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Factors influencing performance of pervious concrete

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Subject review

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Factors influencing performance of pervious concrete

Pervious concrete is an environment friendly solution for eliminating imperviousness-related drawbacks of conventional concrete. Pervious concrete mixes are predominantly composed of cement, coarse aggregate, and water. The partial or complete elimination of fine aggregate results in porous structure, which influences performance of pervious concrete. This article is aimed at reviewing major factors involved in the design of pervious concrete mixes, namely the compaction, aggregate to cementitious material ratio (ACR), sand fraction, water to cementitious material ratio (w/cm), size of coarse aggregate, and void ratio or porosity. The effects of various admixtures, replacement materials, and fibres, are also discussed. The results indicate that pervious concrete acts as an effective medium in promoting the sustainability of urban environments due to its multi-aspectual benefits.

Key words:

pervious concrete, porosity, coarse aggregate, size of aggregates, fibres, compaction

Pregledni rad

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Pregled čimbenika koji utječu na svojstva poroznog betona

Porozni (propusni) beton je ekološki prihvatljivo rješenje u odnosu na nepropusnosti konvencionalnih betona. Porozni beton najčešće se sastoji od mješavine cementa, krupnijeg agregata i vode. Djelomičnim ili potpunim uklanjanjem sitnog agregata dobiva se porozna struktura koja zatim utječe na svojstva poroznog betona. Cilj je ovog rada opisati glavne čimbenike koji utječu na mješavine poroznog betona, odnosno zbijenost, omjer agregata i cementnog materijala (ACR), udio pijeska, omjer vode i cementnog materijala (v/cm), veličina krupnog agregata i udio šupljina ili poroznost. Također, u radu se raspravlja i o učincima različitih dodataka, zamjenskih materijala i vlakana u mješavinama. Rezultati pokazuju da porozni beton djeluje kao učinkovit medij u promicanju održivosti urbanih sredina zbog svojih višestrukih koristi.

Ključne riječi:

porozni beton, poroznost, krupniji agregat, veličina agregata, vlakna, zbijanje

1. Introduction

Conventional concrete pavement, also known as rigid pavement, is characterized by higher compressive and flexural strength, but it prevents storm water seepage into layers of soil beneath the pavement. This is, however, a major threat to the recharge of groundwater, conservation of water, and runoff management, especially in urban environments. Porous concrete or pervious concrete eliminates these negative impacts of conventional concrete through introduction of inter-connected voids that allow water to drain at higher rates than the rate of precipitation. These pores are provided all over the body of pervious concrete by purposely excluding fine aggregates, either completely or partially, in order to achieve inter-connectedness of the pore system. This pervious concrete has other names namely no-fines concrete, porous concrete, enhanced porosity concrete, and permeable concrete [1]. In general, pervious concrete primarily consists of cement, water, and coarse aggregate, which is why it is known as no-fines concrete. The cement paste should be adequate enough to coat the surface of the aggregate and to provide an appropriate bond between aggregate grains. The porosity of pervious concrete generally ranges between 11 and 3 5% [2], with a permeability of 0.2 - 3 cm/s [3]. However, this also engenders a decrease in density ranging from 1600kg/m^3 to 2000 kg/m^3 [4] and compressive strength of 2.8 to 28 MPa [5, 6]. As to its application, pervious concrete can be used in the construction of pervious pavements or floors for sidewalks, parking lots and pavement curb applications [7], overlays in some pavement systems [1], airport fields [8], base course for heavy traffic pavements [1], tennis courts [6], swimming pool decks, embankments, animal barns, stone protection structures [9], etc. Luck et al. [10] determined that pervious concrete can be effectively used for the separation of solids and liquids in agriculture. Lund et al. [11] analysed the use of pervious concrete as stabilizing material between the wearing course and bridge substructure. Similarly, Muthiayan and Thirumalai [12] confirmed that strength values of pervious concrete meet strength requirements for dry lean concrete (DLC), which is primarily used as sub-base and base for flexible and rigid pavements. Erosion of beaches can also be prevented by using pervious concrete along with geo-synthetics [13].

Compared to conventional concrete, heat storage capacity of pervious concrete pavements is lower and the rate of cooling is higher, due to which the underlying soil temperature is quite lower [14]. Pervious concrete acts as a filtering medium for liquids before they reach the surface of soil, and thus this concrete impedes entry of pollutants into soil. Moreover, the problems related to heat and moisture exchange between underlying soil and atmosphere in urban scenarios can be mitigated with the use of pervious concrete. Thus, this concrete reduces the heat islands formation in urban pavements while also reducing urban heat storage [15]. Also, downsizing or complete elimination of expensive irrigation or drainage systems can in some cases be envisaged. However, pervious concrete pavements are susceptible to blocking of pores by vegetation and soil sediments, and thus require regular maintenance to maintain design permeability values throughout their expected lifespan.

