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CIVIL AND ENVIRONMENTAL ENGINEERING REPORTS

E-ISSN 2450-8594

CEER 2021; 31 (3): 0054-0084
DOI: 10.2478/ceer-2021-0034

Original Research Article

RECENT STUDIES ON THE PROPERTIES OF PERVIOUS CONCRETE; A SUSTAINABLE SOLUTION FOR PAVEMENTS AND WATER TREATMENT

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A b s t r a c t

Pervious concrete a sustainable solution with limited fines or no fines and interconnected voids, has many environmental benefits, such as reducing the stormwater run-off, improving the groundwater table, reducing water pollution, and mitigating urban heat island. Many research works have been done in Pervious Concrete (PC) by varying different parameters such as, types of aggregate, aggregate gradation, water-to-cement (w/c) ratio, cement-to-aggregate ratio, geopolymer binder, ultra-high strength Matrix and compaction techniques. All these parameters have direct influences on the strength, porosity, permeability, hydraulic efficiency and durability characteristics of PC. The main aim of this paper is to review the recent work carried out in pervious concrete under six different categories (i) Effect of binders, coarse aggregate, admixtures and fibers used in PC (ii) Mechanical and durability properties (iii) pore structure characteristics (iv) Study on Clogging Effect (v) Role of PC in the water purification process and (vi) Numerical model in PC.

Keywords: pervious concrete, permeability, porosity, water purification, clogging

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1. INTRODUCTION

Due to increased population and modern urbanization, a higher ratio of impervious surfaces in the urban area results in less water absorption by the ground. As a result, the urban stormwater runoff is estimated to be in a higher volume when compared to the natural stormwater runoff [1]. Due to impervious pavements, sidewalks, and landscaping, air and water have many obstacles getting to the roots of green plants and vegetation and making it difficult to grow [2]. Pervious concrete pavement is an effective means to address essential environmental issues and support green and sustainable growth. The advantage of pervious concrete over normal cement concrete is demonstrated in Figure 1. Pervious concrete pavement has many advantages such as water treatment by pollutant removal, less need for curbs and storm sewers, better skid resistance in pavements, recharge to local aquifers [3]. The no-use or minimal use of fine also supports inmicroorganisms' growth, which acts as a slow sand filter and involves the water purification process. It also improve the quality of stormwater by reducing heavy metals like lead, zinc, chromium and copper that are typically found in stormwater run-off. Surface runoff with high concentrations of heavy metal ions, can pose a serious threat to the ecological environment if discharged into the aquatic environment or the underground water [4]. Recent studies on pervious concrete showed that rainwater infiltrates through the pervious concrete, reduces not only the surface runoff but also improves the rainwater quality. Moreover, the pollutants in rainwater can be effectively removed by chemical and physical reactions between the pervious concrete and the microorganism in pores [5]. Moreover, PC plays a substantial role in the dam's drainage zone and its complementary structures, small retaining walls and damp proofing subbase materials [6].

Chandrappa and Biligiri [5] reviewed the developments and state-of-the-art pertinent to pervious concrete research and practices. The investigations on mechanical-hydrological-durability properties of pervious concrete performed in various studies have been reviewed. The storm water purification efficiency of pervious concrete has been documented. Zhong et al. [7] reviewed the state-of-the-art and state-of-the-practice research and application of PC. Emphasis has been laid on the Pore System Characterization (PSC) and its influence on PC's mechanical, hydraulic and acoustical properties. Recently supplementary cementitious materials [8, 9 10, 11&12] alkali-activated slag [13], Steel slag, Porous aggregates [14] recycled aggregate[15&16], Synthetic fibers [17], geo grids [18] and other industrial by-products were used to produce bio-responsive and eco-friendly pervious concrete to which the terrestrial and aquatic microbes can attach themselves and involve in the purification process. Some recent work done on pervious concrete is listed in Table 1. Based on the literature study, it can be ascertained that binding agent, constituent materials, mix design, i.e. (water-to-cement ratio and cement-to-aggregate ratio) plays an important role in the pore system characteristics of PC which significantly influences the strength, permeability, durability and hydraulic conductivity of pervious concrete mixes. This paper aims to review the recent work done on pervious concrete under six categories: pervious concrete materials, pervious concrete mechanical and durability properties, pore characteristics, clogging effect on pervious concrete, pervious concrete in waterpurification and heavy metal ion removal and numerical modeling of pervious concrete.

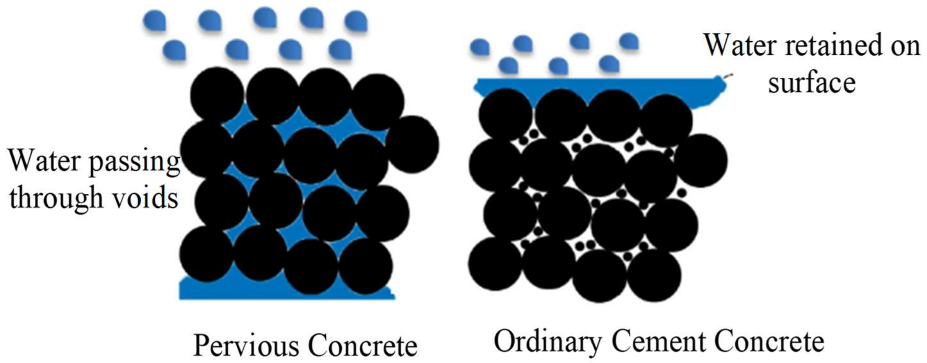


Fig.1 Comparison of Pervious Concrete with Ordinary cement Concrete [6]

Table 1. Overview of literature collection of Pervious Concrete done in the recent past

