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Permeable low-density cellular concrete (PLDCC) as a replacement for aggregate layers in permeable parking lots

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ABSTRACT

This study examines the suitability of permeable low-density cellular concrete (PLDCC), a highly porous concrete with no aggregates, as a partial replacement for aggregate layers in permeable parking lots. Four PLDCCs are developed in the laboratory, and their permeability and compressive strength are tested. The tested PLDCCs have compressive strengths of 0.6–1.8 MPa, permeabilities of 300–1800 cm/h, and air void contents of 70–80%, thus demonstrating the favorable aggregate properties of the PLDCC. The study compares the effectiveness of the PLDCC by creating a conventional permeable paving section and four more sections in which the PLDCC replaces 50% of the aggregate layer. Potable water is then filtered through the developed permeable paving models, and the level of contaminants in the output water of each layer is monitored for 25 cycles. The effluent from the permeable paving with the PLDCC exhibits higher alkalinity, pH, and total dissolved solids than conventional permeable pavements.

1. Introduction

A study conducted by Davis et al. (2010) estimated that the total parking lot area of buildings in the United States might equal the total areas of the states of Connecticut and Massachusetts, thus potentially causing urban sprawl. This is a serious environmental problem as it can increase the level and rate of storm runoff, thus carrying pollutants to the nearby water bodies and impacting the surrounding habitats. The increased runoff also leads to flash floods and impacts the existing drainage system. Hence, permeable parking lots have gained much attention in recent decades for supporting the effective management of stormwater in urban areas. Permeable parking lots offer various ecological benefits, including runoff reduction, infiltration improvement, delayed time to peak flow, among others (Liu et al., 2020b; Winston et al., 2020a,b; Xie et al., 2019).

As with roads, parking lots are constructed as layered systems. Traditionally, permeable paving is designed with thick aggregate layers overlain by either porous concrete or asphalt concrete layers. In addition to stability, the aggregate layer has a high porosity, acts as a reservoir, and purifies the stormwater. However, while there are numerous studies on the surface layers, very few researchers have concentrated on the underlying layers of the permeable paving. Moreover, numerous studies have proposed thick aggregate layers, as shown in Table 1. Here, the average aggregate layer thickness is around 400–500 mm. To put this in context, the construction of a 100 x 100 m parking lot using a 500-mm thick aggregate layer requires 5000 m^3 of aggregate, which is equivalent to 800 14-ton truck loads. If the requisite aggregates need to be hauled from a source 10 miles away, this amounts to a total equivalent of 16,000 miles of transportation. This amount of haulage impacts both the cost and the environment (Inti and Tandon 2021).

For some projects, high-quality aggregates are imported from hundreds and even thousands of miles from other states and, in certain cases, even from other countries (Van Dam et al., 2015). Generally, the cost of hauling aggregates across distances of 48–80 km (30–50 miles) can double the overall cost of the aggregates (Robinson & Brown, 2002). Moreover, the cost of aggregate transport in congested urban areas can be three to four times as expensive. Further, in addition to these costs and environmental impacts, the weight of thick aggregate layers is a burden to weak soils (Ni et al., 2020).

Although several studies have examined the use of alternative aggregate materials such as steel slag, recycled concrete, burnt bricks, etc., these were used to produce surface concrete or asphalt layers rather

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Table 1
Aggregate layer thicknesses proposed by various studies.

Aggregate layer size (mm)	Surface layer type	Publication
300	Porous asphalt, concrete, and block paving	Kumar et al. (2016)
330	Block paving	Turco et al. (2020)
360	Permeable pavement blocks	Tota-Maharaj et al. (2012)
410	Block paving	Ioannidou & Arthur (2020)
457	Concrete brick pavers	Mahmoud et al. (2020)
479	Permeable interlocking concrete pavement (PICP), pervious concrete	Drake et al. (2014)
500	Block paving	Imran et al. (2013)
500, 570, 580	Porous concrete, asphalt, and block paving	Huang et al. (2016)
588	Block paving	Tirpak et al. (2020)
610	Block paving	Winston et al. (2020)

than to replace the reservoir layer. Hence, there is a need to examine the use of alternative pervious materials as a replacement for thick aggregate layers in permeable parking lots. Therefore, the present study focuses on using permeable low-density cellular concrete (PLDCC) as an aggregate replacement. In the above example, if 50% of the aggregate layer is replaced with PLDCC, a saving of approximately 300 truck trips could be achieved because the PLDCC needs no aggregates and approximately 850 tons of cement (1/6th of the aggregates weight) is sufficient to construct the 2500 m^3 of PLDCC.

2. Literature review

2.1. Permeable low-density cellular concrete (PLDCC)

The American Concrete Institute (ACI) 523 defines lightweight (or low-density) cellular concrete as “a mixture of cement, water, and preformed foam.” The synthetic foam used in PLDCC resembles a shaving foam, which contains internal microscopic pores. When the foam is mixed with cement and water, the air voids in the foam occupies a significant volume and, thus, provides a porous texture once the liquid concrete has hardened into a solid. Moreover, the PLDCC uses no coarse aggregates eliminating the need to haul aggregates (Montemayor et al.). In addition, PLDCC has numerous advantages such as superior thermal properties, freeze-thaw resistance, cost-effectiveness, ease of construction, and economy of transportation (Averyanov, 2018). Hence, PLDCC is widely used in buildings such as precast architectural panels, partition walls, noise-abatement structures, masonry blocks, and ground stabilization structures (Chica & Alzate, 2019). However, there are few studies on design and construction guidelines for the use of PLDCC in parking lots and roads.

Averyanov (2018) investigated the long-term performance of PLDCC as an alternate to aggregate subbase layers in highways. The study concluded that the pavement with the PLDCC subbase was more durable than the road with granular aggregate materials of the same thickness. Prior to this, Decký et al. (2016) reported several case studies in which PLDCC has been used as a road construction material. Although the limited published studies agree that PLDCC can be a suitable highway construction material, its usage in permeable parking lots is not well addressed. Typically, PLDCC is used in road construction as a load-bearing material where a minimal amount of water percolates from the road surface to the underlying PLDCC layer. However, in permeable paving, the PLDCC performs the dual function of a load bearing and a permeable reservoir layer.