This review article principally deals with:
- influence of mix parameters, namely the aggregate to cementitious material ratio (ACR), cement content, water to cementitious material ratio (w/cm), porosity or void ratio, and sand fraction
- effect of the properties of materials involved in mix design, especially the size of coarse aggregates
- effect of additives, replacement materials, and fibres when added to the mix

2. Mix properties

2.1. Aggregate to cementitious material ratio (ACR)

Performance of pervious concrete is greatly influenced by the aggregate cement ratio, as coarse aggregates occupy the most of the concrete skeleton, which needs sufficient binding even without fine aggregates. Coarse aggregates contribute by approximately 85 % in the volume composition of high performance pervious concrete (HPPC) mixes [15].

The typical range of cementitious material content recommended by ACI 522R-10 [6] varies between 270 and 415 kg/m^3 (Figure 1). Some researchers made use of lower and higher cement content values than the ones mentioned above in order to understand their effects. The use of higher cement content results in higher compressive strength [13, 16]. In the case of mixes with low cement content, failure occurs through the cement paste by breaking the bond with aggregates, whereas mixes with high cement content failed along the aggregates [13]. A higher cement content increases the thickness of cement paste coating along the surface of aggregates [17]. The thickness of cement paste coating on the aggregate surfaces a plays vital role in describing hydrological and structural properties of pervious concrete [18]. Xie et al. [19] made an attempt to study the effect of maximum paste coating thickness on the aggregate surface that will not hinder the minimum porosity values.

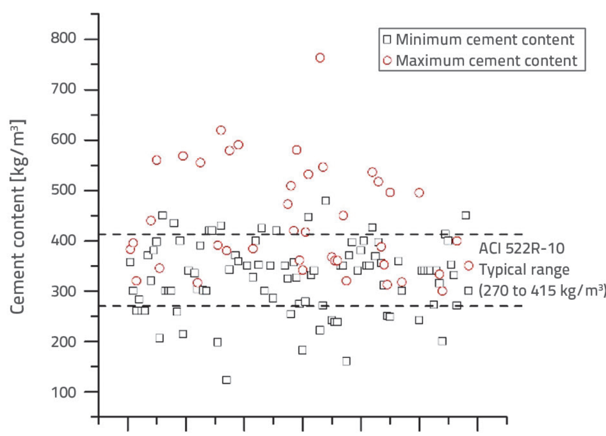

Figure 1. Cement content in pervious concrete mix

In general, the ACR values for pervious concrete ranges between 4 and 6 in terms of mass [20]. Pervious concrete mixes with ACR of more than 4.5 and less than 4.5 could be considered as low paste content mixtures and high paste content mixtures, respectively [5]. Wang et al. [21] recommend the ACR value in the range of 4.17 to 5 for achieving better compressive strength. The ACR alters strength values of pervious concrete as it defines the content of voids [22]. Mechanical strength of pervious concrete decreases with an increase in ACR, which is due to reduction in the content of cementitious material that adheres to the aggregate surface, and to an increase in the size of pores [23]. ACR values contribute by approximately 50 % in the permeability of concrete. A decrease in ACR results in the reduction of inter-granular voids due to higher resistance against compaction provided by lesser aggregates [24]. This is in line with the findings of Emiko et al. [25] and Mohammed et al. [26], who indicate that lower ACR values result in improved strength values whereas higher ACR values result in improved permeability values. The volume of cementitious paste should be chosen based on the thickness of coating that can be obtained on the surface of the aggregates. A thinner coating may result in an inadequate bond strength, whereas a thicker coating may hinder the interconnectivity of pores and result in accumulation at the bottom of concrete [27]. Higher ACR in mix results in lesser fatigue life, which brings about an early failure of the pavement system [28]. ACR values adopted by various researchers are shown in Figure 2.

