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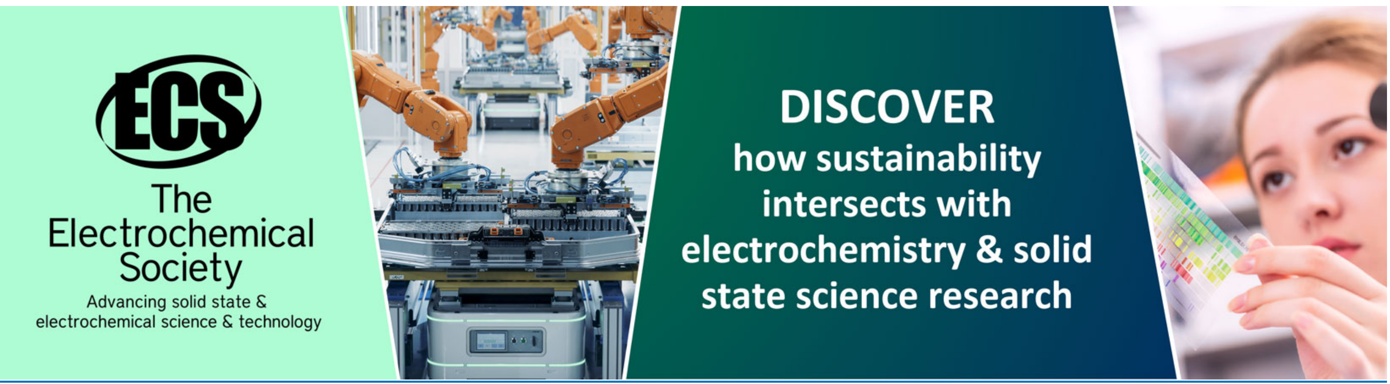

Properties of pervious concrete made with different types of waste aggregate-A literature review

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Abstract. Pervious concrete, also known as porous concrete, contains interconnected pores that allow water from various sources to pass through. This type of concrete is generally used for pavement construction to protect the environment. Pervious concrete contains only coarse aggregate and sometime very small amount of fine aggregate. Many researches were conducted to develop an efficient type of pervious concrete with different types and combination of aggregates. In many studies, along with natural stone aggregate, other types of waste materials were also tried to use as a coarse aggregate in the mix design of pervious concrete. Some of waste materials showed very promising characteristics which can be effectively used in the mix design of pervious concrete with double environmental benefits. This review article provides an overview of some of the earlier investigations on pervious concrete made from waste and industrial by-product materials. The relationships between crushing strength, porosity and water permeability of the pervious concrete with different types of aggregate are presented in this paper. Steel slag, recycled aggregate, and palm oil clicker were among the waste materials utilized as aggregate in pervious concrete, showed comparable performance; even in some instances, better performance was achieved than pervious concrete made with conventional natural aggregate. The shape of waste aggregate, described by the elongation and flakiness indices, greatly affects the strength properties and water infiltration rate of pervious concrete. If these indices are high, the strength properties of the pervious concrete are significantly reduced, but the water permeability is significantly increased.

1. Introduction

Pervious concrete is a special kind of porous concrete that reduces runoff and raises groundwater levels due to its high porosity and ability to allow water from various resources to pass through [1]. This type of concrete is not a recent invention; it was first used in Europe in 1852 but gained popularity around the world in 1923 due to its lower cost compared to the traditional concrete [2]. The US Environmental Protection Agency (EPA) has recognized pervious concrete as a best management practices (BMPs) for first flush pollution control, lowering pollutants in post-construction runoff, and storm water management [1,3]. Figure 1 shows the typical pervious concrete. Since ordinary concrete has very low water and air permeability, it prevents rainfall from being filtered underground. As a result, the groundwater level cannot be recharged and the plants surrounded by the concrete pavement are not growing properly. In contrast, pervious concrete exhibits high permeability, making it a desirable material for urban environment enhancement. Advantages of pervious concrete include its high permeability, low weight, reduced shrinkage, lowered groundwater pollution, and decreased surface water ponding. These benefits could be summarized in the following points: (1) as rainwater enters the earth fast, groundwater resources will be recharged. So the groundwater level will rise. (2) The soil below can be kept moist since the pavement is permeable. This will enhance the surface of the road. (3) The pavement with pervious concrete has ability to absorb noise from running vehicle, resulting in a calm and pleasant environment. (4) The connected pores in the pervious concrete pavement can trap heat and regulate the temperature and humidity of the Earth's surface. As a result, it helps in reducing the urban heat island effect.

