2016; Lu et al., 2020; Oyediji et al., 2021). As a result, excessive transportation-related emissions are generated during commuting and pavement maintenance, resulting in environmental and economic losses. This necessitates the need to focus on roadway systems that result in low-impact development. As the demand for sustainable pavement infrastructure is projected to increase, the construction of pervious concrete pavement (PCP) systems can effectively address the aforementioned problems.

The materials required for construction of PCPs are similar to those of Portland cement concrete pavements (PCCP) except that very little/no sand is required to create an open / gap graded surface wearing course that allows for rapid infiltration of stormwater (ACI 309R, 2005; Singh et al., 2020; Tennis et al., 2004; Zhu et al., 2019). However, the characteristic porous nature of pervious concrete (PC) results in low strength and durability, thereby restricting the application of PCPs to sidewalks, parking lots, medians and low-volume roads (Chandrappa et al., 2018; Dean et al., 2008; Tennis et al., 2004). Adequate research is available that demonstrates the different mix proportioning techniques, which can be adopted to achieve a balance between structural and hydrological parameters (ACI 309R,

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2005; Chandrappa & Biligiri, 2018; IRC 44, 2017). In addition, the formulation of standard test protocols for production as well as characterisation of PC are emerging. In-place densities in the range of 1600–2000 kg/m^3 are commonly obtained with this special porous material (Chandrappa & Biligiri, 2016; Tennis et al., 2004). Although the typical flow rates through PC vary from 0.14 to 1.22 cm/s, values beyond this range have also been reported (AlShareedah & Nassiri, 2021; Nguyen et al., 2014; Tennis et al., 2004). In general, the compressive strength of PC varies from 2.8 to 28 MPa, while flexural strength ranges from 1 to 3 MPa (Ćosić et al., 2015; Deo & Neithalath, 2010; Lori et al., 2019; Zhou et al., 2016).

An investigation utilised recycled aggregates that were treated with silane polymer emulsion to produce PC mixtures. Silane treatment caused redistribution of cement paste, which was more concentrated towards the aggregate contact points rather than developing a uniform coating over the aggregates. As a result, PC with silane treated recycled aggregates resulted in higher strength compared to the untreated mixtures (Liu et al., 2019). Other researchers have suggested that reducing the aggregate-to-cement ratios resulted in improved structural characteristics with a reduction in porosity (Ariffin et al., 2018; Dai et al., 2020; Singh, 2021; Singh et al., 2022). Additional details on the effect of specimen geometry, different mix constituents such as aggregate type and content, cement content, and the addition of waste / recycled materials on the physical, mechanical and hydrological properties of PC can be found elsewhere (AlShareedah & Nassiri, 2021; Singh et al., 2020, 2022; Zhang et al., 2021). Studies report that the installation of PCPs negates the requirement of an underdrain network because of its ability to store stormwater in the reservoir layer before slowly infiltrating into the ground (Tennis et al., 2004; Terhell et al., 2015). However, in areas of frequent and heavy rainfalls, an underdrain network of pipes may be provided to discharge and collect water for harvesting purposes. In addition, PCPs are sustainable roadway systems as they have better sound absorption characteristics, and require lower energy and generate fewer emissions during production and construction compared to conventional concrete pavements (Singh et al., 2020; Zhang et al., 2020). Research studies suggest that frequent cleaning of PCPs is essential, as the pore network structure tends to clog due to the accumulation of fine particulates in its matrix, which ultimately results in the loss of infiltration capacity over time (Coughlin et al., 2012; Kia et al., 2017; Omkar et al., 2010; Sandoval et al., 2020; Singh et al., 2020a; Vancura et al., 2012). A majority of the research studies have utilised conventional materials such as aggregates, cement, admixtures and very little to no sand to construct PCPs (Gupta, 2014; Joshi & Dave, 2021; Singh et al., 2019; Vaddy et al., 2020). However, a recent study utilised cured carbon fibre composites as a reinforcement material along with the traditional mix constituents to augment the strength of these special pavements (AlShareedah et al., 2019).

Researchers in the past have designed PCP surface wearing course layer using the traditional methodologies that are used for conventional concrete pavements. For instance, Delatte developed a design database for PCPs as per the American Concrete Pavement Association (Delatte, 2017). Other investigations have utilised finite element methods to ascertain the performance of PCP systems under varying loading and traffic conditions (AlShareedah & Nassiri, 2019; Vancura et al., 2011). In terms of field performance, PCPs allowed the infiltration of stormwater even after 12 years of construction (Wanielista et al., 2007). Further, PCP systems are known to arrest the heavy elements present in the runoff and improve the overall quality of the resulting discharge (Wanielista & Chopra, 2007). Another field study proposed exponential models to predict the infiltration rate for continuous and intermittent rainfall conditions through the PCP sidewalks (Saaly et al., 2019).

Note that the design and construction practices adopted during the installation of PCPs vary from one region/agency to the other. While some investigations used in-situ concrete mixing followed by manual placement, others have utilised ready-mix concrete for field applications of PC. In addition, majority of the research has focused on assessing the hydrological performance of PCPs, i.e. reduction in the infiltration rate with passage of time. However, limited studies have discussed the structural and durability aspects of in-place PCPs. Furthermore, very little emphasis has been given on quantifying the sustainability credentials of the in-situ and ready-mix PCP construction methods. Overall, there is still a lack of systematic guidelines that assist in identification and classification of distresses specific to PCPs, their associated severity levels, and adequate maintenance strategies at various levels, which could

Table 1. Salient features of two pervious concrete pavement parking lots.

Parameter	MCT	IITT
Aggregate size	12.5 mm and lower sizes (50%) + 6.3 mm and finer size (50%)	
Cement content (kg/m^3)	400 (Ordinary Portland cement 53 grade)	
Water-to-cement ratio	0.32	0.30
Aggregate-to-cement ratio	1:3.75	
Construction method	On-site PC mixing	Ready-mix PC
Compaction	Plate vibratory compaction (90 s per pass)	
Traffic	Two wheelers, cars and light-to-medium commercial vehicles	
Climate	Semi-arid tropical	
Vegetation adjacent to PCP slabs	Yes	No
Exposure to loose soil from surroundings	Yes	No
Porosity (%)	24.56	31.61
Density (kg/m^3)	1868	1725
Compressive strength (MPa)	21.28	8.85
Infiltration rate (cm/s) – falling head method	0.51	1.05

rationally evaluate PCP performance characteristics as well as their sustainability credentials during the design life.