The strength and permeability of PLDCC are mainly derived from its density. In this respect, Mohd Sari and Mohammed Sani (2017) reported that the density of PLDCC used in various construction applications ranges from 300 to 1800 kg/m^3. Previously, the usage of 400–500 kg/m^3 of cellular concrete in road construction over a soft organic underlying soil in Illinois was shown to perform well, with a lower unit cost, shorter installation time, and higher quality of material (Decký et al., 2016). More recently, Averyanov (2018) examined the use of PLDCC with a density of 475 kg/m^3 in highway construction. The choice of PLDCC with densities of between 300 and 600 kg/m^3 is related to pavement construction applications as it provides soil stabilization and road construction functions (Ni et al., 2020). However, as the recommended density of PLDCC is half that of water, there can be significant buoyant forces when water percolates into the PLDCC layer, thus causing damage to the permeable paving. Hence, rather than replacing the entire aggregate reservoir layer, only half of it is replaced with PLDCC in the present study.

2.2. Permeable parking lot design and materials

Although constructed as a typical parking lot with various layers of concrete and aggregates, the main difference in the permeable parking lot is the need for strength to withstand traffic loads along with the requisite permeability for good run-off storage. The permeability depends on the void content of the layer, and the storage capacity depends on both the void content and layer thickness. In general, surface layer with around 20% air voids exhibits appropriate compressive strengths for application in parking areas subject to moderate truck traffic (Eisenberg et al., 2015). Meanwhile, the aggregate layer thickness depends on the hydrologic design, vehicle loading, and frost depth. The aggregate layer should be composed of clean, open-graded aggregate with no fines, while a void space of 36–42% and a minimum thickness of 300 mm–450 mm are recommended in cold climates (Eisenberg et al., 2015).

In permeable paving designed with PLDCC, a surface overflow during rainfall events may arise due to a sudden change in permeability at the interface between different layer materials. In conventional permeable paving, the surface concrete and aggregates have high permeability. Thus, if the aggregate layer is replaced by the comparably low-permeability PLDCC, there will be a sudden drop-in infiltration rate and, thus, an overflow. Hence, it is crucial to examine the infiltration rate of the permeable paving with various layers as a system.

2.3. Quality of runoff from permeable parking lots

Permeable parking lots are typically designed with either retention or detention purposes in mind, where retention allows the runoff to percolate into the underlying soil while detention facilitates the temporary storage and later release of runoff into the existing storm drainage system. While both detention and retention designs help to reduce flash flooding by supporting the reduction of peak runoff, the choice of design depends critically upon the condition of the underlying soil. Irrespective of this choice, the quality of stormwater released from the permeable paving must be checked to ensure that can be safely allowed to percolate through the underlying soil or be released into the existing stormwater system.

For an extended period, researchers have investigated the runoff purification capacity of permeable paving. Thus, permeable paving is known to reduce the levels of pollutants such as suspended nitrogen, phosphorous (Kim et al., 2017), heavy metals such as zinc and copper (Haselbach et al., 2006; Turco et al., 2020), dissolved salts, and suspended solids (Tota-Maharaj et al., 2012). Meanwhile, granular materials such as sand and gravel have been used as filtration media due to their capacity to retain precipitates containing impurities (Paul and Tota-Maharaj 2015). The granular material also screens out most of the bacteria. However, while numerous studies have been published on runoff purification using permeable paving with aggregate layers, very few studies have been conducted on permeable paving with PLDCC (Ramsey, 2017). In the latter design, the natural aggregates are replaced by cementitious material and other chemical additives. While the fine mesh texture of PLDCC traps the precipitates, it may alter the runoff quality as the water percolates through the cementitious material. Hence, there is a risk of groundwater and downstream surface water pollution if the PLDCC runoff is not of acceptable quality.

With the above aspects in mind, the present study is aimed at attaining the following three objectives for examining the use of PLDCC in permeable parking lots:

i. To examine the suitability of PLDCC as an alternative to aggregate layers in permeable paving by investigating its strength and permeability.
ii. To compare the water quality as it percolates through a conventional permeable paving (porous concrete and aggregate layer) and to propose an alternative permeable paving in which 50% of the aggregate layer is replaced by PLDCC.
iii. To compare the infiltration rate of permeable paving made with and without PLDCC.

3. Methods

The study objectives were accomplished through the following three stages of lab testing: (i) testing and selection of PLDCC mixtures; (ii) comparison of the water quality obtained from conventional permeable paving with aggregate layer vs. the proposed permeable paving in which 50% of the aggregate layer is replaced by PLDCC; and (iii) the development and infiltration-rate comparison of permeable paving sections with and without the PLDCC.

3.1. *Stage 1: testing of various PLDCC mixtures and selecting a suitable PLDCC for use in permeable paving*

In the first phase of laboratory testing, the PLDCC was developed by varying its density. Visual surface texture and permeability tests were performed to select the suitable density for permeable paving. Then, PLDCC samples with the selected density were prepared and tested for permeability and compressive strength.

3.1.1. *Mix design of permeable low-density cellular concrete*

PLDCC is a mixture of cementitious materials (Portland cement and pozzolan materials), water, a stable preformed foam, and, in some cases, fine aggregates such as sand. Unlike the Portland cement concrete, there are no standard mix design procedures for PLDCC. In general, a cement slurry or mortar is first prepared, and a preformed foam is then added. The density of PLDCC is verified against the target density (e.g., 400 or 500 kg/m3). If the verified density of PLDCC is higher than the targeted density, then additional foam is added and mixed thoroughly, and the density is verified again. This process continues until the mix yields the required density.

The water-to-cement ratio (W/C) and cementitious content both affect the strength of the PLDCC. In the present study, a W/C ratio of 0.5 was used along with the following two types of cementitious material: (i) 100% Type I Portland cement, and (ii) a 50:50 blend of Type I Portland cement and Class C fly ash. To produce the PLDCC, AQUAERiX™ foam concentrate was diluted with water in the proportion of 1:40. The diluted solution was then converted into a fine micro-bubbled foam by being discharged the solution through a foam generator (compressed air equipment) as showed in Fig. 1a. The resulting foam was then added to the premixed cement slurry and mixed thoroughly with a handheld cement grout mixer. The density of the fresh foamed concrete was then verified against the target density.