However, the high proportion of pores in pervious concrete also diminishes its compressive strength, rendering it unsuitable for high-traffic pavement applications. Nonetheless, pervious concrete is suitable for various low traffic applications such as light traffic pavement, access roads, parking lots, sidewalks and pathways, driveways and entrances, streets/roads shoulders, swimming pool decks, surface courses for tennis courts, drains, zoo areas, friction course for highway pavements, greenhouse floors, and many other possible applications. Aside from its limited application in heavy vehicle traffic zones and reduced compressive strength, another drawback of pervious concrete is its extended curing time [2─5]. Figure 1 shows some typical applications for pervious concrete.

Different types of aggregate and binder are used to produce pervious concrete. To make it more economical and environmental friendly, several waste materials (steel slag, palm oil clicker, burnt bricks, recycled aggregates etc.) were recommended to be used as coarse aggregate in the production of pervious concrete [6,7]. However, the performance of pervious concrete with different types of aggregates are not the same. Moreover, there is no comparative study on the use of waste aggregates in the production of pervious concrete available in the literature. Therefore, this study attempted to summarise the published research studies and pointed out the effect of different parameters on the performance of pervious concrete.

(a) (b)

Figure 1. (a) Pervious concrete [8] and (b) Typical uses of pervious concrete [9].

2. Raw Materials for pervious concrete (PC)

Portland cement, coarse aggregate, and water are the main components of PC. In this type of concrete, the fine aggregates do not exist or appear in a very small portion (less than 10% of the total weight of aggregates). Typically, single size coarse aggregate or aggregate size between 9.5 and 19 mm) are used in the production of PC. It is not suggested to use a wide range of aggregate grading since it reduces the void content or connected pores in the concrete. Admixtures are sometimes used in the concrete mixture to improve the casting performance, because pervious concrete has a low workability; it must be maintained in order to provide adequate working time on the job site. To achieve a stable cement paste and avoid paste drainage to the pavement's bottom during casting and compaction, retarders or hydration stabilizing agents are generally used in the pervious concrete mixture. Agents that increase viscosity (viscosity modifying agents) are also useful because they enable the addition of the required amount of water without causing bleeding and enhance workability [1]. On the use of viscosity modifying agent, water-cement ratio can be kept low which enables to produce relatively high strength pervious concrete [32].

2.1. Typical Mix Design of PC

The typical components of PC are water, binders and aggregate. Sometimes admixtures are added to improve its rheological properties. For a successful design, a balanced composition of the components should be made to ensure the optimal performance of PC in terms of strength, durability and permeability.

The recommended water/cement ratio for PC is between 0.26 and 0.40. The lower water/cement ratio enables to achieve optimum aggregate coating and stable cement paste, as well as to generate the necessary strength and void structure in the concrete. A number of factors influence the relationship between strength and porosity of PC, including the type of binding material, aggregate size, specimen age, and specimen form employed in testing.

The ideal range of cement content in pervious concrete mixture is 350.0 kg/m^3 to 400.0 kg/m^3, which enables to produce PC with adequate strength and water permeability characteristics. The aggregate/cement ratio (A/C) is found to be optimum at 4 to 6 by mass, this will result to an aggregate content of 1400 kg/m^3 to 2400 kg/m^3. When the water/cement (W/C) ratio is raised, the water permeability of PC decreases, which may be caused by cement paste clogging the specimens' pores. The strength is significantly influenced by the aggregate sizes, aggregate-to-binder ratios, and matrix strength [5,10]. The typical range of ingredient quantities for the mix design of PC is given in Table 1. Figure 2 illustrates one of the wet properties of a PC mixture containing varying amounts of water. The water content should be carefully controlled to make a proper pervious concrete mixture. The mixture with correct water content will give a sheen texture and the aggregate will not flow, as shown in Figure 2 (b).

