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ORIGINAL ARTICLE

Evolution of Sustainable and Resilient Pervious Concrete Pavement Technologies in India

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Abstract

Pervious concrete pavement (PCP) systems are engineered roadway technologies that are known to mitigate stormwater runoff attributed to their high porosity. Though significant advancements have been made at the global level, research, and innovation pertinent to PCPs is still emerging in India. Therefore, the objective of this research was to present the evolution of PCP technology in the Indian context. The details pertinent to mix design and characterization, field construction and monitoring, and development of innovative PCP products were presented. Test results indicated that PCPs are suitable for applications in walkways, parking lots, and low-volume roads. It was further observed that the quality control with traditional construction practices was poor resulting in inconsistent mix properties. Though paver blocks offer superior quality products than conventional PCP, they suffer from low strength and maintenance issues. Therefore, recent research focused on designing Pervious All-road class All-weather Multilayered paver (PARAMpave) blocks, whose flexural strength and infiltration rates were higher than 4.8 MPa and 0.77 cm/s, respectively making them suitable for application in all-road-all-weather conditions. Further, PARAMpave consumes lower energy and generates fewer emissions during production. However, additional research must focus on construction of test sections by utilizing pervious concrete paver blocks and PARAMpave products to identify their performance during the design life.

Keywords Pervious concrete pavement construction · Pervious concrete paver blocks · PARAMpave · Environmental and economic lifecycle impacts · Performance monitoring

Introduction

In recent times, climate change has emerged as one of the major causes for deterioration of pavement infrastructure across the globe. The urban dwellers are exposed to an all-time high risk of flooding, harsh weather conditions, and urban heat islands, which not only affect the quality of life but also result in premature failure of pavements [1–3]. Therefore, there is an urgent need to identify and develop resilient pavement systems that address the threats posed by climate change. One such strategy is the design and construction of pervious concrete pavement (PCP) systems, which typically comprise a pervious base/sub-base layer (void content 20–40%) designated as reservoir layer overlying a compacted subgrade and underlying a pervious concrete (PC) surface wearing course (void content 15–30%) [4–6]. PC overlays are primarily designed with coarse aggregates, cement, and water to create an interconnected porous network that allows infiltration of stormwater in the underlying layers.

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Researchers have either used single-sized aggregates or a blend of different aggregate gradations to prepare PC mixtures. In general, the size of coarse aggregates used to design PC mixtures varied from 12.5 to 4.75 mm. However, some other studies have also utilized sand within the PC matrix as a partial replacement of coarse aggregates to address the problem of inherent low strength [7–12]. Further, a blend of different aggregate gradations (9.5 and 4.75 mm) are known to result in the production of PC mixtures with higher density and lower porosity compared to PC with single sized aggregates (9.5 or 4.75 mm) attributed to the ability of smaller aggregate particles to occupy the voids within the coarse aggregate skeleton [13].

Past studies reported that PCPs are sustainable drainage systems that have potential to negate the requirements for design of underground drainage network, which is an important component to collect and convey stormwater in conventional asphalt concrete and cement concrete pavements [5, 14, 15]. Researchers from Florida indicated that PCP systems were capable of allowing infiltration of stormwater even after twelve years of construction [16]. PCPs also act as filtering media, as they have the potential to capture sediments within their interconnected pores, thereby resulting in improved quality of runoff collected at the downstream end [17–19]. Test sections constructed in Ahmedabad, India did not show any signs of structural distress (after one year) and their infiltration rate was over 4.85×10^7 mm/year, which was higher than the average annual rainfall (~ 800 mm/year) in that region [20]. A recent field study conducted at the Indian Institute of Technology (IIT) Roorkee suggested that the porosity of field placed PC mixtures was lower than those of laboratory and the dosage of reclaimed asphalt pavement in PCP must be restricted to 50% as replacement of the virgin aggregates [21]. Arjun et al., evaluated the performance characteristics of PC paver blocks (PCPBs) and found that the highest mechanical strength was obtained for an aggregate blend of 12 mm (80%) and 6 mm (20%) [22]. PCPBs designed with a film thickness of 0.4 mm result in good balance between permeability and strength [23]. Further, the use of 30% recycled concrete aggregates as partial replacement of natural coarse aggregates do not compromise the structural and hydrological characteristics of PCPBs [24].