Reference	Parameters Studied									Significant conclusion from the study
	Ingredients			Experimental parameters	Properties					
	Binders	CA	Fibers		Mechanical Strength	Porosity	Hydraulic Conductivity	Durability	PSC	
[8]	AASC	EAFS		% of voids filled by Binder and Agg type	✓		✓			Pervious concrete made with EAFS and AASC exceeded 35 MPa and permeability > 0.49 cm/s.
[19]	C	NA	PVC fibers					✓	✓	The F-T durability of ultra-high strength matrix out performed HSM, NSM
[20]	C + Silane Polymer	RA		Binder Ratio	✓		✓		✓	Silane polymer emulsion treatment significantly improved the strength of RA pervious concrete
[9]	FaL-G	NA		Size of Aggregate	✓	✓	✓			FaL-G binder pervious concrete can be suggested for future green project
[21]	C-FA-S	SS		binder-to-aggregate ratio	✓	✓	✓			Binder optimize ITZ of PC
[22]	SBR	NA		W/C ratio, Binder ratio	✓				✓	Polymer content led to an increase in the hydration products and > in Comp. Strength
[23]	C	D, SS		Agg type & Size	✓	✓			✓	pervious concrete efficiency is influenced more by the aggregate type than its size
[24] [25]	C	OPKS, CS		Agg type	✓	✓	✓			both shells caused higher void content & permeability
[26]	C	Seashell		Agg type				✓	✓	crushed shells have more influence on the durability than the physical and mechanical properties
[14]	C	NA		Desorption behaviour & internal curing efficiency	✓				✓	Pore structure has intensity effect on equilibrium water in aggregate & no impact on water release rate
[18]	C	NA	Geo Grid	Geogrid Reinforcement	✓	✓		✓		geogrids in PC restrain the generation and propagation of the crack
[27]	C	Cu S		Agg type	✓	✓	✓			porosity and permeability of the pervious concrete were augmented with increase in the Cu S content.
[17]	C	NA	PP	Fiber-Matrix Bond	✓	✓				Chemically treated fibers have shown higher bond strength with the concrete matrix
[28] [29]	C	NA	CCFCM	Fiber reinforcement	✓	✓				CCFCM was successfully implemented as reinforcing elements in PC
[30]	NS, NC	RA	SF, PF	Agg type + Binder+ Fiber	✓	✓				100% RA + 2% SF + 2% NC yields a PC suitable for structural applications

C- Cement; CA- Coarse Aggregate; NA -Natural Aggregate; VF-Volume fraction; PSC-Pore System Characteristics; FaL-G – Flyash Lime Gypsum; RA- Recycled Aggregate; AASC-Alkali Activated Slag Cement; EAFS-Electric Arc Furnace Slag; F-T Freeze Thaw; ITZ- Interfacial Transition Zone; PP- Polypropylene; CCFCM-Cure Carbon Fiber Composite Material; PA-Pozzolanic Admixture; NS- Nano Silica; NC – Nano Clay; SF- Steel Fiber; PF- Plastic Fiber

2. PERVIOUS CONCRETE MATERIALS

The ingredients of pervious concrete are similar to conventional Portland Cement Concrete (PCC) but with no (or small amount of) fine aggregate and with open-graded coarse aggregate, providing a porous medium (15–30% porosity, pore sizes of 2–8 mm, permeability or hydraulic conductivity of 0.076 cm/s to 3.5 cm/s) to infiltrate stormwater rapidly [28]. The density of pervious concrete is from 1600 kg/m^3 to 2000 kg/m^3. The open void structure of pervious concrete has relatively low compressive strength (typically from 3.5 MPa to 28 MPa) comparing to PCC [5]. The water-to-cement (w/c) ratio (range -0.27–0.36) of PC should be controlled carefully to form an appropriate cement paste thickness to coat the aggregates. Otherwise, the superfluous cement paste would significantly decrease the porosity and thereby lower the permeability of PC. The different types of aggregate gradation, water-to-cement (w/c) and cement-to-aggregate, and compaction techniques with variations in efforts play an essential role in providing an optimum balance in the mixture designing of PC mixtures [31]. Broader application of PC could be achieved through increased ravelling resistance and enhanced durability performance [2 &12] which is possible through proper selection of materials and mix proportioning.

2.1. Binders

The strength of the PC is mainly determined by the bonding strength of cement paste and aggregates. According to Zhong and Wille [2] one method to develop high-performance pervious concrete is to use an optimized ultra-high-performance matrix. Ultra-high-performance matrix (UHPM) is used to replace the conventional matrix to cover the aggregate and bind them together (Figure 2). Several studies were carried out using Ordinary Portland Cement (OPC) and blended cement as a binder. One of the effective methods to improve the compressive strength of pervious concrete is to enhance, cement paste characteristics by decreasing the water–cement (w/c) ratio and adding pozzolanic materials such as silica fume, fly ash, metakaolin, blast furnace slag [8]. High strength pervious concrete could be made by coating the coarse aggregates with a reactive powder high-strength concrete matrix [32]. Recently alkali activated slag cement paste used in PC, penetrating air-cooled Electric Arc Furnace Slag (EAFS) forms a strong interlocking effect and produced a high PC compressive strength and greater water permeability [8]. Yeih and Chang [33] revealed that alumina, ferric oxide, tri-sulphate (AFt or ettringite) formed in pervious concrete made with sulpho aluminate cement, resulted in a severe degradation of compressive strength as well as flexural strength. Apart from OPC, fly ash lime-Gypsum binder

(FaL-G), a cement-free green binder made of recycled industrial waste were used to produce PC pavements. Due to the enhanced hydration, matrix formation and densification a high durable PC mix can be obtained using a FaL-G binder [9]. when comparing to OPC, the FaL-G binder gains its full strength after fifty days due to a slow reaction between fly ash, lime and gypsum and also it has increased setting time and relatively low strength. Pervious Concrete cement paste, incorporating Nano Silica (NS) as a partial replacement, reduces the cumulative pore volume by 13.4 %. Nevertheless, the compressive strength of NS modified pervious concrete improved without adversely affecting its void ratio and permeability [10]. Magnesium phosphate cement (MPC), a new type of cementitious material with the characteristics of fast hardening and early strength was used by Lang et al [34]. Fly ash and metakaolin used as a partial replacement for OPC showed that 2% addition of metakaolin decreased porosity by 10 %. The optimum range of fly ash replacement in pervious concrete was between 5 and 15% [11]. When used as supplementary cement material at a superior range of cement aggregate ratio (0.2-0.24) and an optimum content of less than 30%, fly ash will improve the of PC's mechanical properties [3]. The rheological investigation done by Adil et al. [12] stated that paste properties, control pervious concrete workability, compaction, and ultimately performance. From the Rheological properties of a series of paste mixtures, 5.5 % of Silica Fumes (SF) is optimum for workability for the given mixture proportions and admixture dosages. SF replacement also improved strength and durability by decreased void content.