Table 1. Typical mix design for pervious concrete for one cubic meter.

Ingredients	Typical range of quantity
Aggregate (coarse)	1400 ─ 2400 (kg)
*Aggregate (fine)	0 ─ 227 (kg)
Cement	350 ─ 400 (kg)
water-to-cement ratio	0.26─0.40

*Generally, fine aggregate is avoided to use in pervious concrete.

(a) (b) (c)

Figure 2. The formation of ball with pervious concrete mixture containing varying amount of water: (a) insufficient water, (b) adequate water, (c) excessive water [11].

3. Pervious concrete (PC) with different types of aggregate

Many studies were conducted on the use of industrial solid waste materials such as palm oil clinker, steel slag, waste glass, shredded rubber, over-burnt brick aggregate, recycled aggregate and sea shell in the pervious concrete mixture. Table 2 shows a list of different types of coarse aggregate which were utilized in the PC mixtures. Many studies showed that steel making slag could be successfully used as an alternative aggregate to produce PC. The strength properties and water infiltration rate of the PC produced with steel slag exhibited better performance than that of the concrete with natural stone aggregates [12,13].

3.1. Effect coarse aggregate type on the strength and infiltration properties of PC

The properties of pervious concrete are affected by factors like the grading size of the aggregate used to produce the pervious concrete in addition to the type of material used. Meddah et al. [3] replaced part of the natural aggregate by a specific fraction of recycled aggregate of different materials (rubber, crushed seashell, crushed glass, shredded plastic and ferrochrome) in order to produce pervious concrete, as shown in Table 2. It has been noticed that the density of pervious concrete dropped because the recycled aggregate has a different shape and specific gravity than the natural aggregate. On the other hand, no big change has occurred in the void content. Rubberized pervious concrete demonstrated the lowest density and porosity (1700 kg/m^3 and 27.6%, respectively) due to its low specific gravity and capacity to fill the voids, whereas the PC produced with natural aggregates retained on a 5 mm sieve produced the maximum porosity (32.6%) with a medium density of 1735.3 kg/m^3. The average 28-day hardened properties of PCs were tested in this study. It was demonstrated that there is no significant variation in the density of PCs with different types of aggregates. The lowest density was achieved by the incorporation of 10% shredded rubber aggregate. Compressive and flexural strengths were significantly affected by the partial substitution of different recycled materials for natural aggregate, and both of them decreased as the recycled aggregate content increased. Rubberized pervious concrete exhibited the lowest compressive strength (1.9 MPa) while glass aggregate led to the highest strength (10.4 MPa) as compared to the other recycled materials. In contrast, the lowest value of flexural strength was recorded with the seashell aggregate pervious concrete (about 1.5 MPa) and the larger one was in the glass aggregate pervious concrete (2.6 MPa).

Lang et al. [12] studied the influence of steel slag and magnesium phosphate cement on the characteristics of pervious concrete when grain size and molding method were varied. Three different particles sizes were used; fine particles (FP) (2.5 – 5.0 mm), medium particles (MP) (5 – 10 mm) and coarse particles (CP) (10 – 15 mm). Three molding methods were used in the PC casting process, namely vibration molding, tamping molding, and hydrostatic molding. They found that the porosity in all the magnesium phosphate cement mixture (MSPC) was in the range of 23.8% – 26.5% and the water infiltration rate of PCs was in between 5.85 and 7.10 mm/s, but the highest values for porosity and permeability were with the coarse aggregate mixture. Moreover, the study revealed that the type of molding has a negligible effect on the porosity and permeability of PC, although the specimens which were prepared using tamping method had a relatively higher value than the other molding methods.