Despite multiple benefits, the interconnected porous network structure of PCPs is prone to clogging, which results in a reduction in the infiltration rate with passage of time. Studies have suggested that majority of the clogging media is entrapped in the top 10–30 mm of the PCP surface, which is consequential of the reduction in infiltration rate of these special pavements [25–28]. In order to address this limitation, different cleaning techniques have been adopted across the world, which include sweeping [29], pressure washing [30], vacuum cleaning [28], or their combinations based on site-specific requirements [6, 31]. Air pressure of 0.83 MPa and water pressure of 7.15 MPa were suitable to clean clogged PCP systems [31], while another investigation suggested that pressure wash within a range of 5–20 MPa had little effect on the maintenance efficiency [32].

It is well understood that while multiple efforts have been made at the global level to characterize PC material and further construct the PCP systems, only a few attempts have been made at the national level. Some recent studies conducted at the various Institutes of national importance have focused on designing the PC mixtures, investigating their performance characteristics, real-field implementation, performance monitoring, and developing traditional as well as new generation PC paver blocks [21, 22, 33–35]. However, there is limited awareness in India pertaining to the implementation and use-phase benefits offered by the sustainable PCP systems. Thus, the objective of this study was to discuss and present the information pertinent to the evolution of PCP technologies in India. The scope of the effort encompassed: (a) PC mix design, (b) construction of PCP demonstration test sections, (c) monitoring the rate of change in infiltration with time and progression of structural distresses by visual inspection, and (d) development of single and multilayered PC paver blocks. It is envisioned that this white paper will certainly build confidence amongst the implementation agencies to utilize the technology and construct these resilient pavement systems suitably to develop sustainable urban habitats.

Materials and Methods

Research at the Indian Institute of Technology Kharagpur

The research on development and characterization of PCP mixtures began at IIT Kharagpur (IITKGP), where 18 mixtures were designed and tested for different characteristics [36]. In general, PC mixtures with six distinct aggregate gradations, three levels of water-to-cement (w/c) ratios (0.25, 0.30, and 0.35), and three cement-to-aggregate (c/a) ratios (0.33, 0.25, and 0.20) were investigated. Further, the experimental program included structural investigations, namely, compressive strength, flexural strength, and fatigue, while the functional characterization tests included determination of permeability and pore structure properties. In addition, the durability characteristic in the form of abrasion resistance was also investigated. Note that the raw materials were tested for their quality using the relevant Indian Standards [37, 38], while structural characterization tests were performed in accordance with the American Society for Testing and Materials (ASTM) International protocols [39–41], and hydrological properties in the laboratory and field were assessed using falling head tests conforming to the standard procedures [42, 43]. Further, several other domains such as UHI mitigation, use of supplementary cementitious materials, and crumb rubber was also investigated [44–46].

Construction of Pervious Concrete Pavement Systems in India

The first PCP test section that comprised 18 PC slabs (each measuring 3 m × 2 m × 0.15 m) was designed from the laboratory studies and constructed with six different mixtures on-campus IITKGP in April 2017 using labor based on-site mixing. This test section served as a walkway / two-wheeler parking lot, and the details of mix proportions are presented elsewhere [36]. The second PCP demonstration test section (parking lot) was installed in March 2018 using on-site mixing method at the premises of Municipal Corporation of Tirupati (MCT) that was 125 m long and 4 m wide [34]. The slabs were designed with a single PC mix type where the w/c and c/a ratios were 0.32 and 1:3.75, respectively, while the aggregate gradation comprised 12.5 mm and lower sizes. The fresh PC mix was spread and laid within the formwork that was erected to create 4 × 4 × 0.15 m slabs. In May 2019, another PCP parking lot was constructed at the IIT Tirupati (IITT) campus (50 m long and 5 m wide) using ready-mixed PC, which was a first-of-its-kind effort in India where each PC slab had a dimension of 3.0 × 2.5 × 0.15 m [35]. The cross-section of the three PCP test sections is presented in Fig. 1.