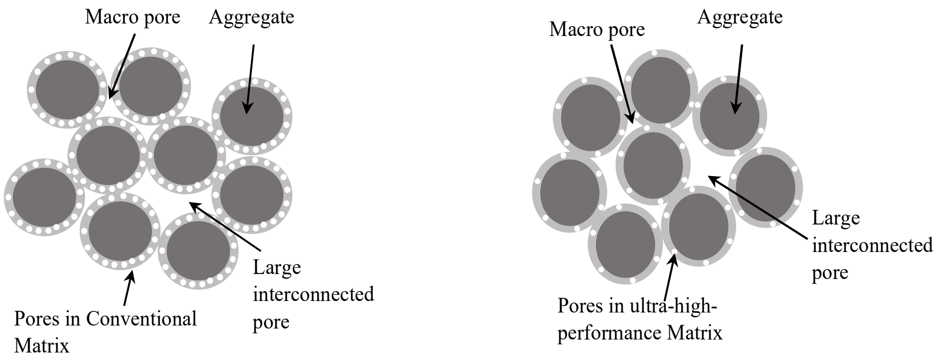


Fig. 2. Comparison of PC with Conventional and Ultra High-Performance Matrix (reconstructed from Zhong and Wille [2])

2.2. Coarse Aggregate

The aggregate comprises the main structure of pervious concrete, which contributes to the strength. Generally, single size aggregates were used to constitute the skeleton structure of the pervious concrete. To guarantee good water permeability and mechanical strength of pervious concrete, the coarse aggregate typically uses a single size grading of either 10–20 mm, or 5–10 mm [35]. The aggregates include conventional aggregate (gravel, cobblestone, sandstone, dolomite) or particular aggregate (light weight aggregate, recycled concrete aggregates, over burnt Bricks) and industrial by-products (Steel Slag (SS), Electric Arc Furnace Slag (EAFS), Copper Slag (Cu S)) which are used to form pervious concrete with large interconnected pores. As a natural lightweight aggregate, the acidic pumice is expected to have much lower density and strength that the crushed stone. Therefore, PCs' mechanical strengths decreased with increasing the pumice's replacement level and had better water permeability and surface abrasion resistance [36]. Over burnt waste bricks can be a potential source of aggregate and effectively reduce the stone aggregate need. Different literature works have shown the feasibility of brick aggregate as an eligible substitute of stone aggregate in PC [15], [37]. Yeih and Chang [33] revealed that PC formed using EAFS and sulpho-aluminate cement result in the release of alumina, ferric oxide, tri-sulphate (AFt or ettringite) which leads to a severe degradation of mechanical strength. Copper slag an innocuous aggregate that does not contain reactive silicates, when used in PC as aggregate does not pose any problem related to volumetric stability. It also results in a high-density fresh concrete mix due its high specific gravity. The shrinkage and deformation caused by creep decreased when natural aggregate was replaced by copper slag aggregate [27]. Prewetted Light Weight Aggregate (PLWA), especially fine aggregate such as expanded shales, clays, slates, or slag aggregate, have shown to provide increased degree of hydration, reduced shrinkage, and general improvements to PC properties [38].

Khankhaje et al. [25 & 24] investigated lightweight aggregates in the PC as coarse aggregate to improve acoustic and thermal insulation. Recycled Concrete Aggregate (RCA) used in PC adversely affects mechanical properties and abrasion resistance due to the weak RCA and aggregate-mortar interface [40 & 41]. They were using RCA as partial replacement of natural aggregate, silica fumes and Nano Clay as binders result in poor characteristics of the ITZ and inferior strength properties, mainly due to RCA's inherent porosity and the weak adhesion between RCA and cement paste [30]. Greener pervious concrete can be produced by combining RCA-along with fine recycled aggregates (RFA) [16]. Microscopic analysis showed that adhered mortar on RFA reduced the crack diversion ability and enhance pervious concrete strength. Different studies were done using steel slag as a partial replacement for natural aggregate [13&42]. Compared to natural aggregate, steel slag has a higher impact and crushing strength. Furthermore, steel slag has excellent anti-skid performance and good adhesion with cementitious materials [34]. Pervious concrete with steel slag as aggregates is sensitive to the binder content [21].

2.3. Polymers and Admixtures

The cement paste and aggregate play a major role in deciding the strength properties of pervious concrete. Adding a large volume of concrete paste can enrich the conjoint points between particles to form structure integration resulting in improved strength. However the increase of cement content would lead to cement segregation and permeability reduction [43]. Increasing the strength of the paste or increasing the bond between the cement paste and aggregate are crucial to develop the PC's strength. The use of chemical admixtures, like polymers and superplasticizers, is a promising technique to improve the flowability and the bond between the aggregates and the cement paste [44]. Jang et al. [45] used bottom ash as coarse aggregate and geopolymeric binder (alkali-activated fly ash/slag paste) as the cementitious binder material. Sun et al. [13] studied PC made with clinker free binder; The binders are alkali-activated slag, metakaolin geopolymer and metakaolin-slag geopolymer. Silane polymer emulsion enhances the membrane-forming behaviour and thickness distribution of cement paste. Silane treatment significantly improved RCA pervious concrete's strength while maintaining acceptable permeability due to the cement paste redistribution (Figure 3). Meso-structure analyses confirmed that more cement pastes gathered around the bonding regions between adjacent RA particles [20]. Tabatabaeian et al. [6] developed a High-Performance Pervious Concrete with polyester and epoxy resins as polymeric composites, in which polyester or epoxy resin completely substituted with ordinary cement. Epoxy resin was the most effective on the mechanical properties, permeability, and freeze-thaw resistance of PC. Recently Yang et al. [46] studied the influence of Vinyl Acetate and Ethylene co Polymer dispersible powder (VAE-P) on the performance and interfacial transition zone of pervious concrete. VAE-P enhances fluidity and air content, and declines the shear viscosity of fresh mortar. ITZ results showed that VAE-P inclusion delays cement hydration, alters pore characteristic and increases the pores volume with the larger size. Dai et al [47] used adhesion admixtures (water-reducing agent and reinforcing agent) and studied pervious concrete properties influence. Adhesion admixtures glued and consumed more fine cement with no cement segregation phenomenon by increasing the adhesiveness of fresh cement pastes, which resulted in a bigger optimum Cement/Aggregate ratio. the influence of Styrene Butadiene Rubber (SBR) on the physical and mechanical properties of PC mixes was studied [22]. It can be concluded that pervious concrete containing various proportions of polymer has positive effects on the strength and permeability, compared to the mixes without polymer.