Wang et al. [13] investigated the effect of using blended steel slag and natural aggregate on different properties including strength and durability properties of PC. Steel slag (SS) and natural aggregate (NA) with sizes ranging from 5 mm to 15 mm, as well as a very small amount of fine aggregate, were used in this investigation. The percentages of replacement of natural aggregate by steel slag were 0%, 25%, 50%, 75% and 100%. The test results revealed that increasing the amount of steel slag aggregate in PC mixtures enhanced the porosity and water permeability (water infiltration rate) of the PC. On the addition of SS aggregate, a positive effect on the strength properties of PC were found. It showed that along with an increase in SS aggregate content in the PC mixture, mechanical strength characteristics of the PC also increased. However, the bulk density of the aggregate mixtures increased as the SS aggregate component in the combination increased. This is phenomenon is attributed to the shape of the SS aggregate. SS aggregate is produced by crushing steel slag and has erratic shapes and numerous sharp edges. Mixtures with 100% steel slag replacement achieved the highest porosity value. Moreover, the permeability had the highest value when the replacement percentage was 75% and 100%, which was about 13 mm/sec. The cube compressive strength with 100% steel slag aggregate was 17.6 MPa which was 34.4% greater than the strength of control pervious concrete (13.1 MPa).

Palm oil clinker (POC) was employed by Ibrahim and Razak [7] as a coarse aggregate in the production of PC. Different percentages of POC were used to replace the natural coarse aggregate. The size of the particles used was between 4.75 and 9.5 mm. The findings of the study revealed that, after 28 days of curing, the density of PC with palm oil clinker varies between 1238 and 1717 kg/m^3, and that was varying with the replacement proportion; as the replacement proportion rises, the dry density of PC decreases. Porosity ranged from 23.9% to 35.18%, which was increased with increasing of the replacement portion. The permeability was found in the range of 46.1 mm/sec − 83.3 mm/sec, and it also depended on the amount of natural aggregate replaced by palm oil clinker aggregates. PC made with natural stone aggregate had a compressive strength of 10 MPa, whereas PCs made with 25% and 50% POC had compressive strengths of 6.7 MPa and 6.6 MPa, respectively. PC made with 100% POC aggregate had the lowest compressive strength, which was 3.43 MPa. This is a result of the high void content in POC aggregate and the rough and flaky nature of POC aggregate.

The impact of utilizing polymer-rubber aggregate on pervious concrete was studied by Shen et al. [14]. The findings showed that the compressive and flexural strengths were 17.5 MPa and 6 MPa, respectively, when the natural stone aggregate was replaced by 14% of the polymer rubber. While the porosity and the permeability were above 18% and 1.16 mm/s, respectively.

Table 2. Summary of research studies on pervious concrete (PC) with various types of aggregates.

study	Material used	Aggregate size (mm)	Compressive strength (MPa)	Permeability (mm/s)	Void ratio (%)
Meddah et al. [3]	Natural coarse aggregate	10.0 - 20.0	15	9.0	19.0
	Rubber		1.8	9.3	12.0
	seashell		4.2	36.0	24.9
	Glass		10.4	10.1	17.6
	Plastic		6.3	16.0	23.0
	Ferrochrome		8.0	20.0	23.0
Lang et al. [12]	Steel Slag	2.5 – 5.0	35.0	6.0	24.0
		5.0- 10.0	37.0	6.5	25.0
		10.0-15.0	34.0	7.0	26.0
Ibrahim & Razak [7]	Palm Oil Clinker	4.75 - 9.5	6.72	46.1-83.3	23.9 - 35.18
Shen et al. [14]	polymer rubber	4.75 - 9.5	17.5	1.16	18.0
Wang et al. [13]	Steel Slag	5.0 – 15.0	16.8	13.0	26.0
Arafa et al. [15]	Waste palm oil products, Biomass aggregate (BA)	5.0 – 10.0	6.4–13.7	18.0-21.0	
Vieira et al. [16]	Recycled aggregate (RA)	4.75–9.5	3.0–14.0	2.5 – 17.5	
Toghroli et al. [17]	Recycled aggregate (RA), Natural coarse aggregate, Fine aggregate	5.0 –10.0	2.8– 28.0	1.3 – 26.3	16.4–30.1
Xu et al. [18]	Steel slag, silica fume,	4.0–20.0	11.6–16.6		
Ćosić et al. [19]	Sand, dolomite, steel slag	4.0–8.0	20.20–69.50		6.3–22.2
Chen et al. [6]	Steel Slag Aggregate (SSA) and limestone (LS)	4.75–9.5	18.0–24.0	4.5	15.0
El-Hassan et al. [20]	Recycled concrete aggregates and slag	4.75–20.0	2.0 – 37.0	1.88-21.14	9.5–22.0
Debnath & Sarkar [21]	Over burnt brick aggregate	2.36–19.0	3.0–10.0	5.3- 21.1	2.14–28.24
Zhang et al. [22]	Steel slag, GGBS, fly ash and/or silica fume	5.0 – 15.0	2.47–5.99	3.0-47.7	20.0–35.0
Chang et al. [23]	Alkaliactivated slag binder (AASC) and Electric arc furnace slag (EAFS) aggregate	2.4–4.8	20.0 – 35.0	0-7.0	16.0–23.5
Mehrabi et al. [24]	Recycled concrete aggregate, pozzolanic additives, pumice,	5.0 – 10.0	8.0–32.5	21.1- 34.2	20.5–36.0
Liu et al. [25]	Sterculia foetida petiole wastes		9.0–13.0	14.4- 30.0	40.0–53.0