Note that alternate PC slabs were constructed for the PCP systems installed at the IITKGP and MCT. However, slabs were continuously laid and simultaneously compacted at the IITT. Isolation joints were provided, and the mastic pads were tucked between two successive PC slabs. Further, the compaction and finishing at all the three test sections was performed by slowly moving a plate vibratory compactor (not more than 90 s per pass). A metal plate was placed underneath the plate vibrator to avoid its direct contact with the fresh PC mixture. Additional information pertaining to the construction steps involved in three case studies are presented elsewhere [33–35, 47].

Field cores of dimensions 100 mm diameter and 150 mm height were extracted to ascertain the porosity, density, and compressive strength immediately after the construction. The porosity and density was determined in accordance with ASTM C1754 [39], while the compressive strength was evaluated as per the procedure described in ASTM C39 [40]. Additionally, the structural and hydrological performance was monitored for a period of over three years by performing site inspections and conducting in-situ infiltration rate tests [42] on the PCP parking lots constructed at MCT and IITT [34, 35].

The environmental burdens produced by the PCP systems and conventional cement concrete pavements of similar configuration were identified and compared to assess their sustainability credentials. A first-of-its-kind methodology was developed for this research, which could be utilized to quantify the environmental impacts of different pavement systems in the field of pavement engineering [48].

Development of New Generation Pervious Concrete Products

Pervious Concrete Paver Blocks

With recent advancements in technology, the concept of PC paver blocks has emerged as a suitable alternative for conventional PCP systems [49, 50]. PCPBs can be easily fabricated using molds used for precast concrete blocks and can be laid on a prepared subsurface layer. This method of using PCPBs is anticipated to reduce the construction challenges and result in improved quality control. In addition, pavements with PCPBs can be made aesthetically appealing by using pigments, as shown in Fig. 2.

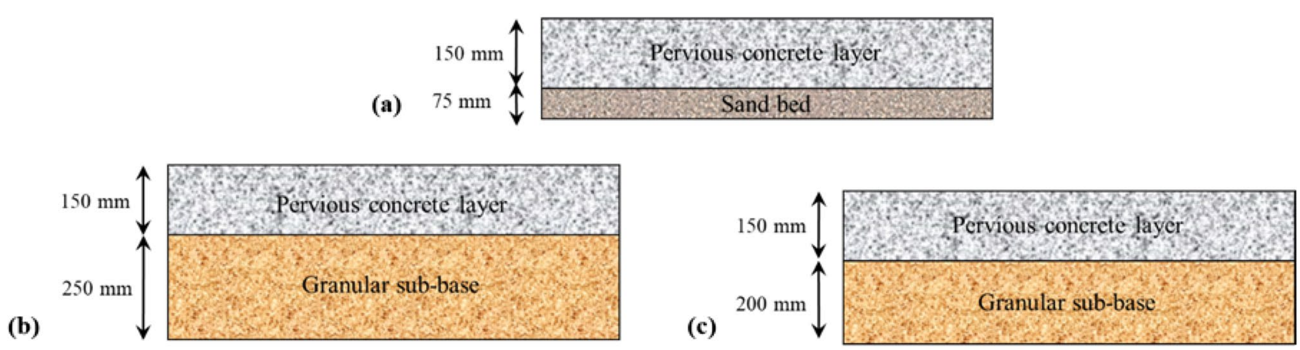

Fig. 1 Configuration of pervious concrete pavement test sections at the: **a** Indian Institute of Technology Kharagpur, **b** Municipal Corporation of Tirupati, and **c** Indian Institute of Technology Tirupati