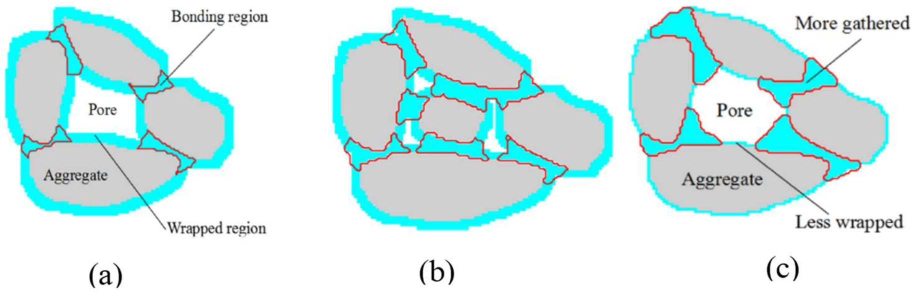
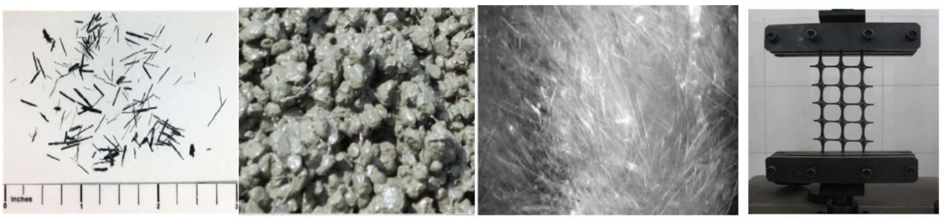


Fig. 3. Schematic illustration of PC structure (a) typical PC showing, aggregate, bonding region and pores (b) conventional method of increasing the bond strength (c) redistribution scenario of cement paste to increase bond strength [20]

2.4. Fibers

Fiber reinforcement is an effective method to enhance the mechanical behaviour of pervious concrete. Fibers enhance the strength properties of concrete through bridging action over the cracks. Due to the presence of many voids, using fibers in pervious concrete, to enhance its strength and stiffness always remains a challenge. Industrial fibers such as steel fiber has been successfully implemented in concrete to enhance the strength properties, especially the flexural strength [30]. Moving towards an eco-friendly approach, recycled fibers such as, Cured Carbon Fiber Composite Material [28], Steel fiber, glass fiber, waste plastic fiber (WPF) [30] are effectively used in enhancing the strength properties of PC mixes. Using 1–1.5% WPF can enhance the flexural strength by about 70% but an increase in the WPF content, reduces the PC's strength properties [48&49]. Steel fibers with a high modulus of elasticity performs much better when compared to polypropylene and plastic fibers. It has better dispersion property and does not form clusters in the mix. The addition of 2% of steel fiber increases the compressive and flexural strength by 68% and 25 % respectively at the age of 7 days. Polypropylene (PP) fiber has a high melting point, better chemical stability, low surface energy and less cost. When mixed into the concrete mixture, the PP fibres will form clusters, and uniform distribution cannot be achieved. Polypropylene fibers have a hydrophobic surface and modulus of elasticity lower than that of the cement matrix. It is assumed that there is no existence of physio-chemical adhesion bonding between polypropylene fibers and cement when they are mixed. However, some chemical treatment process can be used to enhance the surface energy of PP fibers. Plasma treatment is an eco-friendly approaches to increase polypropylene fibers surface energy [17].

Cured Carbon Fiber Composite Materials (CCFCM) are used mainly to manufacture aircraft, automobiles, and other high-performance products. Large quantities of excess CCFCM materials are generated, and they require proper disposal reuse applications. CCFCM elements dispersed well in the PC mixture without creating clumps and balls. CCFCM-PC specimens also showed an increase in tensile and compressive strength. Increasing the CCFCM dosage without reducing aggregate content would further enhance the flexural and tensile strength of PC. Short fibers (13–19 mm) at only 0.3 and 0.9 kg/m3 dosage enhanced the 28-day compressive strength and split tensile strength by 24%, yet these improvements could be attributed to decreased porosity by 13–25 percent. However, when longer fibers (50 mm) were used at the exact dosages, no change was observed in the 28-day [29]. Fiber reinforcement in Pervious concrete could obtain a flexural strength range from 3MPa to 4Mpa. Micro fiber reinforcement could delay the crack generation, but it has limited capability to restrain large deformation especially after cracking. Providing geogrid interlayers in PC pavements will enhance the crack resistance due to increased flexural strength and ductility. The performance of geogrids depends on the constituent materials, the mesh shape and size, the position and the number of layers in the previous concrete structure. Geogrids has high corrosion-resistance and is one effective method to improve PC's strength [18]. The different fibers used in the recent study of PC mix is shown in Figure 4.



CCFCM- Fibers   steel fibers in PC Mix   waste plastic fiber   geogrid

Fig. 4. Fibers used in Pervious Concrete to improve the mechanical property

2.5. Mix-Proportioning

The concept for the mix design of pervious concrete is not the same as the conventional concrete. Many voids or pores are intentionally introduced to the pervious concrete such that good water permeability can be achieved [33]. The properties of pervious concrete depend on the mix proportion of different constituent materials, including coarse aggregate, cement, water, and occasionally, a small quantity of fine aggregate. Water-reducing admixtures are used to maintain sufficient workability for pervious concrete with low water-to-cement ratios [50]. The different types of aggregate gradation, aggregate type, water-to-cement (w/c) ratio, cement-to-aggregate ratio, using cementitious materials and compaction techniques play an essential role in providing an optimum balance in the mixture designing of PC mixtures [46, 47,11&31]. Graded pervious concrete was developed to obtain better mechanical properties [3]. The mix design and the constituent materials play a major role in the strength and durability properties of pervious concrete. The mix design of PC from recent research work are listed in Table 2.

Table 2. Mix proportioning of pervious concrete

Mix proportioning									Author / Year
Cement Kg/m^3	SCM Kg/m^3	Aggregate Kg/m^3	PAR Kg/m^3	Polymers Kg/m^3	SP Kg/m^3	Water Kg/m^3	Paste/ Aggregate Ratio	Water/binder Ratio	
150	FA- 314.69 NS- 11.416	1655	-		6	139.41	2.15	0.3	Mohammed et al. 2018
402.4	-	1611.5	-		-	121		0.3	Kant Sahdeo et al. 2020
292.02	FA- 15.7 M- 6.28	1568	-		1.884	104			Saboo et al. 2019
350	-	1570	-	PE- 188	-	105			Tabatabaeian et al. 2019
350	-	1570	-	Epoxy-220	-	105			Tabatabaeian et al. 2019
326	Si F- 17	1525+77 *	-		-			0.27	Adil et al. 2020
400		1800	-	SBR- 20	-		0.22	0.35	Borhan and Al Karawi 2020
300	-	1800 1620 1440	- AP- 67.2 AP- 134.5		-	90			Oz 2018
467.73	-	-	BA1085.43+158.69*	-	-	130.96		0.28	Debnath and Sarkar 2019
-	SAC 440	-	EAFS 1815			154			Yeih and Chang 2019
340			CS 1680+ 340*		1.7	102			Lori et al. 2019
213		1704				81			Xu et al. 2018
467.73	-	-	OBA1109.63 +76.84*	-	-	130.96		0.28	Debnath and Sarkar 2020
354.6			RCA- 1300 + 130*			124.1			Ibrahim et al. 2020
100	SF+GBFS+ FA 450		SS- 2050			97			Zhang et al. 2020a
284		1453				85			Gaedicke et al. 2016