In general, among the waste aggregates, steel slag shows better performance when used in the production PC in terms of strength, permeability and porosity when compared with PC with conventional stone aggregate, as shown in Table 2. However, all other waste aggregates showed better performance in the porosity and water permeability, but the strength properties were compromised (Table 2). The shape of the waste aggregates has the great effect on the strength properties. Most of the waste aggregates are flaky and elongated in shape, which are negatively effect on the strength properties when used in PC.

3.2. Effect of infiltration rate on the compressive (crushing) strength

Figure 3 illustrates the general relationship between the crushing strength and water infiltration rate of PC. The figure consists of data from different studies with different types of aggregate. Although it has been proved that the aggregate size, type, and admixtures affect the crushing strength of PC, Figure 3 provides a general overview of the relationship between crushing strength and water infiltration rate.

There is an inverse relationship exist between crushing strength and water infiltration rate. For example, the infiltration rate of PC decreases with the increase of compressive strength, as can be seen in Figure 3. Among the aggregate types, steel slag, recycled aggregate, palm oil clinker in pervious concrete performed similarly in terms of strength and infiltration rate compared to the pervious concrete containing natural stone aggregate, as can be seen in Table 2.

3.3. Effect of porosity on compressive strength

The porosity or void ratio of the pervious concrete (PC) is directly correlated with its compressive or crushing strength. An inverse relationship could be used to describe the relationship. It is well established that dense concrete possesses higher compressive strength than porous concrete. The compressive strength versus water infiltration rate of PC with various types of aggregates and admixtures is presented in Figure 4 [3,12,13,15,17,20–24,27–31]. As the connected pores in the concrete increase, the strength of the concrete decreases. It can be observed in Figure 4 that the PC made with recycled aggregate [17,24] exhibited a balanced performance between compressive strength and porosity.