In this direction, the objective of this research was to document the real-time structural and hydrological performance of two PCP parking lots for a period of over three years that were constructed using the in-situ and ready-mix methods. Further, the energy consumed, carbon emissions released and the costs associated with the two construction methods were assessed and compared. In addition, the limitations pertinent to the current construction practices were documented. The guidelines provided in the United States of America Federal Highway Administration distress classification manual were used to identify various distresses. Additionally, infiltration tests were conducted to assess the reduction in the infiltration rate of the special PCPs. Furthermore, this article proposes recommendation strategies for construction and maintenance of PCPs to garner maximum benefits of these specialty pavement systems. It is envisioned that the current study will pave way for the development of rational guidelines to classify various distresses and their severities, which will also encompass adequate maintenance recommendations at various levels, specific to PCPs.

2. Background to PCP parking lots

The first PCP parking lot was constructed using an in-situ concrete mixing technique in March 2018 on the Municipal Corporation of Tirupati (MCT) premises, State of Andhra Pradesh, India. Over 20 PCP slabs, each having dimensions of 4 m × 4 m × 0.15 m were constructed along a 120 m long parking lot, overlaid on a 0.25 m thick sub-base. The details pertaining to the installation and measurement of infiltration rates through the sub-base and surface wearing course layers at the time of construction are explained in detail in Singh et al. (2019). The second PCP parking lot that was about 50 m long and 5 m wide was constructed by utilising ready-mix PC in April 2019 on the campus of the Indian Institute of Technology Tirupati (IITT) India. Over 32 PCP slabs, each measuring 3 m × 2.5 m × 0.15 m were constructed. The details regarding the construction and performance assessment (immediately after installation) have been detailed in Vaddy et al. (2020). Further, the material composition for the two pavements is discussed in Table 1 along with the other salient features as well as test results for porosity, density, infiltration rate and compressive strength, which were estimated immediately after the construction. Note that porosity, density and compressive strength investigations were performed on six cylindrical cores extracted from the in-place PCP systems, while the infiltration rate measurements were performed in the field on the PCP slabs at distinct locations as per the relevant test standards (ASTM 1754/C1754-M, 2012; ASTM C39, 2021; ASTM C1701/C1701, 2017).

The cross-section of the two PCP parking lots is presented in Figure 1, and the construction methodology is discussed below:

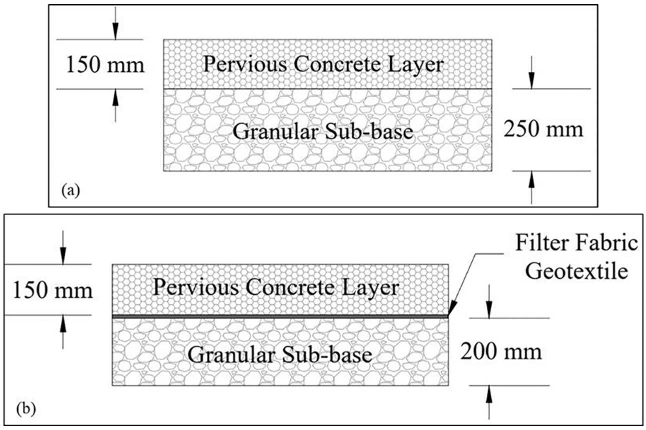

Figure 1. Cross-section of pervious concrete pavement parking lots at (a) Municipal Corporation of Tirupati and (b) Indian Institute of Technology Tirupati, India.

a) Municipal Corporation of Tirupati
   (i) i Excavation and removal of soil to the designed pavement thickness.
   (ii) ii Compaction of existing natural soil with 12 passes using a 10 metric ton static steel wheel roller.
   (iii) iii Placement and compaction of a 250 mm thick granular subbase layer (comprising aggregates passing 12.5 mm sieve and retaining on 1.18 mm having 25% fine content) with a static steel wheel roller.
   (iv) iv Fastening the formwork for preparation of alternative PC slab (mastic pads were placed between two adjacent slabs) each measuring 4 m × 4 m × 0.15 m.
   (v) v Mixing the constituents in desired proportions in an in-situ drum mixer for 180 s.
   (vi) vi Laying fresh PC mixture, and performing compaction with a plate vibratory compactor for 60–90 s by slowly moving it over a flat aluminium sheet to prevent sticking of the material to the compactor.
   (vii) vii Covering the freshly prepared slabs with plastic sheet and curing with water for seven days before opening to traffic.
b) Indian Institute of Technology Tirupati
   - The steps for the construction of PCP at IITT were similar to those for MCT (i to vii), except that the thickness of subbase was 200 mm and construction of the continuous PC slabs of dimensions 3 m × 2.5 m × 0.15 m was undertaken. Further, the PC mix was prepared at a ready-mix plant, and was transported to the site in transit mixers before placement and compaction.

The test sections at MCT were monitored for their hydrological performance by conducting surface infiltration rate (SIR) tests (as discussed in Section 3.1.1) once every six months, whereas falling head infiltration test (detailed in Section 3.1.2) was performed on the test section at IITT. Further, the two PCP systems were investigated for their structural performance, as discussed in Section 3.1.3. Note that brooming (every day at MCT and once a week at IITT) was the only cleaning method adopted for the two pavement sections.

3. Methodology and distress classifications

Once the PCP parking lots were constructed, it was essential to monitor their performance over time to identify the different forms of distresses and their causes, in order to formulate management strategies

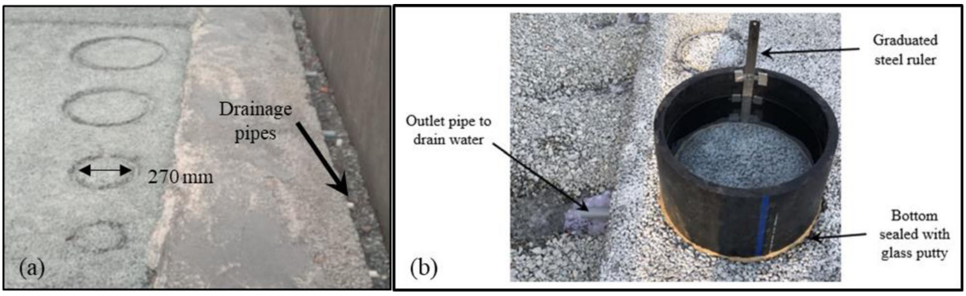

Figure 2. Measurement of infiltration rate at the parking lot constructed on the campus of Indian Institute of Technology Tirupati, India: (a) embedded infiltration ring of 270 mm diameter and (b) test setup.

to maintain PC assets over their design lives. The distresses in the pavement were broadly classified into two categories: (a) hydrological and (b) structural. The methods adopted to examine the performance of two PCP demonstration test sections are discussed below.

3.1. Functional and structural deficiencies

3.1.1. Surface infiltration rate (SIR) test

Surface infiltration rate (mm/h) of in-place PCP systems was determined as per ASTM C1701 (ASTM C1701/C1701, 2017). An infiltration ring with an internal diameter of 300 mm was used with 10 and 15 mm graduations marked on it. Prior to conducting the test, the PCP surface was wiped clean with a broomstick. Note that the interface between the infiltration ring and PCP surface was sealed with glass putty to prevent leakage from the sides.