Fig. 2 PCPBs with Different Shapes and Colors [50]

Pervious All-Road Class All-Weather Multilayered Paver Blocks

Recently, researchers at the IITT developed Pervious All-Road class All-weather Multilayered paver (PARAMpave) blocks that have a bottom structural layer of M40 and an upper water-draining PC wearing surface course [2, 51]. Two holes of 25.4 mm diameter were made across the full depth of PARAMpave to allow the infiltration of stormwater through the product. PARAMpave were tested for their structural and hydrological properties [2]. The top, bottom, and cross-sectional views of the PARAMpave system of products are presented in Fig. 3**.** Further, the PARAMpave blocks were characterized for their different performance characteristics as per standard procedures [9, 52, 53]. In addition, a cradle-to-gate lifecycle assessment was undertaken to assess the environmental burdens of these products that was conducted in accordance with International standards [54, 55] as per the procedure developed by the research team at IITT [48]. For lifecycle analysis, the primary data was collected by conducting interview surveys with the contractors and material suppliers, while the secondary data was collected from literature and published reports. Further, the characterization factors specified by the Intergovernmental Panel on Climate Change [56, 57] were used to compute the emissions. The system boundary for both environmental and economic analysis was kept consistent and additional details relevant to the inventory and assessment may be found elsewhere [2, 51].

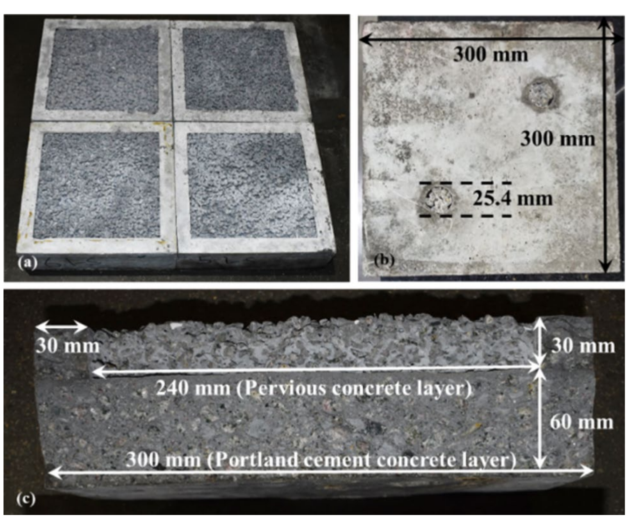

Fig. 3 PARAMpave system of products: **a** top view, **b** bottom view, and **c** cross-section

Prior to the development of these products, thirty six PC mixtures encompassing four aggregate gradations (two control and two sand-modified), and three levels each of w/c and c/a ratios were used to prepare cylindrical specimens (100 mm diameter and 200 mm height) that were characterized for their porosity, density, permeability, pulse velocity, rebound number, and compressive strength, whose results are published elsewhere [9, 51]. Later, the superior performing PC mixtures were ranked using hybrid multi-criteria decision-making framework and used for the design of PARAMpave products. The PC mix proportions that were used to develop PARAMpave products are tabulated in Table 1. The cement content was fixed at 325 kg/m^3, and sand was added as partial replacement of coarse aggregates by weight. Further, a polycarboxylic ether-based superplasticizer conforming to ASTM C494 [58] was added at a dosage of 0.25% by mass of cement.