Trial designs were conducted on PLDCC with densities varying from 320 kg/m^3 to 1041 kg/m^3. The test results suggested that the PLDCC with a density of less than 400 kg/m^3 was too weak and tended to crumble during handling (shown in Fig. 1b), whereas densities above 512 kg/m^3 resulted in a smooth, non-porous surface (shown in Fig. 1c). Hence the two densities of 400 kg/m^3 (25 PCF) and 512 kg/m^3 (32 PCF) were selected for further testing. The selected densities also match the recommended density range of 400–600 kg/m^3 for the use of PLDCC as an alternative to aggregates.

Table 2 presents the mix designs (both weights and volumes of ingredients) for producing one cubic meter of PLDCC. PLDCCs are

Table 2
Mix designs of the PLDCC.

Ingredient Weight/Volume	PLDCC 1	PLDCC 2	PLDCC 3	PLDCC 4
Cement (Kgs)	250.00	125.00	325.00	162.50
Fly ash (Kgs)	0.00	125.00	0.00	162.50
Water (Kgs)	125.00	125.00	162.50	162.50
Volume of Cement (m^3)	0.079	0.040	0.103	0.052
Volume of Fly ash (m^3)	0.000	0.048	0.000	0.063
Volume of Cement (m^3)	0.125	0.125	0.163	0.163
Volume of Foam (m^3)	0.796	0.787	0.734	0.723

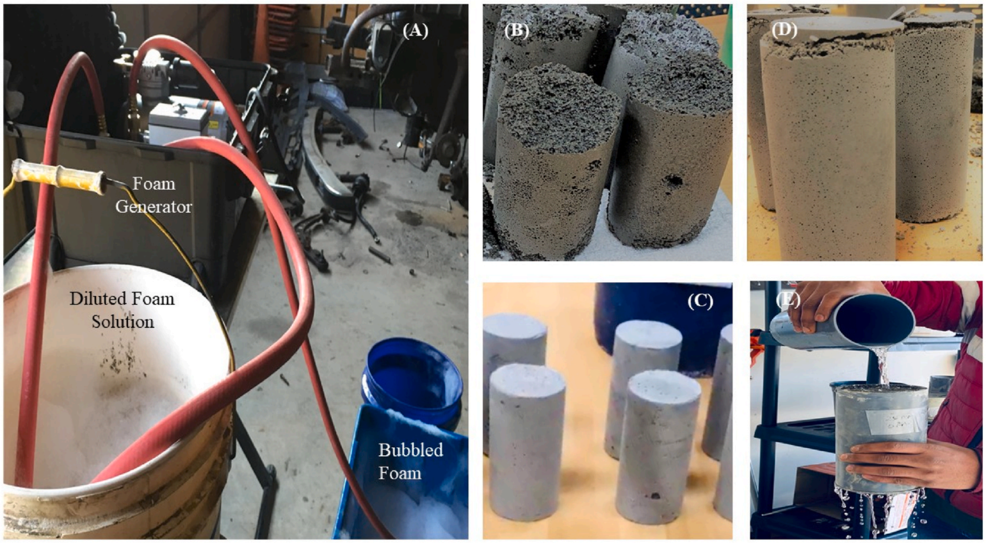


Fig. 1. a) Foam Generator, b) Crumbled PLDCC (Density <400 kg/m^3), c) PLDCC (Density >512 kg/m3), d) PLDCC 512 kg/m^3, e) Water dripping through the PLDCC (Density 400 kg/m^3).

designated hereafter as PLDCC-1 (Density 400 kg/m^3, 100% cement), PLDCC-2 (Density 400 kg/m^3, 50:50 cement/fly ash), PLDCC-3 (Density 512 kg/m^3, 100% cement), and PLDCC-4 (Density 512 kg/m^3, 50:50 cement/fly ash). Fly ash is commonly used in producing the PLDCC. Moreover, various researchers examined the performance of PLDCC with cement replaced with fly ash (Jose et al., 2021; Chen et al., 2021, and Liu et al., 2020a). They confirmed that the addition of fly ash benefits the PLDCC. Hence, the current study tested PLDCC samples with and without fly ash.

3.1.2. Compressive strength testing

As test specimens, three 3 x 6-inch cylinders were cast using each of the PLDCC formulations. The cylinders were cured at room temperature (25 °C) for 28 days. The compressive strengths of the PLDCC specimens were tested as per the ASTM C495/C495M – 12 standard method for testing the compressive strength of lightweight insulating concrete.

3.1.3. Permeability

The most common type of laboratory test employed to measure hydraulic conductivity (permeability) is the falling head permeability test as shown in Fig. 2a (Lederle et al., 2020; Schaefer and Wang, 2006; Xie et al., 2019). Here, the water flows through the permeable concrete samples from the bottom up through a reservoir pipe with an inner diameter of 102 mm. The difference in height between the upstream water and the water outlet acts as the driving pressure head. Earlier researchers used top-down, horizontal, or bottom-up approaches to test permeability (Lederle et al., 2020). This study chooses the bottom-up approach as it enables permeability measurement even for small pressure heads, and the operator has better control to start and stop the test.

In the present work, the PLDCC samples were sealed with rubber membranes on their sides to ensure a flow of water in the vertical direction only as shown in Fig. 2b. The sample was firmly secured to the setup using clamps. Initially, the sample was saturated by opening the ball valve, which was subsequently closed to allow the water to fill the reservoir to a level 203 mm above the sample height. The water could then be allowed to flow through the sample by opening the ball valve again. The time was recorded for the reservoir level to drop from a predetermined starting mark to a predetermined stopping mark. The test was repeated multiple times for various pressure head drops (50 mm–200 mm in an increment of 50 mm), and the permeability was calculated according to the water-level dropping time in cm/h. The average permeability at various head drops is reported.

3.2. Stage 2: comparison of the water quality obtained using the conventional permeable paving with an aggregate layer vs. that obtained using the proposed design in which 50% of the aggregate layer is replaced with PLDCC

In this stage, the effluent quality obtained from the proposed permeable paving is compared with that obtained from the traditional permeable paving in terms of pH, total dissolved solids (TDS), alkalinity, zinc, and copper contents. The pH of the water is crucial because a minute change in pH can affect the water chemistry and have an adverse impact on aquatic life if the effluent is released to the water bodies like lakes and rivers. In this respect, the alkalinity of the water is crucial as a suitable buffer is needed to avoid a sudden shift in pH, which would not be healthy for the aquatic life. Meanwhile, the TDS test provides a qualitative measure of the number of dissolved ions. An elevated TDS may cause the water to be corrosive or result in scale formation. Zinc and copper are the most common metals found in urban runoff that is discharged into water bodies (Sakson et al., 2018).