3.1.2. Falling head infiltration test

In order to perform this test, an infiltration ring of internal diameter of 270 mm was embedded into the PCP surface layer during construction, as shown in Figure 2a. The bottom of the rings was sealed with a geomembrane to restrict the flow of water into the underlying sub-base layer. Additionally, slotted pipes were extended from the base of embedded rings to the side of the PCP for draining the water during testing. More details about the procedure involved in installing the rings within the PCP surface wearing course layer may be found elsewhere (Vaddy et al., 2020). Another ring, identical to the embedded ring in size, was placed over the pavement surface, and their interface was sealed with glass putty (Figure 2b). A graduated steel ruler was fixed over the ring. Initially, the PCP slabs were pre-wetted by pouring water and keeping the outlet of the pipes open. Once the water dissipated from the surface, the outlet was closed and water was ponded to an initial head of 22 cm. After dissipation of the air bubbles, the outlet of the pipe was opened and the time taken by water to fall from the initial head to the final head of 4 cm was noted. The infiltration rate (K) was computed in cm/s.

3.1.3. Site inspections

Site inspections were conducted at regular intervals to assess the structural performance of in-place PCP parking lots. The different structural and functional defects that were identified as part of this investigation are summarised in Table 2. Note that the classifications of various structural and functional deficiencies are based on the guidelines provided in the United States of America Federal Highway Administration distress classification manual (Miller & Bellinger, 2014) as well as visual observations and experience. In the absence of guidelines pertinent to classification of distresses in PCPs, a tentative range has been provided in this research, which could be utilised as a reference in the future. Note that the severity levels were not defined for any distress type.

Table 2. Classification of functional and structural distresses in two pervious concrete pavement parking lots.

S. No.	Distress type	Definition	Measuring units
1	Ravelling	Disintegration of PCP surface due to dislodging of coarse aggregates from PC matrix	• Square meters • Number
2	Joint deterioration	Increase in the joint width (transverse joints) due to the ravelling of aggregates in the PCP caused by the movement of vehicles from one slab to another	• Centimetres • Number
3	Edge cracking	Disintegration of aggregates from the pavement's surface due to the movement of vehicles: (a) near/over the edge and (b) from the PCP surface to adjacent areas	• Number
4	Skid marks	Long tire marks along the longitudinal direction of the PCP slabs	• Metres • Number
5	Surface sealing	Presence of localised patches of excessive cement paste over the surface of PCP restricting the infiltration of water	• Square metres • Number
6	Differential settlement	Difference in the levels of two adjacent PCP slabs due to improper construction practices	• Centimetres • Number

4. Results

4.1. Municipal corporation of Tirupati, India

4.1.1. Functional performance

Surface infiltration rate measurements were performed after every six months to adjudge the hydrological performance of the PCP parking lots. The average SIR immediately after construction was about 1 cm/s. However, six months after construction, the infiltration rate reduced to about 30% of the original, and at the end of the first year of construction, SIR was as low as 0.1 cm/s (90% reduction). Further, the infiltration rate continued to deteriorate, and it was lower than 0.02 cm/s (98% reduction) after 1.5 years of construction. Clearly, the porous matrix of the PC surface wearing course was significantly clogged with fine particulate matter, resulting in reduced permeability with time. The drastic reduction in the infiltration rate was attributed to the fact that the pavement was not sufficiently maintained after construction. Brooming was the only method adopted to clean the pavement surface on daily basis, albeit a superficial technique, which was found ineffective in removing the clogged media within the pores at lower depths from the surface, ultimately deteriorating SIR capacity. Hence, it is imperative to adopt other maintenance strategies such as pressure washing, vacuum cleaning and backwashing or their combinations as per site-specific requirements to maintain the infiltration capacity of PCP systems over time.

4.1.2. Structural performance

The overall structural performance of PCP section was satisfactory. At the time of construction, PCP exhibited no signs of any distress. However, with time, the pavement suffered from various surface defects, which are discussed as follows (Figure 3):

i. *Ravelling:* was encountered across 25% of the total PCP area. Most of the pavement slabs performed satisfactorily, and there were no major signs of ravelling except for the presence of a few loose aggregate particles. However, severe ravelling was observed in three PCP slabs (Figure 3a) on which garbage dump trucks as well as construction and excavation vehicles were parked. This indicated that the aggregates in PCP slabs were either crushed or dislodged from the surface due to heavy static loads and slow moving / stopping operations of the municipal utility vehicles on

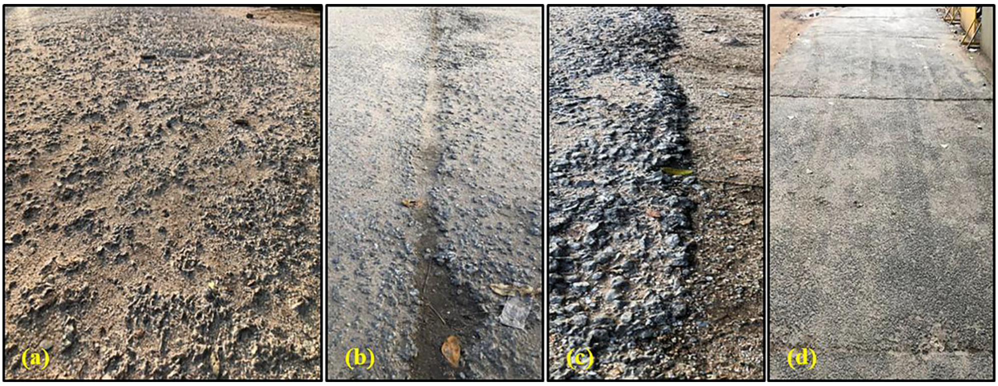

Figure 3. Structural defects: (a) severely ravelled pervious concrete pavement slab, (b) joint deterioration, (c) edge cracking and (d) skid marks.

Table 3. Measurements of surface infiltration rate of pervious concrete pavement since construction, monitored for three years.

Month	May 2019	August 2019	December 2019	April 2020	August 2020	December 2020	April 2021	August 2021	December 2021	April 2022
Infiltration rate (cm/s)	1.43	1.42	1.40	1.39	1.37	1.36	1.35	1.31	1.28	1.26
Standard deviation (cm/s)	0.015	0.015	0.02	0.01	0.006	0.006	0.015	0.015	0.021	0.015
Coefficient of variation (%)	1.07	1.08	1.43	0.72	0.42	0.42	1.13	1.16	1.62	1.21

the pavement surface. This behaviour highlights the need to assess the performance of PCP under static loads for applications in roadway intersections, petrol pumps, etc.

ii. *Joint deterioration:* was one of the major distresses that was encountered between the joints of more than 75% the slabs with high levels of severity, as shown in Figure 3b. Note that joint deterioration was prevalent after one year of construction. Essentially, the joints were filled with loose material (such as soil and other suspended matter) that might have accumulated during seepage of stormwater into PCP system.
iii. *Edge cracking:* was not a significant distress and was observed only across those slabs (Figure 3c) that allowed vehicles to move from PCP surface to the adjacent areas.
iv. *Skid marks:* were generally caused due to sudden braking action of vehicles over low density areas. Although skid marks may serve as the cause for initiation of ravelling, the test sections did not show any signs of ravelled aggregates, as seen in Figure 3d.