Results and Discussions

Research at the Indian Institute of Technology Kharagpur

The results for different properties of PC are as follows: (a) porosity varied from 13 to 37%, (b) density ranged between 1750 and 2250 kg/m^3, (c) permeability varied from 0.1 to

Table 1 PC mix proportions for PARAMpave system of products

PARAMpave product ID	Aggregate size (mm)	Cement-to-aggregate ratio	Water-to-cement ratio
A	6.70	1:3.75	0.33
B	4.75	1:4.25	0.33
C	6.70 + 10% sand	1:3.75	0.27
D	4.75 + 10% sand		0.33
E	4.75 + 10% sand		0.30

5.0 cm/s, (d) compressive strength from 6 to 26 MPa, and (e) flexural strength varied between 1.5 and 3.2 MPa. These results indicated that PC material has high potential to mitigate stormwater flooding and is suitable for parking lots, medians, and low-volume roads. In addition, fatigue testing of PC beams gave a clear perspective on the effect of gradation, w/c ratio and c/a ratio. A mixture of aggregates with 50% passing 9.5 mm sieve and retained on 6.75 mm sieve as well as 50% passing 6.75 mm sieve and retained on 4.75 mm sieve with 0.35 w/c and 0.25 c/a ratios depicted significant fatigue life. Further, this mixture also balanced structural and functional requirements in terms of compressive strength and permeability, respectively [36].

Pervious Concrete Pavement Systems in India

The results for different properties of PCP systems immediately after construction are presented in Table 2. In addition, the infiltration rate after a period of over three years is also reported in Table 2. Based on the results presented in Table 2, the porosity of the parking lot constructed at IITT was about 22% higher compared to MCT, resulting in lower compressive strength. In other words, a 22% increase in porosity resulted in 58% decrease in compressive strength. Further, at the end of three years, the reduction in infiltration rate was substantial at the MCT majorly attributed to the deposition of soil and dust in the pores that were carried over the surface of PCP with stormwater from the adjacent areas [29, 51]. Further, the pavement was not adequately maintained during its service life and brooming the pavement surface daily was the only method used for cleaning, thereby highlighting the need for maintenance of PCPs with vacuum truck sweepers, pressure washing, and their combinations. Figure 4a and Fig. 4b depict the condition of PCP surface immediately after construction and three years later on-campus MCT. Based on these observations, it would be wise to suggest that the PCP sections must be isolated from the surroundings that have excess loose soil, which could easily flow over the surface of PC and cause accelerated clogging.

IITKGP Indian institute of technology kharagpur, *MCT* municipal corporation of Tirupati, *SD* standard deviation, *COV* coefficient of variation, and *IITT* Indian institute of technology Tirupati

Further, no reduction in the infiltration rate at IITT was noted ascribed to the fact that PCP was subjected only to the rainwater and stormwater from adjacent surfaces did not flow over the pavement. Therefore, appropriate maintenance strategies must be devised for PCPs constructed in areas subjected to heavy discharge of pollutants from stormwater, while regular brooming (once in two weeks) will be sufficient for PCPs exposed to only rainwater. Further, the major structural distresses were joint / edge deterioration, and raveling of aggregates from PCP [29] as presented in Fig. 5**.** In addition, poor quality control during construction owing to the lack of skilled labor was another concern that affected the overall performance of PCP slabs.

More so, the lifecycle assessment study results (see Table 3) indicated that PCPs are sustainable roadway systems whose environmental impacts were lower than that of conventional cement concrete pavements by about 3% irrespective of the mixing method, i.e., in-situ or ready-mixed concrete. Further, the capital cost analysis results (Table 3) suggested that for in-situ mixing, the PCPs were cheaper

Table 2 Infiltration rate of pervious concrete pavement systems immediately after construction and three years

S. No	Property	After construction							After three years				
		IITKGP	MCT	SD	COV	IITT	SD	COV	IITKGP	MCT	IITT	SD	COV
1	Porosity (%)	-	25	0.49	2.61	32	6.26	19.82	–	–	–	–	–
2	Compressive strength (MPa)	-	21	2.73	12.86	9	2.08	23.56	–	–	–	–	–
3	Infiltration rate (cm/s)	1.50	0.51	0.05	23.30	1.43	0.01	1.07	–	0.01	1.35	0.01	1.13