Earlier studies used urban runoff to examine the effectiveness of permeable paving. In the present study, however, potable water was used to understand how the PLDCC alters the water quality. Instead of simply testing the effluent quality from all the layers together as one system, effluent samples were collected at various stages of passage through the layers (i.e., surface concrete only, surface concrete + aggregates, and surface concrete + aggregates + PLDCC). By this approach, the role of PLDCC in improving or degrading the water quality can be elucidated.

The test setup developed for this assessment is shown schematically in Fig. 3. Thus, the parking lot materials were compacted in plastic containers of around 3 liters in volume. The bottom surface of each container was perforated with multiple 1-mm holes to allow easy drainage of the water. Each container was then stacked according to the sequence shown in Fig. 3.

Thus, during the test, 1.5 L of potable water (50% of the container volume) were first passed through the porous surface concrete, then a 100-ml sample was removed for testing while the remaining water was allowed to pass on through the aggregate layer. Another 100-ml sample of the output water from the aggregate was then taken, and the remainder could pass through the PLDCC. Since any fine dust particles

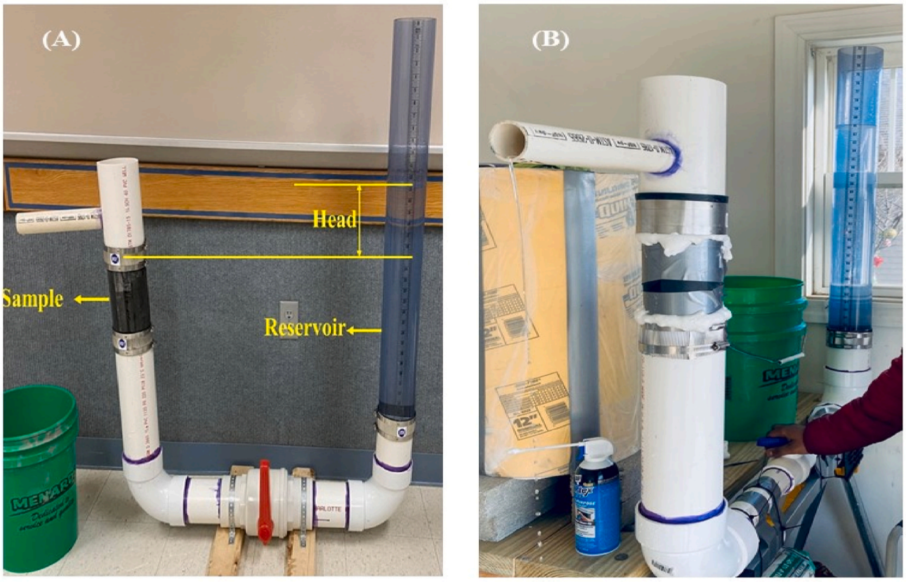


Fig. 2. a) The falling head test apparatus, b) Testing the permeability of PLDCC 1.

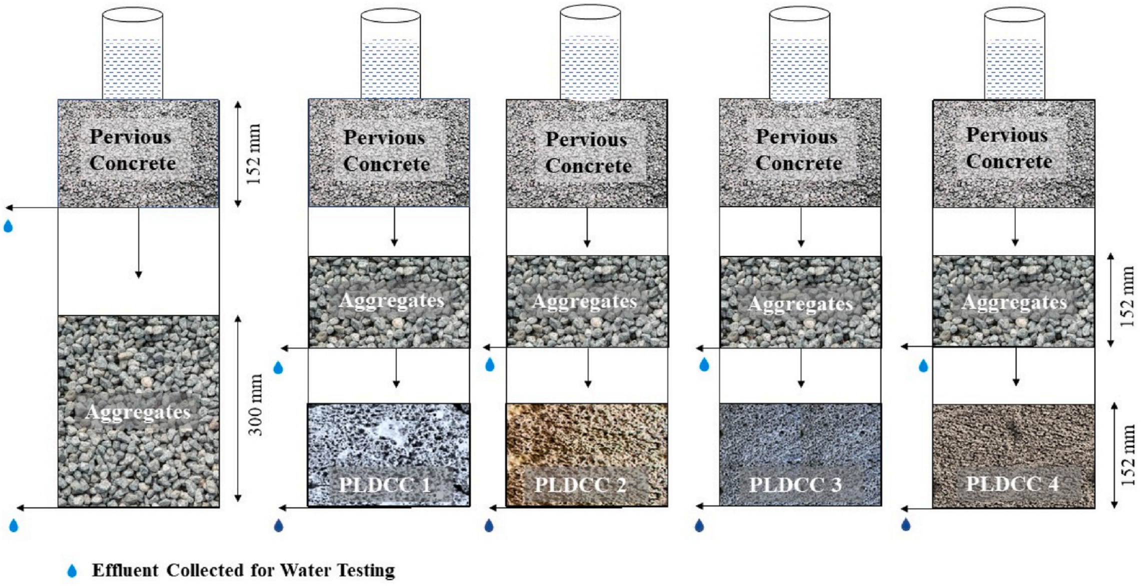


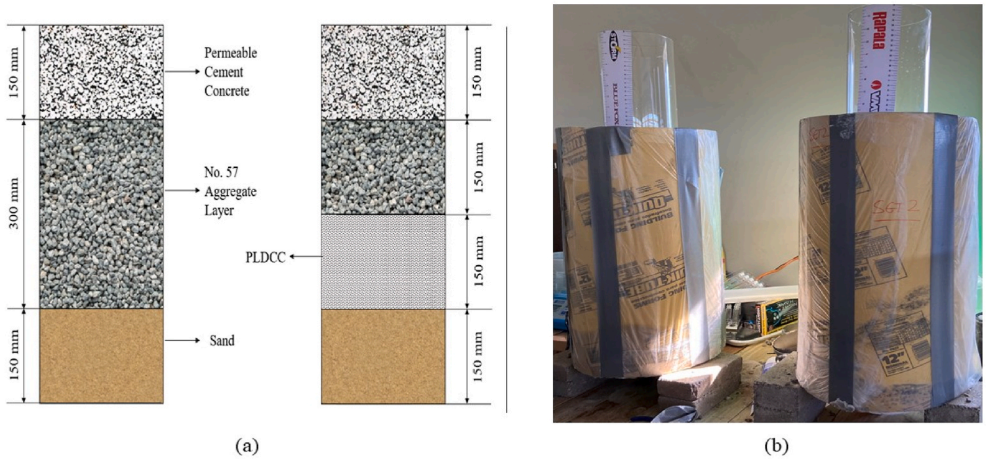
Fig. 3. Laboratory setup for effluent testing from various permeable paving designs.