4.2. Indian Institute of Technology Tirupati, India

4.2.1. Functional performance

The pavement test sections constructed on-campus IITT were monitored for their hydrological performance every three months, and the results are presented in Table 3. In order to monitor infiltration rate, a 300-mm diameter infiltration ring was embedded in the PCP system, as discussed in Section 3.1.2 (Figure 2b). Further, the time taken by water to fall from an initial (22 cm) to final (4 cm) level was noted to compute the permeability based on the falling head permeability test.

The PCP section was frequently cleaned (once every week) by manual brooming of the surface. It was observed that there was a marginal (6%) reduction in the infiltration rate over two years. Even

Figure 4. Severely sealed surface of pervious concrete pavement slab.

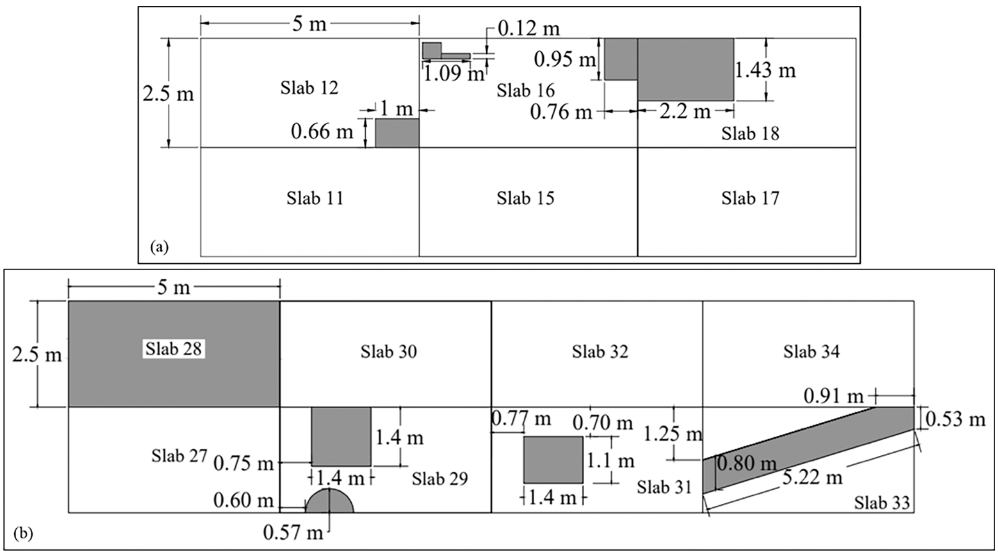

Figure 5. Schematic of the pervious concrete pavement slabs with sealed surface.

though this parking lot was placed behind a construction site, the pavement was rarely subjected to sediment loads due to runoff. The primary traffic source on this pavement was two-wheelers, although occasionally medium-to-heavy vehicular loads such as ambulances, vans, cars, tractor-trailers and trucks were encountered.

Surface sealing was another functional distress observed in PCP, and Figure 4 depicts a severely sealed PCP surface. Surface sealing was caused due to: (a) improper mix design, (b) addition of water during placement to allow free flow of stiffened PC from RMC trucks, (c) excessive spraying of water to prevent moisture loss from PC prior to compaction, and (d) over compaction. Figure 5 presents the schematic and locations of the PCP slabs that were subjected to different levels of sealing.

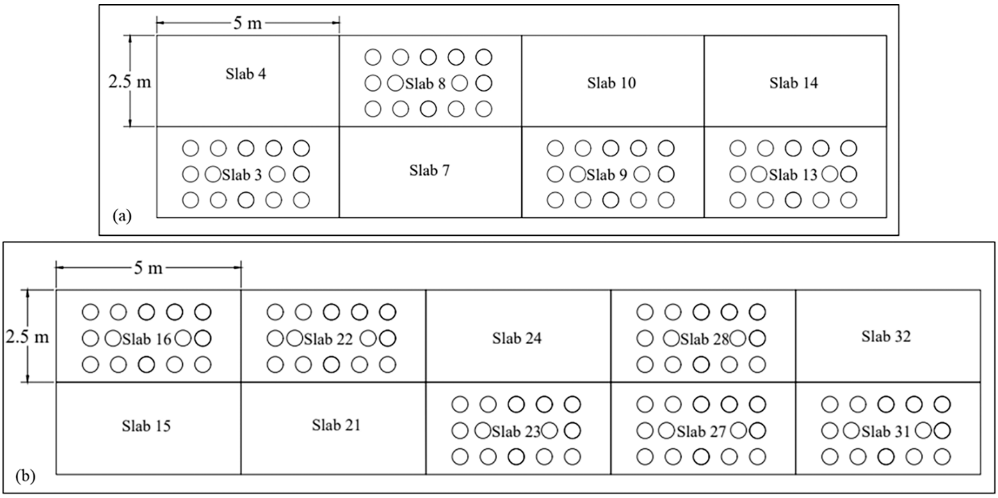

Figure 6. Schematic of the ravelled pervious concrete pavement slabs.

4.2.2. Structural performance

In terms of structural performance, the test section did not perform well compared to the PCP system built on-campus Municipal Corporation of Tirupati. The various distresses and their causes of IITT test sections are discussed below:

i. *Ravelling:* The schematic of slabs subjected to ravelling are presented in Figure 6. Ravelling was attributed to: (a) improper compaction at the time of construction resulting in low-density mixtures, (b) heavy loading at premature age and (c) sudden stopping of vehicles.
ii. *Joint deterioration:* similar to the PCP parking lot at MCT, joint deterioration was one of the major distresses observed in these pavement sections. Loss of aggregates at the joints between PCP slabs (Figure 7) was observed across eight locations, whereas 11 locations at the junction of PCP and PCCP shoulders (Figure 8) were found to be severely ravelled with prominent visibility of mastic pads (that were used between slabs during construction). Joint deterioration was attributed to (a) improper joint installation and (b) placement of tires at the junction of PCP and PCCP systems.
iii. *Differential settlement:* was observed across three adjacent PCP slabs (Figure 9), and occurred due to: (a) improper levelling during construction and (b) over compaction.