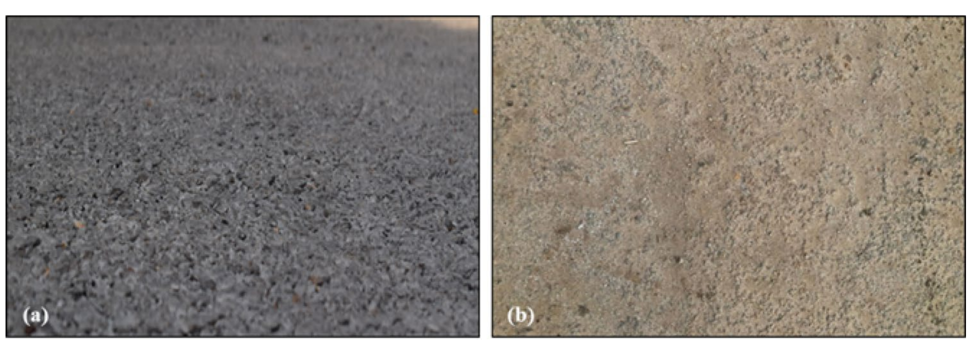

Fig. 4 Pervious concrete pavement surface condition at the Municipal Corporation of Tirupati after: **a** construction, and **c** three years

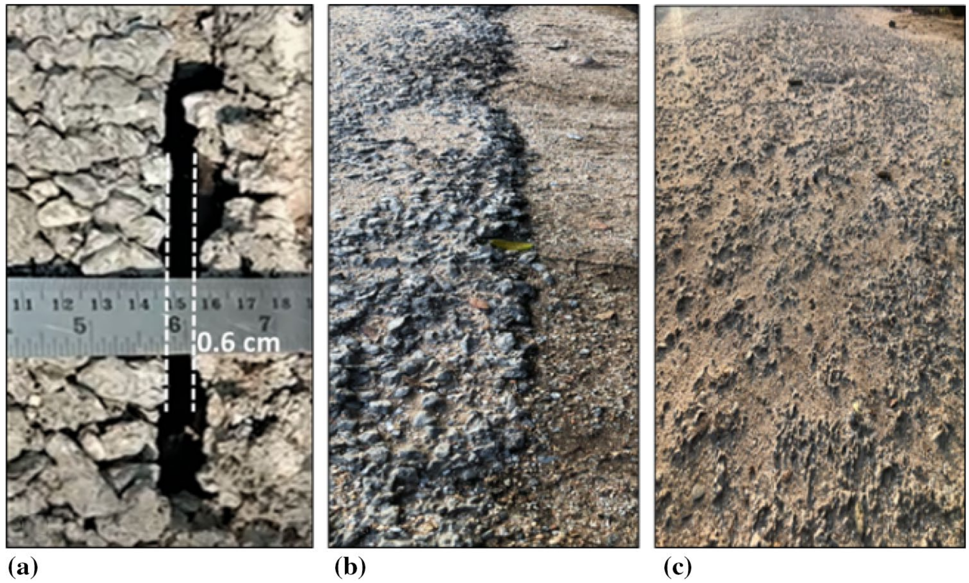

Fig. 5 Structural defects in pervious concrete pavement systems: **a** joint deterioration, **b** edge cracking, and **c** raveling

Table 3 Lifecycle assessment results for pervious concrete and Portland cement concrete pavement systems

Mixing scenario	Pervious concrete			Portland cement concrete		
	Embodied energy ($\times 10^3$ MJ/km)	Greenhouse gas emissions ($\times 10^3$ kg CO_2 eq./km)	Capital cost (INR)	Embodied energy ($\times 10^3$ MJ/km)	Greenhouse gas emissions ($\times 10^3$ kg CO_2 eq./km)	Capital cost (INR)
Ready-mixed concrete	1750.08	220.11	5,670,494	1801.99	225.93	5,601,997
In-situ	1730.39	221.64	6,440,845	1785.09	227.73	6,706,571