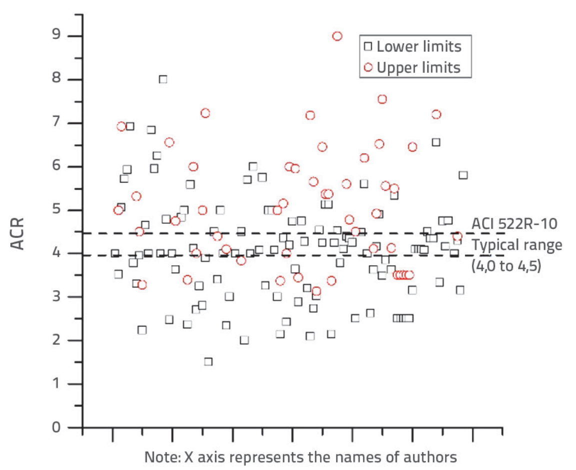

Figure 2. Aggregate to cementitious material ratio (ACR) of pervious concrete mix

2.2. Water to cementitious material ratio (w/cm)

Pervious concrete with uniformly distributed or, in other words, consistent cement paste all over the specimen is essential to optimize its performance. Consistency of cement paste relies mainly on the water cement ratio and admixtures, and on the type and amount of binder [29]. Higher w/cm ratio results in an increased workability of the cement paste, which can also be obtained at low w/cm ratios by using superplasticizers [7].

The water to cementitious material ratio (w/cm) of pervious concrete generally varies from 0.27 to 0.43 [20, 30], as shown in Figure 3. Nguyen et al. [31] recommend 0.34 to 0.40 as the w/cm for mixes without admixtures. The absence of fine aggregates makes this low w/cm sufficient to completely surround coarse aggregates. The lack of fine aggregates results in a decreased surface area of contact thereby demanding less water for binding the aggregates. However, using additives such as superplasticizers or other workability modifiers, the water requirement can be further decreased to provide an effective bonding of aggregate surfaces with cement paste. Higher w/cm can lead to bleeding by displacement of cementitious material under gravity to the bottom of the mix leading to an uneven distribution of voids [32]. The w/cm of more than 0.38 retains cement paste in liquid state, which settles under gravity [31]. The porosity and permeability properties of pervious concrete drop with an increase in w/cm [33].

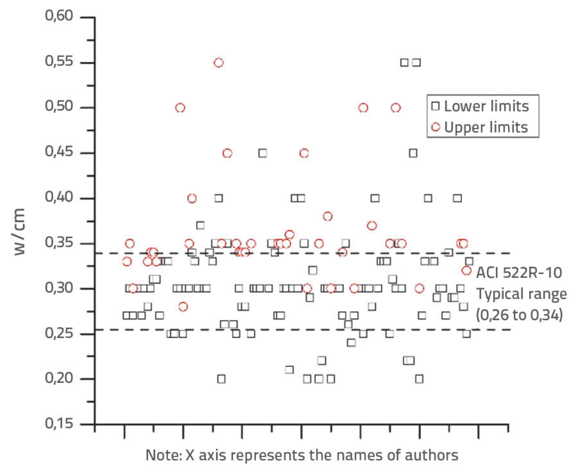

Figure 3. Range of w/cm adopted in pervious concrete mix

The w/cm of less than 0.25 results in a harsh mix due to higher resistance to compaction [24], which results in weaker bonding between aggregates and cement paste [34]. Lim et al. [16] define this mix with lower w/cm as dry and brittle. Thus, adoption of an optimum water content is vital to avoid both segregation and bleeding. Various researchers incorporated agents/admixtures like superplasticizers [35-37], viscosity modifying agents [3], water reducing admixtures [20], rheology modifying admixtures [5], retarding admixtures [6], air entraining admixtures [38], etc. to ensure sufficient workability without increasing the w/cm beyond an optimum level. The use of polymer-based superplasticizers tends to improve mechanical properties of pervious concrete [16]. In comparison with the porosity and size of aggregates, the effect of w/cm is quite minimal and insignificant [32].

2.3. Sand fraction

Nguyen et al. [31] suggest the incorporation of 7 % of sand with respect to the weight of coarse aggregates for attaining balance between the permeability, mechanical strength, and durability properties. An increase in the fine aggregate proportion considerably improves mechanical properties of pervious concrete [1, 39, 40]. The volume of cement paste to coat the aggregate surface increases due to an increase in sand fraction [41]. When fine aggregate is used, its water absorption affects the hydration process and consequently mechanical strength [42]. The performance of high w/cm ratio mixes improves considerably with the inclusion of sand compared to the low w/cm ratio mixes, as water absorption by sand can reduce the hydration of cement in the latter case [41].