present will adhere to the aggregate and concrete surfaces, the initial effluent may contain dirt and, hence, might not be a representative sample. Hence, in order to understand the variability in effluent quality, the tests were performed for 25 cycles, where one cycle indicates the passage of 1.5 L of potable water through the permeable paving layers with the sampling of the effluent from each layer for subsequent testing. The alkalinity, zinc content, and pH were measured using a Hanna multimeter photometer (HI83399), while the high-range Hanna HI702 copper colorimeter was used to measure the copper content. The TDS was measured using a Vivosun TDS meter.

The permeable paving sections were selected according to the recommendations of Eisenberg et al. (2015) and Kumar et al. (2016). The porous cement concrete top layer was designed for an air void content of 20% and the calculations were performed according to the American Concrete Institute (ACI) 522 R-14. The water-to-cement ratio was 0.29, with a cementitious content of 267 kg/m^3 (75% type I Portland cement and 25% Type C fly ash). The aggregates used in the study consisted of a blend of 55% coarse aggregates with a nominal maximum size of 19 mm and 45% aggregate chips with 9.5 mm nominal maximum size. While the 19-mm aggregates were open-graded, the chips were single-sized aggregates. Both type of aggregates is of limestone. No fines were used in the concrete, and a superplasticizer admixture was added. Three 4-inch by 8-inch cylinders were tested for 28-day compressive strength. Rather than rodding the cylinder with a 1-inch rod, which is common practice, a 2.5-kg proctor hammer with a 305-mm drop was employed in the present study to replicate the effects of roller compaction. The concrete cylinders were cast in four layers, and each layer was compacted 25 times using the proctor hammer. The measure concrete porosity is ~20% when tested according to ASTM C1754/C1754M – 12 on 4-inch by 8-inch cylinders.

3 Stage 3: The development of permeable paving sections with and without PLDCC for the comparison of infiltration rates.

While the falling head test set-up shown in Fig. 2 measures the permeability of independent PLDCC and concrete materials, stage 3 assesses the infiltration rate of the overall paving system. Stage 3 tests the reduction in infiltration rate due to the inclusion of the PLDCC layer in the permeable parking according to ASTM C 1701/1701M-17a. For comparison, the infiltration test was conducted on conventional permeable paving and on the developed permeable paving in which 50% of the aggregate layer was replaced with PLDCC 3, as shown in Fig. 4. While PLDCC layer requires no compaction, the other layers are compacted using a 2.5 kg proctor hammer in 50 mm layers.



(a)

(b)

Fig. 4. Infiltration test: (a) schematic diagrams of the permeable paving with and without PLDCC; b) the laboratory sections.

For the infiltration test, a 152-mm diameter infiltration ring was placed above the top concrete surface and fixed in place with plumber's putty to create a watertight seal (shown in Fig. 4b). The surface was then pre-wetted with 3.6 kg of potable water poured into the infiltration ring and the time at which no free water remained on the pervious surface was recorded. Within 2 min after pre-wetting, 3.6 kg of potable water was poured into the infiltration ring. The time was recorded as soon as the water touched the pervious concrete surface, and the timer was stopped when no free water was visible on the surface. The infiltration was calculated using Eq. (1):

$$I=\frac{kM}{(D^2\ t)} \tag{1}$$

where I is in the infiltration rate (cm/h), M is the mass of water (kg), D is the diameter of the infiltration ring (cm), t is the time (s), and k is a constant.

4. Results and discussion

4.1. Compressive strength and permeability of PLDCC

The results in Fig. 5 indicate that the compressive strength of the PLDCC increases, and the permeability decreases, with increasing density. Thus, the compressive strengths range from 0.6 to 1.8 MPa across the PLDCC density range of 400–512 kg/m^3. Meanwhile, the permeability decreases from ~1800 cm/h for the PLDCC-1 to 500 cm/h for the PLDCC-3 and reaches a minimum of 300 cm/h for the PLDCC-4. Thus, the addition of fly ash is found to reduce the permeability of the PLDCC.

The compressive strength results are consistent with the findings of Averyanov (2018), who reported a compressive strength range of 0.5–1.5 MPa across the density range of 400–600 kg/m^3. Moreover, the same study employed a falling weight deflectometer to demonstrate that cellular concrete with a similar density, when used as a subbase layer in highway construction, exhibits a better elastic modulus than that of the aggregate layer.

The surfaces of the four PLDCC samples are shown in the photographic images in Fig. 6. While the PLDCC-1 and -2 have theoretical air volumes of 78–80% (Table 2), the PLDCC-3 and -4 have theoretical air volumes of around 72–73% (Table 2). Thus, the size of the air voids decreases with increasing density and with replacement of the cement with fly ash in the PLDCC, thus resulting in lower permeability. Considering the previously reported infiltration rate of 25–3600 cm/h for crushed gravel (Borgwardt (2006); Miyagawa (1991)), the permeability range of 300–1800 cm/h observed in the present study demonstrates that the PLDCC can provide a comparable performance. However, it should be noted that the lateral flow of water is restricted in permeability testing whereas the infiltration test allows the water to flow in all directions. Hence the measured infiltration rates are typically higher than the permeability numbers for the same material. The compressive strength and infiltration rate of the surface porous concrete layers used in phases 2 and 3 of the present experimental study were 14.5 MPa and 4125 cm/h respectively.

4.2. Infiltration rate of permeable paving sections with and without PLDCC

Infiltration tests are conducted on the permeable paving sections shown in Fig. 4. Table 3 presents the results of the pre-wetting and infiltration rate for paving sections with and without PLDCC.