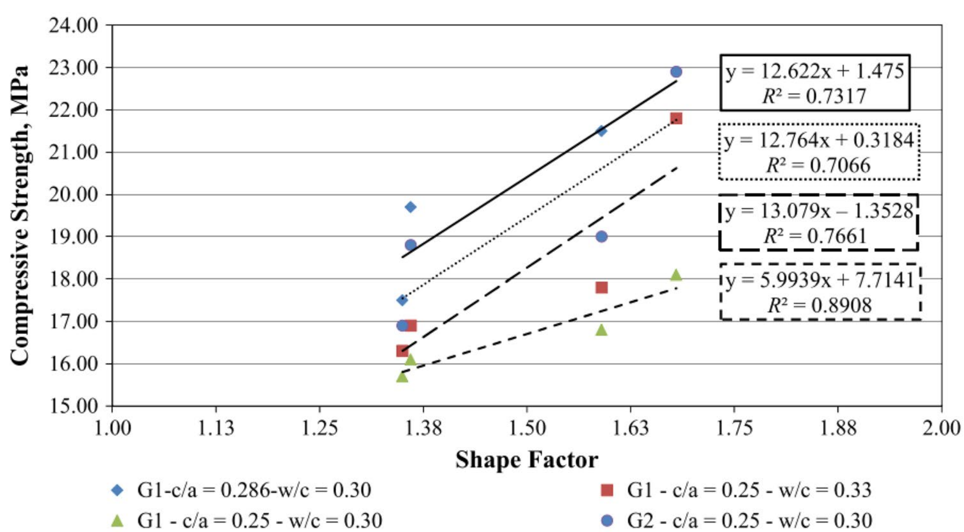

Fig. 6 Relationship between compressive strength and shape factor [50] (c/a cement to aggregate ratio; w/c water to cement ratio).

than conventional concrete pavements by about 4%, while for ready-mixed concrete, the cost of PCP systems was larger than cement concrete pavements by about 1%.

New Generation Pervious Concrete Pavement Products

Pervious Concrete Paver Blocks

PCPBs of different shapes were fabricated using PC mixtures. In order to understand the effect of shape on the compressive strength characteristics, shape factor was calculated and correlated with the strength parameter. The shape factor represents the ratio of total side surface area to the top surface area. The four different shapes of PCPBs included Dumble, Milano, zigzag, and trihex. The correlation between strength and shape factor is shown in the Fig. 6 [50]. G1 represented aggregate sizes passing 4.75 mm and retained on 2.36 mm sieve, while G2 represented aggregates passing 6.75 mm and retained on the 2.36 mm sieve. In other words, G2 was relatively coarser than G1 gradation. It was observed that the compressive strength of the PCPB significantly depended on the shape factor, which is the ratio of total side surface area to the top surface area, which indicated that the strength of PCPBs can be optimized by adjusting the shape factor for a given mix.

Pervious All-Road Class All-Weather Multilayered Paver Blocks

The results for different properties of the PARAMpave system of products are summarized in Table 4.

Based on the results, it may be stated that structural and hydrological parameters associated with PARAMpave products were higher than the minimum requirements prescribed in literature and standard protocols. For instance, the respective porosity and permeability of PARAMpave blocks was higher than 15% and 0.54 cm/s, which are the general requirements for PC material as specified by the American Concrete Institute [6]. In addition, the water absorption was lower than 5% and flexural strength was above 3.8 MPa for all PARAMpave blocks, which satisfy the criteria mentioned in IS: 15,658 [52], thereby making them suitable for application in all-road classes and all-weather conditions. Detailed discussion on the performance characteristics of PARAMpave are published elsewhere [2].