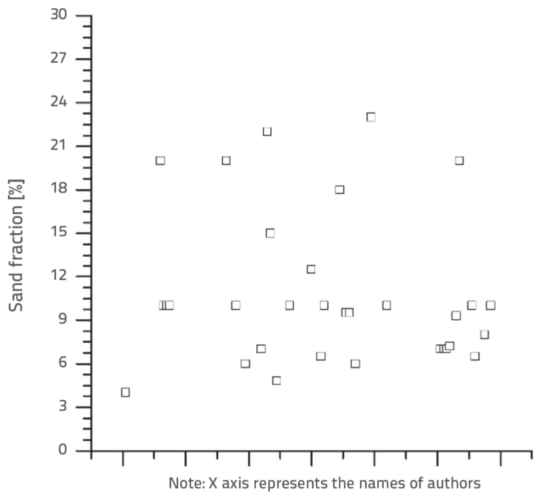

Figure 4. Proportion of sand included in pervious concrete mix

The absence of fine aggregates contributes to the void ratio and permeability of concrete [1, 40, 42]. However, a little fine aggregate content in pervious concrete tends to improve its durability and strength [20]. Comparable observation is made by Muthaiyan and Thirumalai [12] and Maguesvari and Narasimha [43] in all ranges, who state that this improvement is due to the enhancement of interfacial bond. Figure 4 shows the sand fraction incorporated in the pervious concrete mix by various researchers. The flexural strength and split tensile strength of pervious concrete are also enhanced by the increment in the sand fraction [43]. An increase of sand proportion in pervious concrete from 15 % to 20 % leads to the 43 %, 46 % and 64 % increase in compressive strength, flexural strength, and split tensile strength, respectively [1]. The weight loss of specimens subjected to Cantabro abrasion test dropped considerably with an increase in sand fraction [41].

2.4. Porosity or void ratio

Porosity is a fundamental property that serves the purposes of porous concrete due to the permeation of water. Liu et al. [44] mention that porosity plays a predominant role in describing properties of pervious concrete. However, porosity does not offer any advantage in mechanical properties of concrete and can hence be considered as the weakest portion of the porous concrete structure [45]. Similarly, when establishing the relation between porosity and strength of pervious concrete, Lian et al. [46] mention pores as defects contributing to the fracture of the specimen. The porosity of pervious concrete is predominantly influenced by the size of aggregates, shape of aggregates, and nature of aggregates [47]. The grading of aggregates may decrease the porosity through better packing of the voids [29]. Li et al. [48] identified the particle size distribution and compaction as the most influencing factors with respect to porosity. The void ratio at the bottom portion of the specimen is usually slightly less than 10 % lower compared to the top and middle sections due to high paste content and higher flow of paste under vibration aided with gravity [49]. The absorption capacity of binder materials also results in the difference between porosity values [18].
Pervious concrete has three types of porosities, namely closed pores, open pores and connected pores [27]. Zhong and Wille [50] define effective porosity and total porosity as the ratio of connected pores volume and ratio of total pore volume (sum of connected and non-accessible pores) to the total volume of the specimen, respectively. The permeation of water initiates from the open pores which are connected to the outside environment [48]. Connected pores play a major role in influencing the porosity and drainage properties [27, 48] whereas the open porosity influences the strength properties of pervious concrete [48]. Liu et al. [44] determined that the total porosity involves 10 to 20 % of closed pores and 80 to 90 % of effective or connected pores.