The pre-wetting infiltration rate of the permeable paving with the aggregate reservoir layer is 7621 cm/h, while that of the aggregate reservoir layer with partial replacement by PLDCC is 7948 cm/h. Within 2 min of prewetting test, another test is performed referred in the table as infiltration test. The infiltration rate of the paving section with PLDCC layer was observed to decrease by 1795 cm/h, while that of the permeable paving + aggregate layer was 3357 cm/h. It should be noted, however, that the lateral movement of water was restricted in the present test such that the runoff was constrained to travel through the bottom layers. The present authors believe that there will be an improvement in the infiltration rates of the traditional and proposed permeable paving designs if the test is performed in the field. Nevertheless, the present test indicates that the potential of runoff overflow exists during heavy precipitation if a high-density PLDCC is used. Hence, a suitable PLDCC density must be selected according to the regional intensity, duration, and frequency of precipitation.

4.3. Comparing the quality (pH, alkalinity, and TDS) of effluents from the various layers

The pH, alkalinity, and TDS values of the effluent from each permeable paving layer during 25 cycles are plotted in Fig. 7 through 9 and summarized in Table 4. Here, no significant differences are observed between the various types of contaminants across the 25 cycles. Hence, the average results are discussed in the following paragraphs.

The potable water used in this phase has an average pH of 7.2, an alkalinity 66 mg/l as $CaCO_3$, a TDS of 293 ppm, and zero metals (zinc and copper). After percolating through 152 mm of permeable concrete (green dash-and-dot line, Fig. 7 through 9), the pH, alkalinity, and TDS are seen to have increased to 10.4, 155 mg/l ($CaCO_3$), and 495 ppm, respectively. No zinc is detected in the effluent but, during the initial cycles, a minute amount of copper (0–0.12 mg/l) is observed (Table 4). Thus, the TDS in the effluent is about 500–600 ppm during the initial five cycles and subsequently decreases to 360 ppm by the 25th cycle.

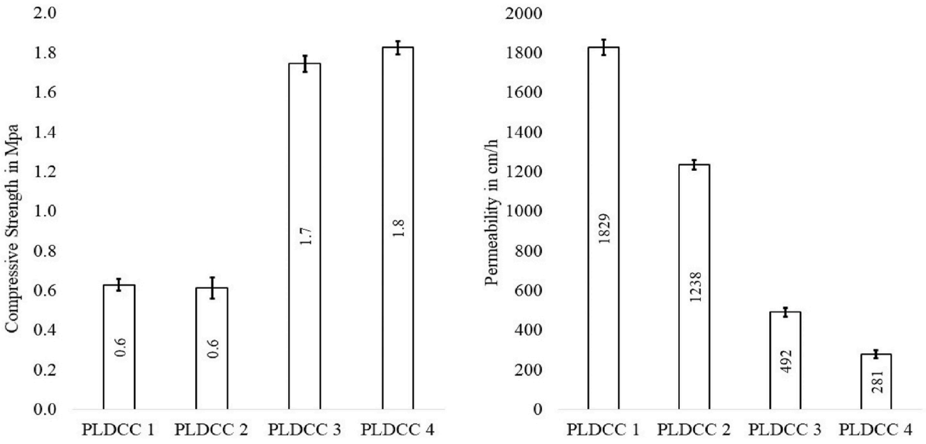
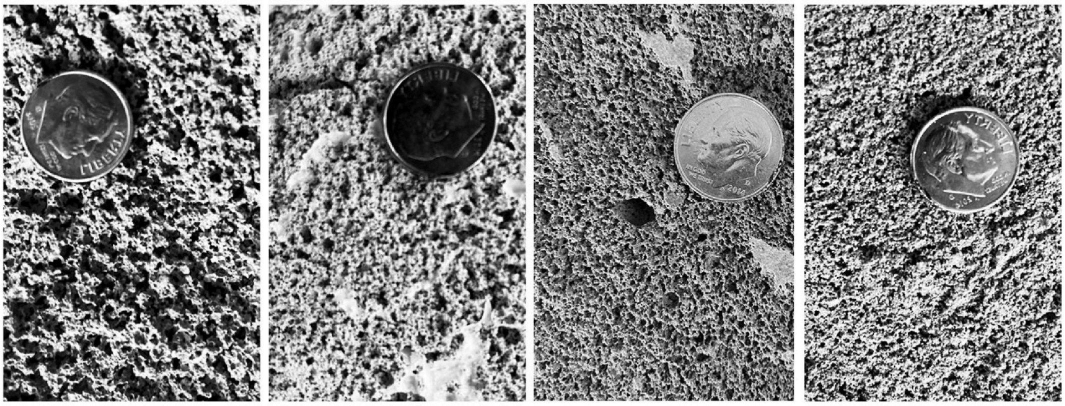


Fig. 5. The compressive strength and permeability of various PLDCC samples.



PLDCC 1 **PLDCC 2** **PLDCC 3** **PLDCC 4**

Fig. 6. Photographic images of the various PLDCC surfaces.

Table 3
Infiltration rates for permeable paving sections with and without PLDCC.

Permeable Paving Section	Time in seconds for infiltration of 3.6 kgs of water		Infiltration Rate (cm/h.)	
	Prewetting	Infiltration Test	Prewetting	Infiltration Test
Set 1 Without PLDCC (150 mm Pervious Concrete + 300 mm Aggregate Layer)	9.45	21.45	7621	3357
Set 2 Without PLDCC (150 mm Pervious Concrete + 150 mm Aggregate Layer + 150 mm PLDCC 3 Layer)	9.06	40.12	7948	1795

Meanwhile the pH of the effluent from the permeable concrete remains constant at around 10.4 over the entire 25 cycles, while the alkalinity decreases. Further, when the effluent from the permeable concrete is passed through the aggregate layers (grey dotted line, Fig. 7 through 9), the quality of runoff is seen to improve. Thus, the pH decreases from 10.4 to 9.9, the alkalinity decreases from 155 mg/l to 68 mg/l, and the TDS decreases from 495 to 404 ppm. While no zinc or copper is detected in the effluent from the aggregate, dirt is present during the initial three to five cycles (Table 4).