SCM- Supplementary Cementious Material; PAR- Partial Aggregate Replacement; SP- Super Plasticizer; SAC- Sulpho Aluminate Cement; AP- Acidic Pumice; BA -Brick Aggregate; OBA- Over Burnt Brick Aggregate; EAFS- Electric Arc Furnace Slag; CS- Copper Slag; RCA- Recycled Concrete Aggregate; SF- Silica Fume; GBFS-Ground Granulated Blast Furnace Slag; FA-Fly Ash; SS- Steel Slag; * - Fine Aggregate

3. PERVIOUS CONCRETE MECHANICAL PROPERTIES

The aggregate comprises the main structural part of pervious concrete, that provides strength. Due to a lack of fine aggregate and high porosity, the pervious concrete strength is somewhat inferior compared to the conventional concrete. Hence the pervious concrete application is limited to footpaths, parking lots, sidewalks, or low volume roads. To extend the use of pervious concrete, increasing the mechanical strength and durability properties becomes an important issue. To overcome this problem, researchers have used different methodologies to increase the strength of pervious concrete. The recent research on compressive strength, flexural strength, abrasion resistance, and free thaw durability are discussed below.

3.1. Compressive and Flexural Strength

Typically pervious concrete has 28-day compressive strength lower than 21 MPa, which is due to its connected porosity and to maintain its high-water permeability [8]. To extend the use of pervious concrete, increasing the compressive and flexural strength becomes an important issue. The mechanical properties of Macro Porous pervious Concrete (MPC) are lower than conventional pervious concrete. Nevertheless, the substitution of virgin aggregates with 100% recycled aggregates did not compromise the compressive strength or modulus of MPC' elasticity [50]. Pervious concrete with high compressive strength (35 MPa) could be achieved by using EAFS and AASC. The porous nature of EAFS provided a strong interlocking effect and the AASC was a more robust binding material than OPC [8]. Using light weight aggregates such as oil palm Kennel Shell and Cockle Shell slightly reduces the compressive strength due to escalated void content. However, the values obtained were still within the acceptable range for pedestrian's pathways, light traffic roads and parking lots ([24], [25]). Many research works have been carried out using Recycled Concrete Aggregate (RCA) as an environmentally friendly alternative for natural aggregate in PC, but using recycled concrete aggregate has a significant negative effect on compressive strength and flexural strength of PC. Increased recycled aggregate levels in pervious concrete increases pervious concrete degradation and it is critical to use 100% recycled aggregate in pervious concrete ([52], [40], [16]). About 25% increase in permeability and about 60% reduction in strength properties of mix incorporating 100% RCA could be observed. The addition of silica fumes and nano clay enhances the strength properties because of micro-filling ability and pozzolanic reactivity [30]. The compressive strength of pervious concrete is hardly impacted by the compressive strength and the hydration of hardened binder pastes. In contrast the binder pastes with different mineral admixtures can optimize the ITZ to improve pervious concrete's compressive strength [21]. Many researchers have carried out a numerical investigation in recent years to predict the mechanical properties by varying mix proportions, material characteristics, porosity, aggregate type, and other parameters of PC ([51], [53], [47], [54]). Flexural fatigue testing on pervious concrete with different porosities and aggregate types revealed that, the fatigue life of pervious concrete was mainly controlled by stress ratio and Porosity did not influence PC's fatigue behaviour [29]. When the void ratio was fixed at 20%, 3–5% silica fumes showed ease in compaction and improved compressive strength. In other words, with an increase in rheology the compressive strength of PC increases [12]. Based on the excellent bonding strength of magnesium phosphate cement, the Magnesium phosphate cement Steel slag PC (MSPC) has better flexural strength than traditional PC, and the maximum 28-day flexural strength reaches 8.0 MPa [34]. The compressive strength of different pervious concrete mix using different binders, aggregates, admixtures and different mix proportions are shown in Figure 5.

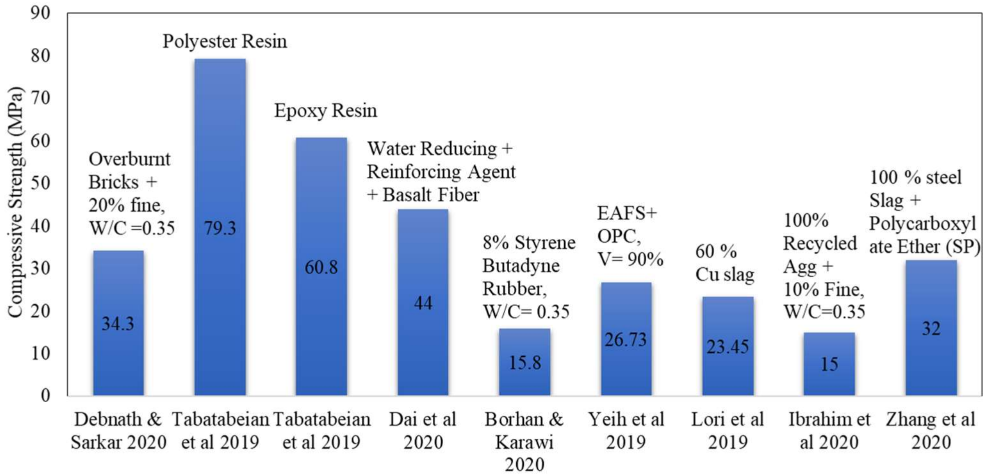


Fig. 5. Compressive strength of the different pervious concrete mix

3.2. Freeze-Thaw, Abrasion and Raveling resistance

The durability properties of pervious concrete can be improved by, replacing the coarse and fine aggregate, adding fibers, and replacing binders. Increasing the dosage of silica fumes reduces the PC's workability, which leads to improper paste to aggregate bonding. Reduction of density leads to poorer intraparticle contact and the ability to resist internal Freezing and Thawing (F-T) stresses [12].