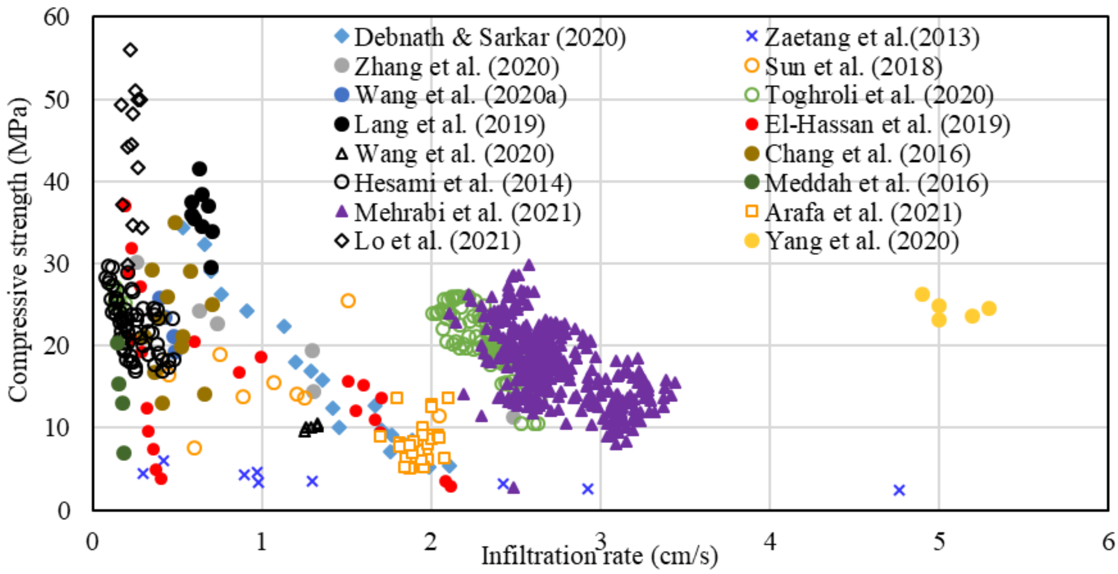

Figure 3. Compressive strength versus water infiltration rate of PC.

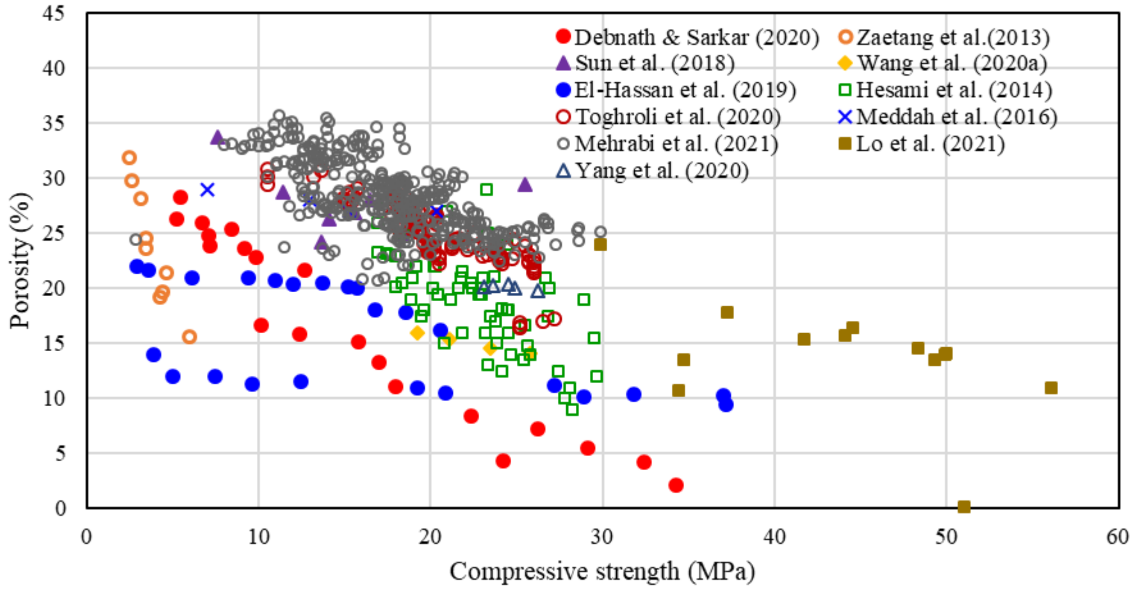

Figure 4. Porosity versus compressive strength of PC.

3.4. Effect of porosity on the infiltration rate

Figure 5 illustrates the relation between the porosity and water infiltration rate (permeability) of pervious concrete. As anticipated, the water infiltration rate is almost proportional to the porosity of the porous or pervious concrete. Almost all the studies showed that as the pore content in pervious concrete increases, the rate of water infiltration increases (see Figure 5). The porous concrete with recycled aggregate, burnt brick and steel slag aggregates showed good connectivity between the porosity and water infiltration rate. Meanwhile, the porous concrete made with recycled aggregate demonstrated balanced porosity and water infiltration rate. However, porous concrete with other waste aggregates also achieved the minimum characteristics of pervious concrete as specified by different codes.