4.3. Maintenance recommendations

Based on the observations from the two different PCP parking lots, it was inferred that the PCP site be monitored continuously and cleaned periodically to identify the best maintenance solutions at the very early stage of distresses so they could be controlled from deteriorating further. To summarise, the maintenance recommendations for the different structural and hydrological distresses discussed in the two PCP case studies are presented in Table 4.

4.4. Lifecycle analysis of PCP parking lots

In order to quantify the energy consumed and emissions generated from the construction of PCPs using two distinct PC production techniques, a cradle-to-gate lifecycle assessment (LCA) study was undertaken. The embodied energy, carbon dioxide equivalent (kg CO_2 eq./km), and economic burdens were computed using the models proposed by (Singh et al., 2020), which are presented through

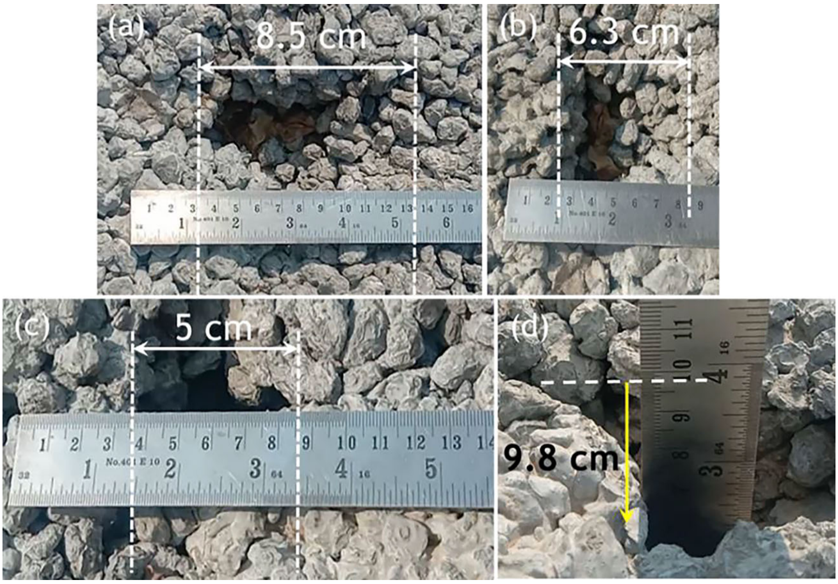

Figure 7. Deterioration at the junction of longitudinal and transverse joints in pervious concrete pavement: (a) length between slabs 15 and 16; (b) width between slabs 15 and 16; (c) width between slabs 19 and 20; and (d) depth between slabs 19 and 20.

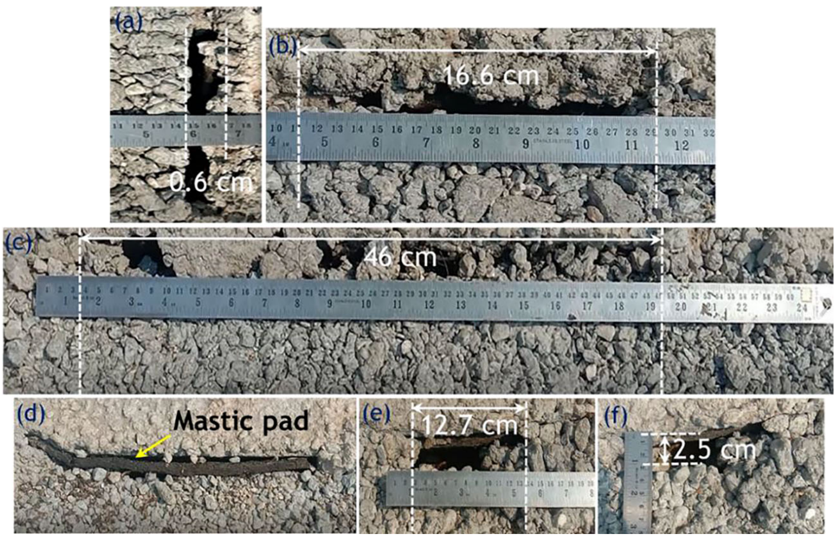

Figure 8. Deteriorated joints at the junction of pervious concrete pavement and Portland cement concrete pavement shoulders: (a) width at slab 11; (b) length at slab 11; (c) length at slab 13; (d) visible mastic pad; (e) length at slab 25; and (f) width at slab 29.

Equations (1)–(3) respectively. The functional unit was 1 km long, 3.5 m wide and 0.15 m thickness PC surface wearing course layer. The primary inputs were collected from the construction agency whereas the secondary data was gathered from (*India Construction Materials Database of Embodied Energy and Global Warming Potential* - Methodology Report, 2017). This comparative analysis was carried out in accordance with the International Standards Organization (ISO: 14040, 2006; ISO: 14044, 2006), and environmental lifecycle results are shown in Table 5. In addition, the results of the capital costs for the

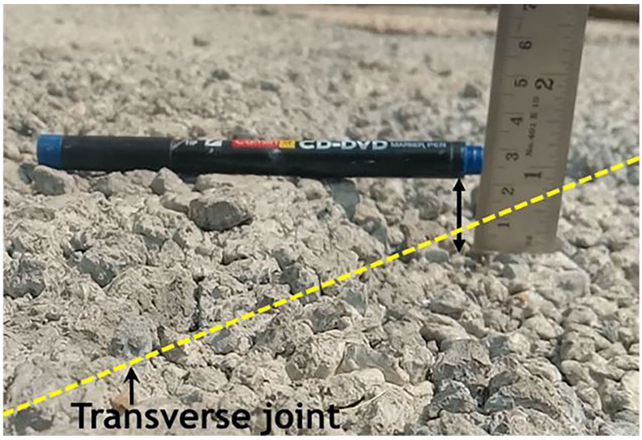

Figure 9. Differential settlement across slabs 27 and 29 of pervious concrete pavement.

Table 4. Pavement distress maintenance recommendation.

Distress type	Potential maintenance strategies
Ravelling	Sweeping Sweeping and vacuuming Localised milling, vacuuming and replacement Structural overlay
Joint deterioration	Sweeping and vacuuming Localised milling, vacuuming and replacement Avoid creating isolation joints and use of pizza-tool joint cutter Saw cut after 24 h under very hot conditions, else between 36 and 72 h of PC placement under wet conditions
Edge cracking	Sweeping and vacuuming Localised milling, vacuuming and replacement
Skid marks	Localised milling, vacuuming and replacement
Surface sealing	Localised milling, vacuuming and replacement
Differential settlement	Localised milling, vacuuming and replacement Structural overlay
Clogging	Sweeping Sweeping, vacuuming, pressure washing, back washing, or their combination

ready-mix and in-situ construction methods are reported in Table 6.