Finally, the effluent from the aggregate layers is percolated through 152 mm of PLDCC. The results in Fig. 7 indicate that the pH of the effluent approximately 12.5 across the four PLDCC types, while the alkalinity is increased (Fig. 8). Thus, the effluent from PLDCC-1(orange line with filled orange squares) and PLDCC-2 (purple line with filled purple circles) has an alkalinity of 480–485 mg/l as $CaCO_3$, while that of the effluents from PLDCC-3 and PLDCC-4 is higher than the equipment measuring capacity of 500 mg/l. Further, the TDS of the effluent is increased from 404 ppm for the aggregate to 3420 ppm for the PLDCC-1, 1672 ppm for the PLDCC-2, 4430 ppm for the PLDCC-3(red line with filled red rhombus), and 3250 ppm for the PLDCC-4 (green line with filled green triangles). The high alkalinity and TDS of the effluents from the PLDCC-3 and -4 samples are due to the extended time that the water is in contact with these PLDCCs due to their lower permeabilities. It is also noted that the samples containing fly ash produce effluents with lower TDS and alkalinity than those obtained from the samples without fly ash.

To examine the statistical significance of the measured changes in the pH, alkalinity, and TDS of the water as it passes through the various layers, the student's t-test was performed. The statistical parameters imply a significant difference in the contaminant levels as the potable water percolates through the porous concrete, then through the aggregate layer, and then through the PLDCC. However, no significant difference is indicated in the contaminant levels of the effluents from the

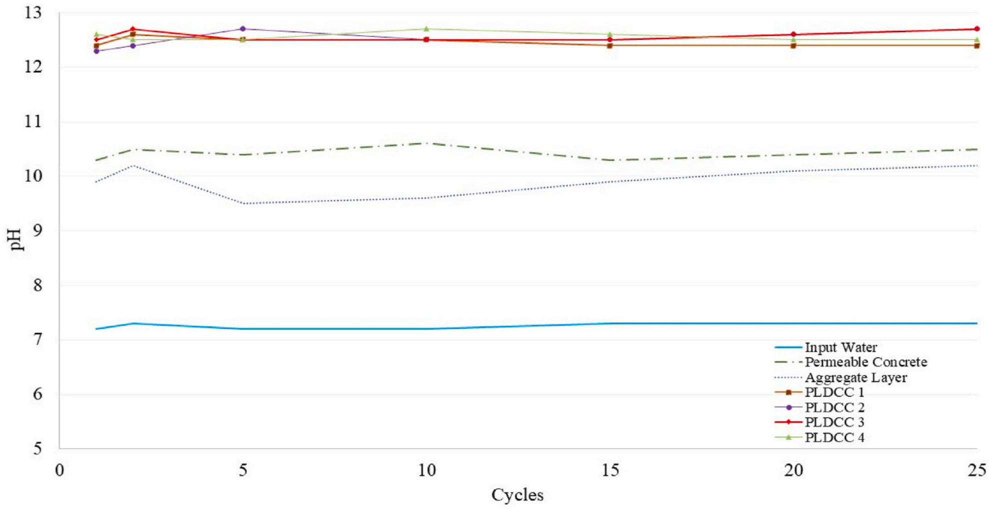


Fig. 7. Effluent pH of across various types of PLDCC and other pavement layers.

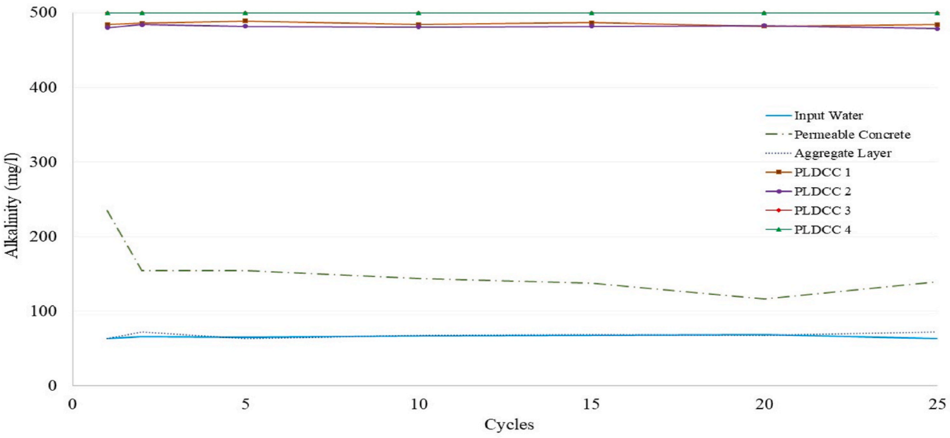


Fig. 8. Effluent Alkalinity of across various types of PLDCC and other pavement layers.

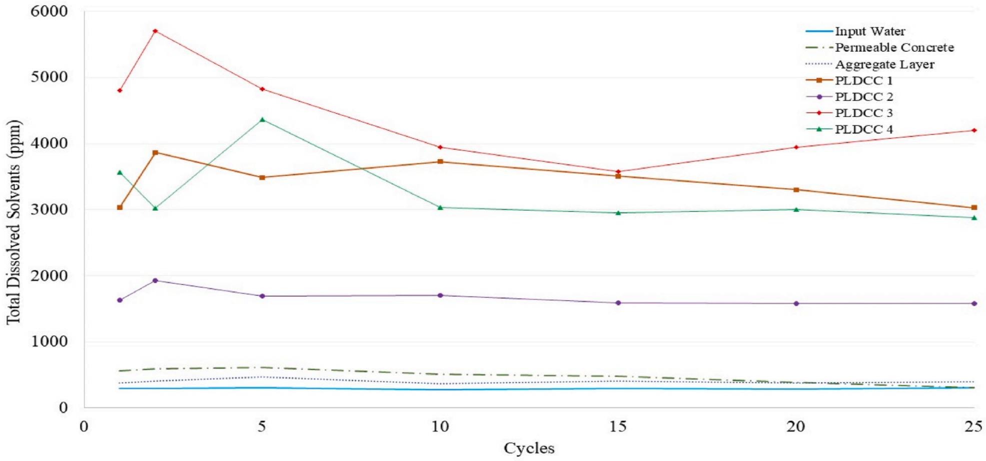


Fig. 9. Effluent Total Dissolved Solvents of across various types of PLDCC and other pavement layers.

Table 4
Quality of effluents obtained from the various layers of conventional and proposed permeable paving designs.