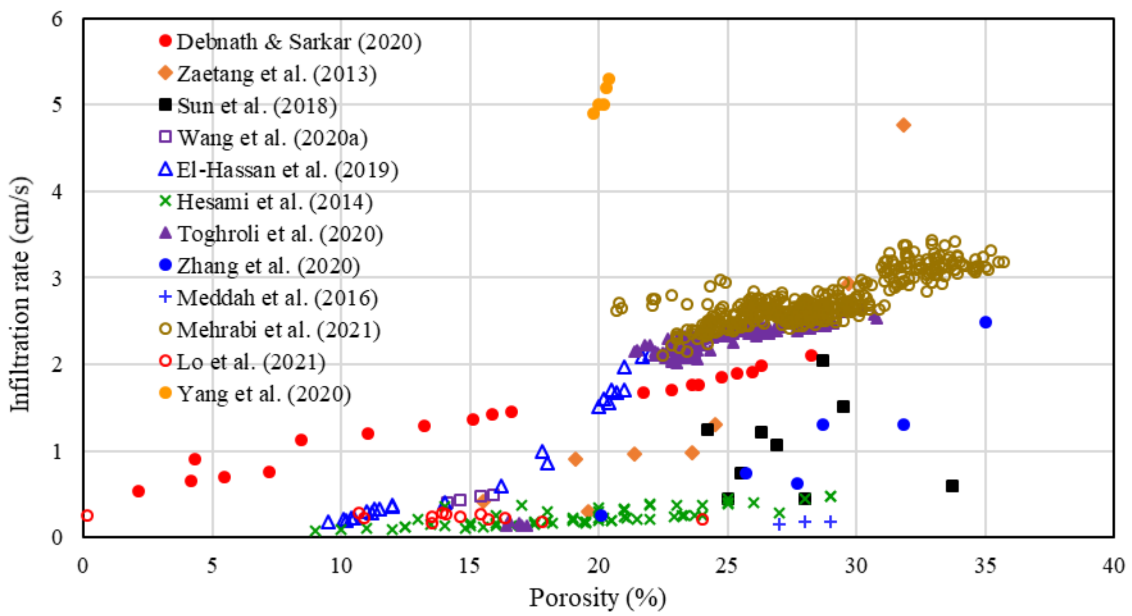

Figure 5. Porosity versus infiltration rate of PC.

4. Research gap and future direction of research

Although a significant number of research studies on the application of various types of aggregate in the pervious concrete mixture can be found in the literature, the durability aspect of porous concrete was not systematically studied. Some of the waste aggregates show promising effects on the strength and water infiltration properties of the pervious concrete. However, very little is known about the environmental effects, such as the heavy metal leaching and the durability of pervious concrete with waste aggregates. In addition, long-term effects such as creep, shrinkage and fatigue performance of the PC with waste aggregate are not studied well. Future research may address all of these parameters, allowing the construction industry to select the best materials for their intended use of PC in infrastructure development.

5. Conclusions

A short review on pervious or porous concrete (PC) with different waste aggregates, namely steel slag, glass, burnt bricks, recycled aggregate, polymer rubber, shredded plastic, waste glass and palm oil clicker aggregates, is discussed in this paper. A detailed database is presented for the pervious concrete with waste materials. General relationships with different parameters of pervious concrete were established and detailed comments were provided. From the analysis of the literature listed in the paper, the following conclusions can be made:

Some waste materials, namely steel slag, recycled aggregate and glass waste, can be used to produce pervious concrete for light traffic pavement, walkways and other applications.

If the flakiness and elongation indexes of the waste aggregates are high, then the porosity and water permeability of the PC may increase significantly when compared to the PC with natural stone aggregate. However, the strength properties of the PC with waste aggregate may be significantly reduced.

The porosity and crushing strength of pervious concrete are inversely proportional. The crushing strength of pervious concrete diminishes significantly as its porosity increases. The water infiltration rate and the compressive strength of pervious concrete were also shown to have a similar connection.

Among the aggregate types studied in this paper, steel slag, palm oil clinker and recycled aggregate showed comparable performance in terms of strength and infiltration rate compared to the porous concrete produced with natural stone aggregate.

The weather effect, leaching properties and long-term effect of the porous concrete with waste materials are not studied systematically. Future studies need to address these issues to facilitate the construction industries to use certain types of waste aggregates in their structure.

From this literature review, it is possible to conclude that different industrial solid by-products can be successfully used to produce porous concrete, which will reduce the demand for natural aggregates and will help to achieve green and sustainable development in the road and pavement sector.

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