$$\text{Total embodied energy}\left(\frac{\text{MJ}}{\text{km}}\right) = \sum(1000 \times W \times (T \times D_n \times (P_e + M_e + (T_e \times D_i)) + C_e) \quad (1)$$

$$\text{Total kg CO}_2\text{ eq./km} = \sum(1000 \times W \times (T \times D_n \times (P_g + M_g + (T_g \times D_i)) + C_g) \quad (2)$$

$$\text{Total cost}\left(\frac{\text{Rs}}{\text{km}}\right) = \sum(T \times W \times (M_c + T_c + C_c) \quad (3)$$

where

T = Thickness of layer in m,
W = Width of the road in m,
D_n = Density of pavement material in kg/m^3,
P_e = Material production value in MJ/kg,
P_g = Material production value in kg CO_2 eq./kg,

M_e = Material mixing value in MJ/kg,
M_g = Material mixing value in kg CO_2 eq./kg,
T_e = Transport from production site to application site in MJ/kg-km,
T_g = Transport from production site to application site, kg CO_2 eq./kg-km,
D_i = Distance from material production site to application site in km.
C_e = Material compaction value in MJ/m^2,
C_g = Material compaction value in kg CO_2 eq./m^2,
M_c = Material cost in Indian Rs./km/m^2,
T_c = Material transportation cost in Indian Rs./km/m^2,
C_c = Construction cost in Indian Rs./km/m^2.

For the construction of PCP surface wearing course layer using ready-mix PC, embodied energy was about 1.28% higher than in-situ mixing. The consumption of higher energy during ready-mix placement was majorly attributed to the excessive fuel consumption during transportation of fresh PC compared to in-situ mixing where PC material was transported manually in wagons prior to placement and compaction. Further, the carbon emissions generated by in-situ mixing were about 0.74% higher than ready-mix concrete mixing. This was ascribed to longer transportation distances involved in delivering the raw materials directly to the construction site as well as generation of larger emissions due to higher consumption of diesel during PC production. In addition, a capital cost analysis was performed, which indicated that the cost involved in the construction of PCP surface wearing layer using ready-mix PC was about 16% higher compared to the in-situ mixing. This was due to the additional charges involved in PC mixing at the batch plant as well as transportation through ready-mix concrete trucks. Based on the findings, it may be stated that the construction of PCPs for small-scale projects may utilise in-situ mixing methods as they are economical and provide relatively uniform mix consistency. However, for large-scale projects where rapid construction is desired, ready-mix PC may be used despite higher cost only after achieving a balanced mix design using retarders.

Table 5. Lifecycle assessment results for 1 km long, 3.5 m wide and 0.15 m thick pervious concrete surface wearing course with ready-mix and in-situ mixing methods.

Pervious concrete						
Mixing method	D_n (kg/m^3)	P_e (MJ/kg)	M_e (MJ/kg)	$T_e \times D_i$ (MJ/kg)	C_e (MJ/m^2)	Embodied energy ($\times 10^6$ MJ/km)
Ready-mix	2022	1.34767	0.00178	0.09959	0.02484	1.54
In-situ	2022	1.34767	0.00467	0.07816	0.02484	1.52
Portland cement concrete						
Mixing method	D_n (kg/m^3)	P_g (kg CO_2 eq./kg)	M_g (kg CO_2 eq./kg)	$T_g \times D_i$ (kg CO_2 eq./kg)	C_g (CO_2 eq./m^2)	Carbon dioxide equivalent ($\times 10^6$ kg CO_2 eq./km)
Ready-mix	2022	0.18669	0.00006	0.00657	0.01069	2.05
In-situ	2022	0.18669	0.00034	0.00773	0.01069	2.06

Table 6. Cost analysis results for 1 km long, 3.5 m wide and 0.15 m thick pervious concrete surface wearing course with ready-mix and in-situ mixing methods.

Mixing method	M_c (US\$/day)	T_c (US\$/day)	C_c (US\$/day)	Length of road constructed per day (m)	Capital cost (US\$)
Ready-mix	1499	282	264	48	42,614
In-situ	999	90	89	32	36,812

4.5. Summary and learnings from the case studies

The two PCP parking lot field case studies adopted two distinct methods of concrete mixing. For the PCP sections constructed with RMC technology at IITT, most of the distresses were developed within the first few months of construction, pointing that mix consistency was non-uniform raising concerns on the application of RMC for PCP systems. The poor consistency of PC mixtures may be due to the following reasons: (a) time taken by RMC trucks to reach the site (from the plant) was about 45–60 min depending on traffic; and (b) addition of small proportions of water to the fresh mixture during construction to facilitate free flow of stiff PC. In order to address the problem of stiffening of PC mix on-site, additional proportion of water was added at the RMC plant itself. However, the first few loads of the resulting mix had high paste content, and the problem persisted. On another account, though in-situ mixing technology results in production of uniform and high-quality PC, its application is limited to small-scale work due to the prolonged time taken during construction.

Based on the two case studies, it was understood that despite recent developments in the domain of PCP construction, their applications are limited to low-volume roads such as sidewalks, and parking lots due to its low characteristic strength and the need for frequent maintenance. Further, the construction of PCPs often suffers from quality control issues associated with traditional mixing and construction practices. In this direction, there is a significant need to develop high-quality PCP systems for field applications that possess consistent mix characteristics, high strength without compromising on the infiltration rate, and addresses other problems such as slow construction rate and labour requirements along with throwing light on the utilisation of PCP as a potential long-term pavement maintenance and preservation strategy.

5. Conclusions and recommendations

The real-field studies illustrated in this paper attempted to monitor the performance of two PCP parking lots that were built using in-situ and ready-mix pervious concrete. The extent of severity and the locations of different functional and structural distresses that were developed in the two PCPs were identified and their causes were discussed. In addition, the environmental and economic performance parameters of the PCP systems constructed using two distinct mixing methods were detailed in this technical note. Further, maintenance recommendations were provided to address the various distresses that could occur in PCP systems.

- Ravelling was majorly observed in the areas where utility vehicles were parked. Joints and edges formed the weakest zones in the PCP slabs.
- Non-uniform compaction was another concern, as it led to occurrence of locations with low density and also caused differential settlement.
- The addition of small amounts of water to extract PC from ready-mix trucks during placement caused surface sealing during compaction, resulting in a total failure of the infiltration capability.
- Regular brooming was efficient in retaining the infiltration rate of PCPs only when they were subjected to direct rainwater and no polluted discharge from the nearby sources.
- The embodied energy of PCP surface wearing course layers prepared with ready-mix PC was about 1.28% higher than in-situ mixing, while the carbon emissions generated by in-situ mixing were about 0.74% higher than ready-mix concrete mixing.
- Surface wearing course layer constructed using ready-mix PC was about 16% expensive compared to in-situ mixing method.

Essentially, though tentative guidelines provide recommendations to mitigate clogging and structural distresses, there is a significant need to develop standard specifications and guidelines that classify the various distresses and severity levels specific to PCPs, which also encompass recommendations for adequate maintenance strategies at various levels. Such an approach is expected to pave way for formulation of potential global standards for maintenance of the PCP systems.