Contaminant	US EPA secondary drinking water	Potable water used in the present study	Permeable concrete	Aggregates	PLDCC types			
					1	2	3	4
pH	6.5–8.5	7.2	10.5	9.9	12.5	12.5	12.6	12.6
Alkalinity (mg/l)	<250	66	150	68	485	481	>500	>500
TDS (ppm)	<500	293	478	404	3420	1672	4428	3258
Copper (mg/l)	<1.0	0.00	0.04	0.00	0.24	0.25	0.73	0.63
Zinc (mg/l)	<5.00	0.00	0.00	0.00	1.01	1.08	1.65	0.81

four distinct PLDCC designs. This result is comparable to that obtained in a previous study by Ramsey (2017) on various types of cellular concrete, where the pH of the effluents were around 12.5 with no significant difference between the types of cellular concrete.

Even though the infiltrated runoff from permeable paving is not used for drinking purposes without treatment, Table 4 compares the effluent quality with the US EPA secondary drinking water regulations in order to better understand the performance of the conventional and proposed permeable paving designs. Here, the effluent from conventional permeable paving (Aggregate's column) has a higher pH than the US EPA standard, while the other contaminants are all within the regulations. By contrast, the effluent from the PLDCCs has a higher pH, alkalinity, and TDS than the regulation values. This result may lead to the hasty conclusion that the effluent from PLDCCs is contaminated and, hence, incurs the risk of groundwater and downstream surface water pollution. However, the present authors believe that the quality of the runoff that seeps into the permeable paving plays a role here. In this respect, Ramsey (2017) demonstrated that hydrated cellular concrete can be beneficial for the removal of dissolved inorganic nutrients such as nitrates from water systems. Moreover, Martemianov et al. (2017) reported that cellular concrete can be used for the abatement of aqueous arsenic and heavy metals.

5. Discussion

This study proposes a partial replacement of the aggregate base with PLDCC (50% thick aggregate layer replaced with PLDCC). Hence, the proposed pavement structure is a three-layered system (Pervious concrete, aggregate layer, and PLDCC). The vehicle load is distributed between these three layers, with the top two layers carrying the maximum load, and PLDCC takes less load. Although the compressive strengths of PLDCCs shown in Fig. 5 seem of concern, here, the PLDCC is not the structural concrete; instead, it is used as a sub-base layer. Typically, the PLDCC is 5–10 times stronger than an average compacted soil or granular material (Taylor and Halsted 2021; Maher and Hagan 2016). Moreover, the overall weight of PLDCC is lower than soil or aggregate layers reducing the burden on the soil. Hence, PLDCC can be considered as a sustainable replacement for aggregates in permeable parking. It reduces the usage of virgin aggregates and minimizes aggregate transportation which are considered as the best practices in aggregate sustainability by Van Dam et al. (2015).

Studies conducted by Averyanov, S. (2018) on examining the long-term performance of cellular concrete as a subbase material revealed that no structural failure occurred in the pavements constructed with cellular concrete as a subbase. In the present study, we used a similar PLDCC density as Averyanov. S. (2018). This study expects PLDCC supports the parking system to withstand the load for long-term parking vehicles. However, a future study is warranted to study the longstanding loads on the proposed sections.

One of the common concerns of permeable paving is clogging of the porous surface with dirt, thus reducing the infiltration capacity. However, does replacing the aggregate layer partially with PLDCC, which has a sponge-like texture accelerate the clogging in the permeable pavements? Although the current paper authors agree that clogging is a problem in permeable paving, we differ that the PLDCC usage will accelerate the clogging. In this respect, we refer to previous studies on the long-term performance of permeable parking lots, which indicates that the clogging in permeable parking is mainly in surface layers.

I. Kayhanian et al. (2012) examined 20 permeable parking lots in California and tested their permeabilities. They identified that the most clogging occurs near the pavement's surface and the drop in permeability is proportional to the age of the parking lot. They concluded that it is easier to remove the surface particles by vacuum or other cleaning mechanisms.
II. Kumar et al. (2016) investigated the four-year performance of an employee permeable parking lot in Chicago. They identified a decline in infiltration rate in four years, yet, the infiltration rates were four to five times higher than regional rainfall. They identified the drop in the infiltration rate varied across various surface layers, indicating the importance of the surface layer. They concluded that clogging could be countered by suction cleaning as preventive maintenance and by high-pressure water jet washing followed by suction as remedial maintenance.

In the proposed study, we placed PLDCC 300 mm below the parking lot surface, and we hypothesize that it will have less influence on system clogging. However, a future study is warranted to examine our hypothesis.

6. Conclusions

This study investigated the suitability of PLDCC as a subbase layer for permeable paving. The following are the key findings of the study:

- The critical contribution of the study is that the PLDCC can be effective as a subbase material and can partially replace thick aggregate layers in permeable parking construction.
- This study investigated four PLDCC's as a subbase layer, and the lab testing revealed that PLDCC possesses adequate compressive strength (0.6–1.8 MPa) (Taylor and Halsted (2021)) and permeability (300–1800 cm/h).
- The infiltration rate of the paving section (pervious concrete + aggregate layer + PLDCC) with PLDCC is around 1795 cm/h, whereas without PLDCC is 3357 cm/h. Even though there is a drop-in infiltration rate in paving sections due to the inclusion of PLDCC, it is still within limits (500–7600 cm/h) proposed by Eisenberg et al. (2015).
- The PLDCC density is a crucial design parameter as it influences the strength, storage, and infiltration rate of permeable paving. The lower density of PLDCC provides higher permeability with low strength. This study recommends 512 kg/m^3 density PLDCC as it offers good strength with reasonable permeability.
- The effluent from the PLDCC has a higher pH and alkalinity compared with effluent from conventional permeable paving. However, previous studies have indicated that the PLDCC can help remove heavy metals (Martemianov et al. (2017))and nutrients (Ramsey (2017)) from runoff. Hence, future research on the effectiveness of PLDCC in the purification of urban runoff needs to be investigated further.
- Since PLDCC is a lightweight material, it can cause buoyancy forces during rainfall events and damage the parking surface. Hence, permeable parking lots with PLDCC need to be designed appropriately. A future study is required to guide the designers in developing buoyant free permeable parking lots by choosing appropriate PLDCC layer thickness, permeability, and density.
- Although many studies, including the present one, have stated that the PLDCC reduces the usage of natural aggregates and, hence, reduces the cost of hauling and environmental impacts. Further analysis is needed to validate this assertion by examining the overall benefits of PLDCC over aggregates.

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Declaration of 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.

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