The lifecycle results for the PARAMpave products suggested that they consumed 8% lower energy during manufacturing and emitted 8% lower emissions compared to concrete paver block of similar dimensions. Further, the PARAMpave products were about 10% cheaper than PCC paver blocks of similar configurations. The environmental as well as economic aspects of PARAMpave products are presented in

Table 4 Properties of PARAMpave products

PARAMpave product ID	Porosity (%)	SD (%)	COV (%)	Permeability (cm/s)	SD (cm/s)	COV (%)	Water absorption (%)	SD (%)	COV (%)	Flexural strength (MPa)	SD (MPa)	COV (%)
A	17.46	0.76	4.37	0.83	0.01	1.09	1.07	0.03	2.45	6.13	0.10	1.70
B	23.56	0.92	3.91	1.33	0.05	4.12	1.02	0.01	0.73	5.26	0.53	9.99
C	16.60	0.42	2.55	0.77	0.03	4.05	1.28	0.06	4.46	5.39	0.17	3.08
D	21.49	0.42	1.97	1.17	0.06	5.17	1.56	0.05	3.09	5.02	0.38	7.67
E	22.22	1.48	6.66	1.25	0.05	4.00	1.21	0.05	4.21	4.83	0.57	11.84

Table 5 Environmental and economic aspects of PARAMpave products and Portland cement concrete paver block

PARAMpave product ID	Embodied energy ($\times 10^3$ MJ/km)	Greenhouse gas emissions ($\times 10^3$ kg CO_2 eq./km)	Capital cost / paver block (INR)
A	908.48	123.87	40.36
B	911.32	124.07	40.75
C	908.43	123.87	40.45
D			
E			
Concrete paver block	992.99	135.27	44.77

Table 5. Additionally, PARAMpave weighed around 17 kg, which is about 10% lighter than a cement concrete paver block of similar configurations. All these results indicate that PARAMpave products are superior performing paver blocks compared to conventional cement concrete blocks.

Conclusions

This paper discussed the status of research and advancement in PCP technologies in India, including the mix design and characterization at IITKGP as well as construction and field monitoring of PCP parking lots on the campuses of IITKGP, MCT, IITT, and other parts of India. Further, research on PC paver blocks of varying geometries designed as per industrial practices was discussed. Though paver blocks offered higher quality control, they did not address the problems of inherent low strength of PCPs. Therefore, to address these issues, PARAMpave system of products was developed with a bottom structural layer overlaid with a PC surface wearing course layer.

Test results indicated that the general range of porosity, density, permeability, and compressive strength ranged from 13 to 37%, 1750–2250 kg/m^3, 0.10–5 cm/s, and 6–26 MPa, respectively. Further, the reduction in infiltration rate of in-place PCPs as well as their structural deterioration were functions of the traffic loading and adjacent exposure conditions. The PARAMpave products that were designed to address the limitations of conventional PCP systems and paver blocks possessed the following properties: porosity of 17–24%, permeability from 0.66 to 1.33 cm/s, and flexural strength of 4–6 MPa. Further, the environmental and economic burdens of PARAMpave were about 8–10% lower compared to the conventional cement concrete paver blocks of similar dimensions. These attributes indicated that the PARAMpave products have high potential for application in different road classes and varied rainfall conditions.

Despite a multitude of benefits offered by PCP systems and PARAMpave products, it is proposed that several research test sections must be built in future to ascertain the performance and sustainability credits of these special pavement products over their design complete lives. In addition, the local municipalities and governments should take initiative in constructing test sections for societal benefits and monitor over long-term to develop design guidelines and standard specifications, which will include material properties, mix designs, performance testing, field instrumentation and monitoring, lifecycle assessment, and lifecycle cost analysis.

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Author Contributions KPB conceptualized and supervised the studies. All authors contributed to the study conception and design. Material preparation, data collection and analysis were performed by AS, AKC, and KPB. The first draft of the manuscript was written by AS and AKC and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

Data Availability All data generated or analyzed during this study are included in this published article.

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