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Disclosure statement

No potential conflict of interest was reported by the author(s).

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References

ACI 309R. (2005). *Guide for consolidation of concrete*. American Concrete Institute.

AlShareedah, O., & Nassiri, S. (2019). Methodology for mechanistic design of pervious concrete pavements. *Journal of Transportation Engineering, Part B: Pavements*, *145*(2), 04019012. https://doi.org/10.1061/JPEODX.0000117

AlShareedah, O., & Nassiri, S. (2021). Pervious concrete mixture optimization: Physical, and mechanical properties and pavement design: A review. *Journal of Cleaner Production*, *288*, 125095. https://doi.org/10.1016/j.jclepro.2020.125095

AlShareedah, O., Nassiri, S., Chen, Z., Englund, K., Li, H., & Fakron, O. (2019). Field performance evaluation of pervious concrete pavement reinforced with novel discrete reinforcement. *Case Studies in Construction Materials*, *10*, e00231. https://doi.org/10.1016/j.cscm.2019.e00231

Ariffin, N. F., Jaafar, M. F. M., Shukor Lim, N. H. A., Bhutta, M. A. R., & Hussin, M. W. (2018). Mechanical properties of polymer-modified porous concrete. *IOP Conference Series: Materials Science and Engineering*, *342*, 012081. https://doi.org/10.1088/1757-899X/342/1/012081

ASTM 1754/C1754-M. (2012). *Test method for density and void content of hardened pervious concrete*. ASTM International.

ASTM C1701/C1701. (2017). *Test method for infiltration rate of in place pervious concrete*. ASTM International.

ASTM C39. (2021). *Standard test method for compressive strength of cylindrical concrete specimens*. ASTM International.

Chandrappa, A. K., & Biligiri, K. P. (2016). Influence of mix parameters on pore properties and modulus of pervious concrete: An application of ultrasonic pulse velocity. *Materials and Structures*, *49*(12), 5255–5271. https://doi.org/10.1617/s11527-016-0858-9

Chandrappa, A. K., & Biligiri, K. P. (2018). Methodology to develop pervious concrete mixtures for target properties emphasizing the selection of mixture variables. *Journal of Transportation Engineering, Part B: Pavements*, *144*(3), 04018031. https://doi.org/10.1061/JPEODX.0000061

Chandrappa, A. K., Maurya, R., Biligiri, K. P., Rao, J. S., & Nath, S. (2018). Laboratory investigations and field implementation of pervious concrete paving mixtures. *Advances in Civil Engineering Materials*, *7*(1), 20180039. https://doi.org/10.1520/ACEM20180039

Ćosić, K., Korat, L., Ducman, V., & Netinger, I. (2015). Influence of aggregate type and size on properties of pervious concrete. *Construction and Building Materials*, *78*, 69–76. https://doi.org/10.1016/j.conbuildmat.2014.12.073

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*(1), 68–73. https://doi.org/10.1061/(ASCE)HE.1943-5584.0000424

Dai, Z., Li, H., Zhao, W., Wang, X., Wang, H., Zhou, H., & Yang, B. (2020). Multi-modified effects of varying admixtures on the mechanical properties of pervious concrete based on optimum design of gradation and cement-aggregate ratio. *Construction and Building Materials*, *233*, 117178. https://doi.org/10.1016/j.conbuildmat.2019.117178

Dean, S. W., 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*(2), 101320. https://doi.org/10.1520/JAI101320

Delatte, N. (2017). *Concrete pavement design, construction, and performance*. CRC Press.

Deo, O., & Neithalath, N. (2010). Compressive behavior of pervious concretes and a quantification of the influence of random pore structure features. *Materials Science and Engineering: A*, *528*(1), 402–412. https://doi.org/10.1016/j.msea.2010.09.024

Gupta, R. (2014). Monitoring in situ performance of pervious concrete in British Columbia—A pilot study. *Case Studies in Construction Materials*, *1*, 1–9. https://doi.org/10.1016/j.cscm.2013.10.001

Harvey, J. T., Meijer, J., Ozer, H., Al-Qadi, I. L., Saboori, A., & Kendall, A. (2016). Pavement Life-Cycle Assessment Framework (FHWA-HIF-16-014; p. 244). Federal Highway Administration. https://www.fhwa.dot.gov/pavement/sustainability/hif16014.pdf

India Construction Materials Database of Embodied Energy and Global Warming Potential—Methodology Report. (2017). International Finance Corporation.

IRC 44. (2017). *Guidelines for cement concrete mix design for pavements* (p. 60). Indian Roads Congress. https://mis.wbprd.gov.in/Engineering/Codes/IRC44.pdf

ISO: 14040. (2006). *Environmental management—Life cycle assessment—Principles and framework*. International Organization for Standardization. https://www.iso.org/cms/render/live/en/sites/isoorg/contents/data/standard/03/74/37456.html

ISO: 14044. (2006). Environmental management—Life cycle assessment—Requirements and guidelines. International Organization for Standardization.

Joshi, T., & Dave, U. (2021). Construction of pervious concrete pavement stretch: Ahmedabad, India – Case study. *Case Studies in Construction Materials*, *16*, 1âĂŞ17. https://doi.org/10.1016/j.cscm.2021.e00622

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

Liu, T., Wang, Z., Zou, D., Zhou, A., & Du, J. (2019). Strength enhancement of recycled aggregate pervious concrete using a cement paste redistribution method. *Cement and Concrete Research*, *122*, 72–82. https://doi.org/10.1016/j.cemconres.2019.05.004

Lori, A. R., Hassani, A., & Sedghi, R. (2019). Investigating the mechanical and hydraulic characteristics of pervious concrete containing copper slag as coarse aggregate. *Construction and Building Materials*, *197*, 130–142. https://doi.org/10.1016/j.conbuildmat.2018.11.230

Lu, D., Tighe, S. L., & Xie, W.-C. (2020). Impact of flood hazards on pavement performance. *International Journal of Pavement Engineering*, *21*(6), 746–752. https://doi.org/10.1080/10298436.2018.1508844

Miller, J. S., & Bellinger, W. Y. (2014). *Distress identification manual for the long-term pavement performance program (fifth revised edition)* (FHWA-HRT-13-092; pp. 1–142). Federal Highway Administration. https://www.fhwa.dot.gov/publications/research/infrastructure/pavements/ltpp/13092/13092.pdf

Nguyen, D. H., Sebaibi, N., Boutouil, M., Leleyter, L., & Baraud, F. (2014). A modified method for the design of pervious concrete mix. *Construction and Building Materials*, *73*, 271–282. https://doi.org/10.1016/j.conbuildmat.2014.09.088