An increase in the resin content leads to an increase in the F-T resistance, whereas, the coarse aggregate size and the resin type had an insignificant effect on the F-T resistance [6]. Kevern et al. [55] and Zhong and Wille [19] studied that ravelling and surface abrasion resistance were significantly improved by adding fibers in PC. The addition of high strength matrix along with fiber reinforcement enhances the F-T resistance of PC. Longer length fiber showed a positive effect on the F-T durability, and the short length fibers showed improvement only at a higher dosage. Oz [36] revealed that the addition of pumice aggregate showed a positive effect on abrasion resistance. the pumice surface has a half open texture leading to a better chemical reaction between cement and water. The high silica content of the acidic pumice leads to better resistance against the surface abrasion. High amount of chloride, organic matter, and seashells impurities cause unfavourable interactions with the cement matrix, thereby producing a harmful effect on PC's F-T resistance [26]. The freeze-thaw performance of PC using UHSM is better than those using normal and high strength matrix, attributed mainly due to smaller void-to-void distance and lower initial degree of saturation. The influence of pore system characteristics on the F-T durability of PC is attributable to the void size and tortuosity. Using larger aggregates creates larger void sizes, higher tortuosity, and premature F-T failure [19]. The freeze-thaw durability of one pervious concrete baseline mix with three different entrained air levels was evaluated using operational modal analysis. This modal analysis provides a very accurate and reliable method to assess pervious concrete's internal damages due to freezing and thawing [56]. Ravelling is the individual loss of aggregate or cement-coated aggregate particles resulting in loose material on the pavement surface (Figure 6). The work carried out by [12] showed that limestone specimens had around 30% mass loss and silica Fumes caused a noticeable decrease in mass loss and potential ravelling for the river gravel samples. Silica fumes had more significant impact on the mitigation of raveling in the river gravel samples than limestone.

Fig. 6. Raveling due to (a) poor paste -aggregate bonding (b) insufficient compaction [12]

4. PERVIOUS CONCRETE PORE STRUCTURE CHARACTERISTICS

The performance of pervious concrete strongly depends on its pore structure characteristics. The pore structures generally include porosity, pores size, pore distribution and tortuosity of macro voids. The compressive strength of PC was found to be influenced by, the pore size, pore distribution and pore spacing. The average pore size of pervious concrete increase with the increase in the size of coarse aggregate, which affects the porosity and permeability. Pore size distribution was generally obtained from mercury intrusion porosimetry or image analysis method ([20], [57]& [58]). The pervious specimens had more pores with smaller pore size in the top region, while the pore number at the bottom decreased by approximately 40%, but with far large pore size. In order to establish the relation between pore structure and properties of pervious concrete, many research works have been done in the recent year using image analysis ([53], [15], [27] & [59]).

4.1. Porosity

The most singular characteristic of pervious concrete is its interconnected porosity that allows water to flow through, at high rates [60]. Increasing aggregate size increases the total porosity of resulting pervious concrete [58]. The presence of fine aggregate in the porous mix aid in filling up the available voids/pores in the mix and tends to reduce the porosity and permeability of the mix [15]. Increase in the percentage of copper slag aggregate in the mixture increases the porosity, this increase was related to the shape of the copper slag aggregate which has a glassy texture and its sharp angle is less than dolomite aggregate [27]. The optimal aggregate type for preparing pervious concrete from the hydrologic point of view is diabase, its sharp grain edges, allow the water to pass smoothly through the pore system [42]. The replacement of OPKS and CS as the natural aggregate decreased the compressive strength, while the angular shape of both shells caused higher void content and permeability as compared to those of control pervious concrete [24]. The smaller size aggregate increases the strength but reduces the porosity and permeability of the mix. Compared to single and dense graded mixes, the single graded aggregates showed high porosity but with a low strength [37]. From the perspective of the internal structure of recycled permeable concrete, the factors affecting its strength and porosity are the paste properties, the coating thickness of paste on the surface of aggregate and the void content of aggregate [61]

The average porosity of permeable bricks made of coarse bottom ash as an aggregate was around 19.1–30.3%, while that of permeable bricks made of fine bottom ash as an aggregate was 15–16%, substantially lower than the lower bound specified by ACI [62]. The volumetric porosity and area porosity of no sand PC increases with an increase in the large aggregate proportion. The pore distribution is not homogenous in the PC mix with maximum content of large-sized coarse aggregate [63] Pore characteristics of pervious concrete were studied based on CT imaging and Computed Fluid Dynamics (CFD) modelling based on CT reconstructions of pore structures. The connected pore network models simulate the water seepage flow using the CFD method [59]. Pervious concrete porosity does not solely depend on the coarse aggregate size, but also the aggregate gradation, size, pore size, connected porous network, and cement paste thickness. The effective porosity rather than the total void is expected to determine its permeability pattern [16]. There was a strong relationship between the porosity-density-strength properties and it says as porosity increases, the density decreases, which lowers the strength of concrete. In fact, it was also observed that the increase in porosity would definitely lead to an increase in the permeability coefficient as well, and subsequently, decreases the density [31].

4.2. Permeability/ Hydraulic Conductivity

Permeability is an important property that is essential in the functional design of PC pavement system. It is defined as the ease with which water can flow through any porous material. The pore characteristics such as pores size, distribution and specific surface areas play a dominant role in the permeability of PC. The permeability coefficient of PC depends on continuous porosity, the larger the porosity, the larger the volume of fluid transport in unit time and larger the permeability coefficient of pervious concrete [63]. On comparing single graded and dense graded mix, the single graded mix increases the permeability of the mix [15]. On the other hand, acidic pumice has positive effect on the permeability of pervious concrete which may be attributed to its porous structure and quite round shape via the accelerating water passes [36]. Dolomite aggregate increases the permeability of PC, and the highest permeability of 3.53 mm/s could be obtained for 100 % replacement of dolomite with Cu slag aggregate [27]. The use of recycled aggregate, polypropylene fibers, rubber fiber and crumb rubber slightly affect the permeability indices where the use of silica fume and styrene-butadiene latex yields more pronounced effect on the permeability indices [40]. The permeability increases up to 25% at 100% RCA content, and the permeability rate of cement with SF and NC has a minor effect on the permeability. Also, the addition of fibres does not affect the water permeability of pervious concrete mixes significantly. It is possible to enhance the mechanical strength of pervious concrete by using pozzolanic additives and fibres without reducing the permeability [30]. Pervious concrete statically compacted exhibited a nonhomogeneous vertical pore structure distribution characterized by increasing porosity, pore area fraction and pore size, but decreasing pore number from top to bottom [57]. The size of aggregates plays a crucial role in the porosity, density, and permeability of PC mixes. The larger size of aggregates induces higher porosity and more interconnected pores within the PC matrix, despite being well graded in nature [31]. The effect of different gradations at varying w/c ratio on the porosity and permeability of PC mixtures cured till 28 days is shown in Figure 7

Yu et al [58] used 2D/3D CT images to investigate the relationship between pores characteristics and permeability. Simulations showed the permeability increased with the increase of 2D/3D pores size and decreased with the increase of the total pore surface area. Permeability is more sensitive to the content of small pores compared to large pores and medium pores. To avoid the time-consuming and expensive lab tests for determining permeability coefficient of pervious concrete, Sun et al. [53] proposed a convenient method to predict those values using MATLAB algorithm. Beetle Antenna Search algorithm is more reliable and efficient than random hyper-parameter selection. The relationship between seepage velocity and pressure gradient was obtained and fitted by the nonlinear Forchheimer formula. The acquired hydraulic conductivity can be used to assess the seepage flow capacity [59]. Response Surface Methodology (RSM) can be used to design the mix proportion of recycled aggregate pervious concrete. Ideal paste thickness, actual coating thickness and the void content are introduced to quantify and optimize, through RSM [54].