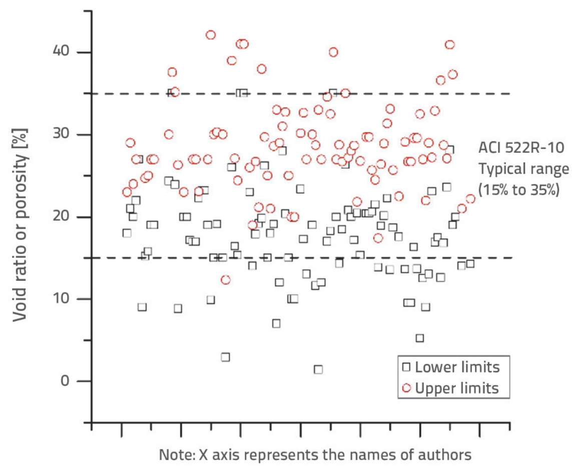

Figure 5. Porosity or void ratio range adopted in previous studies

The porosity of concrete decreases with the reduction in aggregate size [9, 30, 42]. The total voids of pervious concrete tend to drop with an increase in fine aggregate content. The workability of concrete is affected by the use of superplasticisers and other agents due to change in total voids. Regardless of the size of aggregates, the incorporation of single sized aggregates resulted in a narrow range of porosity in comparison with graded aggregates [29]. The use of blended aggregates, i.e. the aggregates with varied sizes, resulted in lower porosity due to the filling effect of smaller sized aggregates on the pores of larger sized aggregates [22]. For a given paste volume, both open and connected porosities decrease steadily with an increase in w/cm due to the filling up of pores [48]. An increase in the volume of paste increases the filling effect of paste on the voids, which influences the porosity for a fixed w/cm ratio [48]. The porosity of concrete decreases with an increase in thickness of cement paste that coats the aggregate surfaces [17].

The porosity of pervious concrete increases with an increase in ACR values [51]. Localised porosity in the proximity of the fracture face influences the fatigue life and flexural strength more than the total porosity [28]. An addition of pozzolanic materials strengthens the concrete matrix by decreasing porosity values [52]. An increase in void content of the pervious concrete mix results in an increased weight loss [12]. It should be noted that an increase in design porosity has meagre impact on the size of the pores, but it influences the number of open and connected pores [53].

Industrial waste is found to possess higher porosity in comparison with recycled aggregates, which is due to heterogeneity of recycled aggregates [52]. An attempt on proportioning the pervious concrete mix to attain the desired porosity using high and low cement paste content was made by Deo and Neithalath [5]. The connected porosity was found to decrease with a decrease in the size of aggregates used [54]. The number of frost resistance cycles drops with an increase in the connected porosity of concrete, while the rate of mass loss increases with an increase in the number of freeze thaw cycles [27, 32]. Observation of the stress-strain curve reveals brittle nature of low porosity pervious concrete, which is in line with the findings for conventional concrete [5]. Yao et al. [27] recommend the use of 15 % porosity for pervious concrete when used as base course for extreme site conditions, such as higher annual mean temperature differences, and severely heavy traffic conditions. Voids present in pervious concrete systems have been found to absorb sound quite efficiently [55]. Ng et al. [7] recommend the void content of pervious concrete ranging from 15 % to 25 % as the acceptance criterion for ensuring the quality of concrete. Figure 5 shows the range of porosities adopted by previous researchers.

Table 1. Properties of pervious concrete

Sl. No.	References & Description	ACR	Sand fraction [%]	Cement [kg/m³]	w/cm	e/n [%]	k [mm/s]	Aggregate size [mm]	f_c [MPa]	f_r [MPa]	f_t [MPa]	Density [kg/m³]
1	[9] - HPPC	3.52-5..00	-	300-395	0.30-0.35	18-23^e	2-20	13-20 5-13 2.5-5	16-25	3.5-5.0	-	1620-1740
	[9] - CPC	5.06-6.92	-	260-320	0.27-0.30	21-29^e	2.5-33	13-20 5-13 2.5-5	11-15	2.2-3.2	-	1620-1740
2	[3] - LSLD	6.92	-	260	0.27	27^n	8.6^C	10	9	-	0.98	1855
	[3] - HSHD	3.78	-	370	0.30	9^n	2.4	10	35	-	3.04	2228
3	[36] - SPC	3.30-5.32	-	320-440	0.28-0.33	15-25^n	-	4.75 9.5	35-47	4.2-6.1	-	-
	[36] - PPC	3.95-4.50	-	380	0.30-0.34	16-25^n	-	4.75 9.5	38-51	4.8-7.4	-	-
4	[23]	4.00	-	-	0.25-0.28	-	2.52-2.64	4.75-9.5 9.5-16 16-19	13-32	2.2-4.5	-	-
5	[37]	3.63-4.75	-	340	0.30	20-23^n	3.05-3.53	2.36-9.5	18-23	3.2-3.8	2.55-3.01	1900-2500
6	[45]	3.40-4.40	-	342-579	0.35-0.45	3-12^n	3.1-13.3^C	0.24-0.48 0.48-0.95	8-28	2.6-4.2	1.4-3.1	1990-2391
7	[29]	5.70	-	351	0.30	18-27^n	-	2-4 4-8	25-51	-	1.69-2.95	-
8	[49]	2.14-3.37	-	254-509	0.21-0.36	15-25^e	-	5-13	15-44	-	-	-
9	[56]	4.36-5.15	-	356-420	0.30	10-20^n	1.58-7.5^F	10 20	15-54	-	2.5-4.5	2036-2359
10	[52]	2.42-4.00	-	326-580	0.40	10-20^n	1.88-21.14^F	20	3-37	0.9-3.1	0.68-3.10	1625-1984