Omkar, D., Milani, S., & Narayanan, N. (2010). Permeability reduction in pervious concretes due to clogging: Experiments and modeling. *Journal of Materials in Civil Engineering*, *22*(7), 741–751. https://doi.org/10.1061/(ASCE)MT.1943-5533.0000079

Oyediji, R., Lu, D., & Tighe, S. L. (2021). Impact of flooding and inundation on concrete pavement performance. *International Journal of Pavement Engineering*, *22*(11), 1363–1375. https://doi.org/10.1080/10298436.2019.1685671

Saaly, M., Hedayat, M. M., & Golroo, A. (2019). Performance of pervious concrete pavement under various raining conditions. *Road Materials and Pavement Design*, *20*(7), 1653–1663. https://doi.org/10.1080/14680629.2018.1474791

Sandoval, G. F. B., de Moura, A. C., Jussiani, E. I., Andrello, A. C., & Toralles, B. M. (2020). Proposal of maintenance methodology for pervious concrete (PC) after the phenomenon of clogging. *Construction and Building Materials*, *248*, 118672. https://doi.org/10.1016/j.conbuildmat.2020.118672

Singh, A. (2021). *Development of Pervious All-Road class All-weather Multilayered paver (PARAMpave) blocks* [Ph.D. Dissertation]. Indian Institute of Technology Tirupati.

Singh, A., Biligiri, K. P., & Sampath, P. V. (2022a). Engineering properties and lifecycle impacts of pervious All-road All-weather multilayered pavement. *Resources,: Conservation and Recycling*, *180*, 106186. https://doi.org/10.1016/j.resconrec.2022.106186

Singh, A., Charak, A., Biligiri, K. P., & Pandurangan, V. (2022b). Glass and carbon fiber reinforced polymer composite wastes in pervious concrete: Material characterization and lifecycle assessment. *Resources,: Conservation and Recycling*, *182*, 106304. https://doi.org/10.1016/j.resconrec.2022.106304

Singh, A., Jagadeesh, G. S., Sampath, P. V., & Biligir, K. P. (2019). Rational approach for characterizing in situ infiltration parameters of two-layered pervious concrete pavement systems. *Journal of Materials in Civil Engineering*, *31*(11), 04019258. https://doi.org/10.1061/(ASCE)MT.1943-5533.0002898

Singh, A., Sampath, P. V., & Biligiri, K. P. (2020a). A review of sustainable pervious concrete systems: Emphasis on clogging: Material characterization, and environmental aspects. *Construction and Building Materials*, *261*, 120491. https://doi.org/10.1016/j.conbuildmat.2020.120491

Singh, A., Vaddy, P., & Biligiri, K. P. (2020b). Quantification of embodied energy and carbon footprint of pervious concrete pavements through a methodical lifecycle assessment framework. *Resources: Conservation and Recycling*, *161*, 104953. https://doi.org/10.1016/j.resconrec.2020.104953

Tennis, P. D., Leming, M. L., & Akers, D. J. (2004). Pervious concrete pavements. Portland Cement Association, Skokie, Illinois, and National Ready Mixed Concrete Association, Silver Spring, Maryland, USA. http://citeseerx.ist.psu.edu/viewdoc/download?doi = 10.1.1.626.1739&rep = rep1&type = pdf

Terhell, S.-L., Cai, K., Chiu, D., & Murphy, J. (2015). *Cost and benefit analysis of permeable pavements in water sustainability* (p. 8). University of California Agriculture and Natural Resources: Davis, CA. http://watermanagement.ucdavis.edu/files/5414/3891/2393/A03_Terhell_Cai_Chiu_Murphy_ESM121_FinalReport.pdf

Vaddy, P., Singh, A., Sampath, P. V., & Biligiri, K. P. (2020). Multi-scale in situ investigation of infiltration parameter in pervious concrete pavements. *Journal of Testing and Evaluation*, *49*(5), 3519–3527. https://doi.org/10.1520/JTE20200052

Vancura, M., MacDonald, K., & Khazanovich, L. (2011). Structural analysis of pervious concrete pavement. *Transportation Research Record*, *2226*(1), 13–20. https://doi.org/10.3141/2226-02

Vancura, M. E., MacDonald, K., & Khazanovich, L. (2012). Location and depth of pervious concrete clogging material before and after void maintenance with common municipal utility vehicles. *Journal of Transportation Engineering*, *138*(3), 332–338. https://doi.org/10.1061/(ASCE)TE.1943-5436.0000327

Wang, C., Wang, Z.-H., Kaloush, K. E., & Shacat, J. (2021). Cool pavements for urban heat island mitigation: A synthetic review. *Renewable and Sustainable Energy Reviews*, *146*, 111171. https://doi.org/10.1016/j.rser.2021.111171

Wang, W., Wang, L., Miao, Y., Cheng, C., & Chen, S. (2020). A survey on the influence of intense rainfall induced by climate warming on operation safety and service life of urban asphalt pavement. *Journal of Infrastructure Preservation and Resilience*, *1*(1), 1âĂŞ4. https://doi.org/10.1186/s43065-020-00003-0

Wanielista, M., & Chopra, M. (2007). *Report 4 of 4: Performance assessment of a pervious concrete pavement used as a shoulder for an interstate rest area parking lot* (p. 38). Stormwater Management Academy University of Central Florida Orlando, FL. http://stormwater.ucf.edu/wp-content/uploads/2015/10/Final-Report-4-of-4-Shoulder-June-2007.pdf

Wanielista, M., Chopra, M., Spence, J., & Ballock, C. (2007). *Hydraulic performance assessment of pervious concrete pavements for stormwater management credit* (p. 74). Stormwater Management Academy University of Central Florida Orlando, FL. https://rmc-foundation.org/wp-content/uploads/2017/07/PerformanceAssessmenFBD13pdf.pdf

Zhang, Y., Li, H., Abdelhady, A., & Yang, J. (2020). Effect of different factors on sound absorption property of porous concrete. *Transportation Research Part D: Transport and Environment*, *87*, 102532. https://doi.org/10.1016/j.trd.2020.102532

Zhang, Y., Li, H., Abdelhady, A., Yang, J., & Wang, H. (2021). Effects of specimen shape and size on the permeability and mechanical properties of porous concrete. *Construction and Building Materials*, *266*, 121074. https://doi.org/10.1016/j.conbuildmat.2020.121074

Zhou, J., Zheng, M., Wang, Q., Yang, J., & Lin, T. (2016). Flexural fatigue behavior of polymer-modified pervious concrete with single sized aggregates. *Construction and Building Materials*, *124*, 897–905. https://doi.org/10.1016/j.conbuildmat.2016.07.136

Zhu, H., Yu, M., Zhu, J., Lu, H., & Cao, R. (2019). Simulation study on effect of permeable pavement on reducing flood risk of urban runoff. *International Journal of Transportation Science and Technology*, *8*(4), 373–382. https://doi.org/10.1016/j.ijtst.2018.12.001