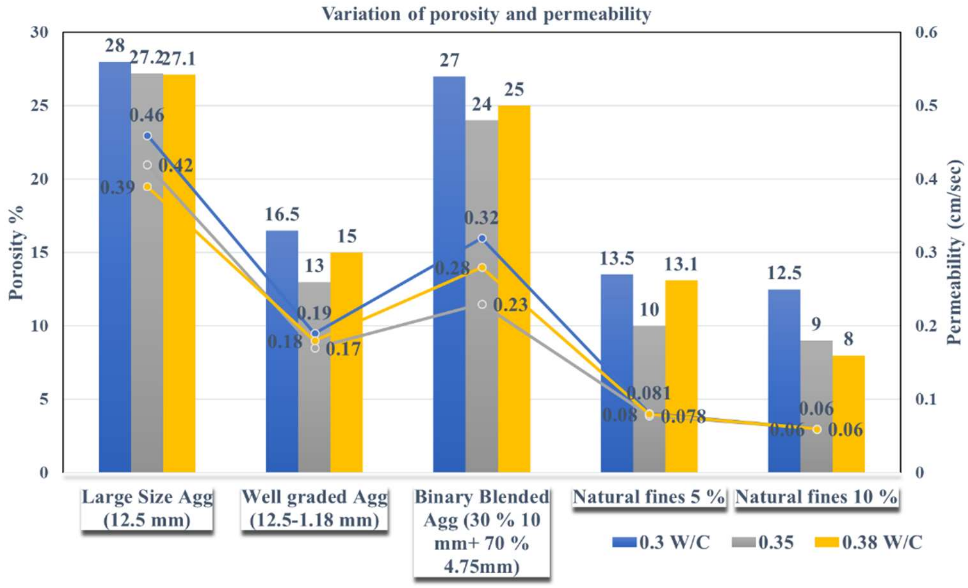


Fig. 7. Effect of gradation of aggregate on the permeability and porosity for different W/C ratio (recreated from Sahdeo et al [31])

5. CLOGGING IN PERVIOUS CONCRETE

Clogging is a phenomenon in which the internal voids are partially or totally filled by sediments causing reduction of permeability in the PC. The filled sediments decrease the cross-section and interconnection of voids causing an increase in tortuosity, decreasing the permeability and affecting the durability and functionality of PC over time [64]. The low strength, high likelihood for clogging and inconvenient maintenance are three main challenges for the broader application of pervious concrete pavement. Li et al [32] developed a high strength pervious concrete with accessible pores to overcome such challenges. The specimen and schematics are shown in Figure 8. using a miller super slab system. A drainage system was developed to efficiently exclude the clogging dusts in the HSPC pavement pores, where the clogging dusts were excluded from bottom to top.

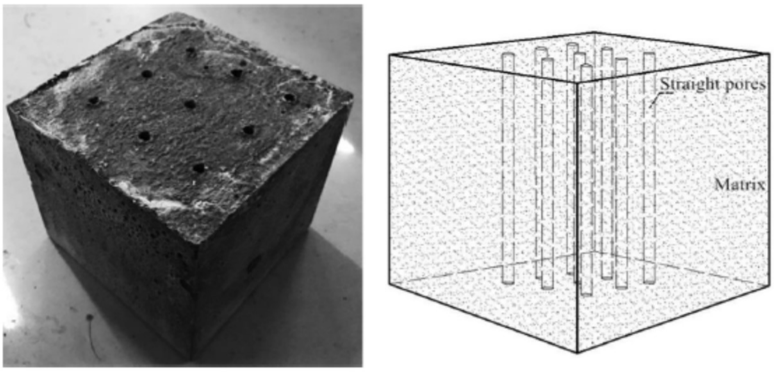


Fig. 8. High Strength pervious Concrete Specimen and Schematics [32]

Zhou et al. (2019) suggested active and passive methods to solve the clogging of the permeable pavement. The active way is to avoid clogging of pervious concrete through optimizing the design (select a suitable aggregate size). The passive method is to rejuvenate the permeability through road maintenance. The clogging level is mainly influenced by the size ratio of clogging particle to the pores of pervious concrete. When the size ratio is between 0.6 and 0.8, it is easy to cause clogging.

Sandoval et al. [67] carried out both laboratory and field investigation on PC using sand, clay, and combination of sand and clay. They developed an analytical model to estimate the clogged PC's permeability based on a parameter called the "potential of clogging" of PC. This model predicts when the clogging phenomenon reaches values higher than expected and therefore, when engineers need to maintain the PC structures. [68] studied the phenomenon of clogging in PC with natural aggregates and recycled aggregates, subjected to three types of sediment. They concluded that PC with recycled aggregates have the best hydraulic performance when compared with PC with natural aggregates. It also proved the hydraulic advantage of implementing the use of recycled aggregates for PC production. [67] also studied the more efficient cleaning method to recovery permeability in PC (pervious concrete) and suggested a periodicity of cleaning to maintain the permeability close to the initial level.

6. PERVIOUS CONCRETE IN WATER PURIFICATION

Pervious Concrete with its interconnected honey combed void structure has some environmentally friendly functions such as sound absorption, water permeability, water quality purification [69]. Stormwater runoff increasingly induces contaminants to the groundwater to imperil the sustainable development of human society. Pavement can be considered as the first line of defense for contaminant removal of the stormwater runoff. [70]. Many research works have been carried out to study the effectiveness of pervious concrete for heavy metal removal and water purification. Jang et al. [45] developed a novel type of eco-friendly porous concrete made entirely with industrial by-products such as, coal bottom ash as coarse aggregate and geopolymer as a binder. The concentrations of heavy metals, leached from the bottom ash in porous concrete were below the selected criteria, and the characteristics of geopolymer dominantly affect the diffusion of heavy metals from bottom ash. [71]) conducted a column study to investigate the potential use of pervious concrete as a reactive barrier for treatment of water impacted by mine waste. The high rate of acid reduction and metal removal by pervious concrete is attributed to dissolution of portlandite which is a typical constituent of concrete. Formation of gypsum, goethite, and Glauber's salt were identified to contributes for the removal of sulphate. Precipitation of metal hydroxides is the dominant metal removal mechanism. Kim et al. [72] studied the water purification characteristics of pervious concrete fabricated with calcium sulfo-aluminate cement and coal bottom ash aggregate. The purification performance of calcium sulfo-aluminate cement was similar to that of ordinary Portland cement. Suspended nitrogen and phosphorous contents were significantly reduced by the physical filtration of voids in the previous concrete, resulting in an improvement of the turbidity. The dissolved phosphorous was adsorbed by the formation of hydroxyapatite in both cements. Pervious concrete is an effective medium to remove lead from aqueous solutions [73]. Hydraulic retention time was found to be vital in the filtration performance of pervious concrete. The organic contaminant namely the cancerogenic Polycyclic Aromatic Hydrocarbons (PAHs), delivered by the stormwater runoff would inevitably pollute the groundwater system by cumulative effect. Shang and Sun [70] developed a Green pervious concrete by introducing organoclay to the conventional pervious concrete as a remediation function for PAH removal. PC with a small addition of organoclay could substantially remove PAHs contaminants and it also has much stronger adsorption and retardation capacity than the conventional pervious concrete [66] . PC has a great potential to be used as a pavement material with the stormwater purification function. Recently Chen et al. [74] developed a kind of alkali-activated slag pervious concrete to purify rainwater and to prevent it from polluting groundwater resources. Chitosan was used in the cementitious material paste to enhance the adsorption capacity for heavy metal ions and other pollutants. The influences of the Bulk Porosity of Aggregate (BPA) and the ratio of Paste to Aggregate (P/A, mass ratio) on water purification capability, water permeability, and mechanical properties of the AAS-PC were investigated. From the study it was concluded that Considering the

water purification, water permeability and strength properties of the pervious concrete, the optimum BPA was 30% and the optimum P/A was 0.25.
Influence of C/A and fly ash on physic-mechanical properties of pervious concrete, and then purifying effect and biotoxicity of pervious concrete was studied [3]. pervious concrete samples can effectively remove the suspended substance and partly remove Total phosphorous (TP) and ammonia Nitrogen (AN). The leaching solution obtained directly from pervious concrete containing fly ash has strong alkalinity which has significant influence on creatures and the disposed solution could be recycled for its lower toxicity and higher survival [3].
It is recommended that the falling head test, constant head, and constant flow test be considered as equally valid means of testing the infiltration rate of pervious concrete in isolation [75].

7. FUTURE WORK IN PERVIOUS CONCRETE

Recently research work was carryout using light weight aggregate namely, expanded clay aggregate (ECA) and crushed sea shells (CSS), as partial replacement for natural aggregate in pervious concrete. For each aggregate type six different mix i.e., PC with 0% (Control), 10%, 20%, 30%, 40% and 50% of coarse aggregate were replaced with light weight aggregate. Initially compressive strength flexural and split tensile strength was studied. The photograph of casted specimen along with the replaced light weight aggregate is shown in Figure 9. The porosity, permeability, compressive & flexural strength were determined in the first phase. The durability properties namely the, abrasion resistance, freeze thaw durability will be studied in the second phase. The light weight aggregates, casted specimen, testing of specimen and falling head permeability setup is shown in figure 9. From the first phase study it can be concluded that the compressive strength and flexure strength of ECA and CSS replaced PC is very low. The maximum compressive strength is around 10 MPa and Flexure Strength is 2MPa. As the density of aggregate decreases the mechanical property is affected [76].The ECA pervious concrete showed more permeability when compared to CSS pervious Concrete. Due to the uneven nature of seashell the porosity of CSS PC is less than ECA pervious Concrete.

(a) Expanded Clay aggregate; (b) Crushed Seashell; (c) Casted specimen; (d) Compression test (e) Split tensile Strength test (f) Falling head Permeability test

Fig. 9. Light weight aggregate pervious concrete

8. CONCLUSION

- Pervious concrete, due to its high permeability, is used as a good alternative for flood control and reduces the Urban Heat Island effect. Pervious concrete used as pavements provides better anti-skid performance on rainy days and better sound absorption capability. Thus, pervious concrete serves as an environmentally friendly material in many aspects. Minimal use of fine also supports microorganisms' growth, which acts as a slow sand filter and involves the water purification process. It also improves the quality of stormwater by reducing heavy metals like lead, zinc, chromium, and copper that are typically found in stormwater run-off.
- Recently, many industrial products, recycled aggregate, and activated slags are used to produce bio-responsive and eco-friendly pervious concrete. The terrestrial and aquatic microbes can attach themselves and be involved in the purification process. High strength pervious concrete could be made by coating the coarse aggregates with a reactive powder high-strength concrete matrix. Alkali activated slag cement paste penetrates the air-cooled electric arc furnace slag and form a strong interlocking effect by producing a PC with high compressive strength and greater water permeability.

- Adding admixtures is found to be more effective than increasing C/A or the content of fine aggregate. Adhesion admixtures wrap more cement and result in higher C/A and surplus cement filler. The aggregates' size plays a crucial role in the porosity, density, and permeability of PCP mixes. The larger size of aggregates induces higher porosity and more interconnected pores within the PC matrix, despite being well graded in nature.
- The addition of fiber produces a positive effect on the mechanical and durability properties of pervious concrete than fine solid waste products. Microfiber reinforcement could delay the crack generation, but it has limited capability to restrain large deformation, especially after cracking. Providing geogrid interlayers in PC pavements will enhance the cracking resistance due to the increase in flexural strength and ductility.
- The high silica content of the acidic pumice leads to better resistance against the surface abrasion. High amounts of chloride, organic matter, and impurities of sea shells cause unfavourable interactions with the cement matrix, thereby producing a harmful effect on the PC's freeze-thaw resistance.
- The use of recycled aggregate, polypropylene fibers, rubber fiber, and crumb rubber slightly affects the permeability indices. The use of silica fume and styrene-butadiene latex yields a more pronounced effect on the permeability indices.
- The active way to avoid clogging of pervious concrete is through optimizing the design by selecting a suitable aggregate size. The passive method is to rejuvenate the permeability through road maintenance. The clogging level is mainly influenced by the size ratio of the clogging particle to pervious concrete pores. When the size ratio is between 0.6 and 0.8, it is easy to cause clogging.
- The high rate of acid reduction and metal removal by pervious concrete is attributed to the dissolution of portlandite, a typical constituent of concrete. The formation of gypsum, goethite, and Glauber's salt was identified to contributes to the removal of sulphate,
- In the present study, lightweight aggregate such as ECA and Seashell was used to produce pervious concrete, and the mechanical and permeability properties were studied. Recently a number of numerical investigations were also done to develop an optimum design of eco-friendly pervious concrete.

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Editor received the manuscript: 08.03.2021