Table 1. Properties of pervious concrete

Sl. No.	References & Description	ACR	Sand fraction [%]	Cement [kg/m^3]	w/cm	e/n [%]	k [mm/s]	Aggregate size [mm]	f_c [MPa]	f_r [MPa]	f_t [MPa]	Density [kg/m^3]
11	[55]	2.88-3.44	-	447-532	0.20-0.30	13-27^{n}	2.95-6.48^{C}	5-12 12-16	13-36	-	-	-
12	[48]	2.09-7.18	-	222-763	0.20-0.35	1-33^{n}	0-24^{C}	5-10	8-76	-	-	-
13	[46]	4.54-4.00	0 do 18 %	-	0.30-0.38	17-34^{n}	-	4.75-9.5 6.7-9.5 4.75-13.2	12-46	-	-	1734-2240
14	[47]	4.35-4.78	23 %	340	0.30	20-22^{e}	3.05-3.46	12.5-4.75	18-23	3.2-3.7	2.55-2.8	1870-2005
15	[15] – PR	4.49	-	350	0.30	20-30^{e}	8.9-16.6	4.75-9.5 9.5-19	9-79	1.3-12.9	1.3-12.8	-
	[15] – ER	4.49	-	350	0.30	20-30^{e}	8.9-16.6	4.75-9.5 9.5-19	9-61	1.3-12.3	1.3-12.2	-
16	[50] - UHSM	2.50-3.50	-	-	0.22	10-27^{n}	-	1.2-4.8	15-66	-	-	-
	[50] - HSM	2.50-3.50	-	-	0.45	16-30^{n}	-	1.2-4.8	9-23	-	-	-
	[50] - NSM	2.50-3.50	-	-	0.55	14-30^{n}	-	1.2-4.8	8-23	-	-	-
17	[16]	3.15-6.45	-	242-495	0.20-0.30	5-32^{n}	1.13-22.8	1.18-9.5 9.5-19	8-52	1.9-4.5	-	-
18	[58] - w/cm 0.27	4.10	7 %	340	0.27	12-27^{n}	1.08-2.8^{F}	2.36-19	13-25	2.2-4.3	1.7-3.2	-
	[58] - w/cm 0.33	4.10	7 %	340	0.33	9-22^{n}	0.8-2.4^{F}	2.36-19	13-29	2.2-4.9	1.8-3.3	-
	[58] - w/cm 0.40	4.10	7 %	340	0.40	13-29^{n}	2.6-4.8^{F}	2.36-19	12-24	2.1-4	1.6-3.2	-
19	[1]	4.35	0-20 %	315-333	0.30	13-37^{e}	2.4-8.8	4.75-9.5 9.5-16 16-25	10-33	1.0-5.0	0.34-3.52	1825-2338
20	[59]	5.80-6.84	10 %	300-350	0.33	14-22^{n}	-	0-4 4-8 8-16	20-27	2.8-4.9	-	2077-2435

Note: f_c - Compressive strength, f_r - Flexural strength, f_t - Split tensile strength, ^{e} - Void ratio, ^{n} - Porosity, ^{F} - Falling head method, C - Constant head method, HPPC - High performance pervious concrete, CPC- Conventional pervious concrete, LSLD - Low strength/low density mix, HSHD - High strength/high density mix, SPC - Supplementary cementitious material modified pervious concrete, PPC - Polymer modified pervious concrete, PR - Polyester resin, ER - Epoxy resin, NSM - Normal strength matrix, UHSM - Ultra high strength matrix, HSM - High strength matrix.

3. Size of aggregates

Typically, single sized aggregate between 19 and 9.5 mm [6] is ideal for pervious concrete as it enhances the permeability of concrete [20]. However, the compressive and tensile strength of pervious concrete can be increased by the use of two sizes of aggregates instead of single sized aggregates [29]. The maximum size of aggregates suggested by Yang et al. [40] for pervious road base is 26.5mm. The size of aggregates incorporated in previous studies is presented in Table 1.

Variation in the size of aggregates causes no considerable effect on the workability of pervious concrete [9]. The porosity of aggregates decreases with the use of graded aggregates due to the close packing of pores resulting in decreased permeability. Uniform gradation of aggregates has a considerable impact on the permeability of pervious concrete [60]. Uniform gradation of aggregates does not make concrete denser due to smaller range of aggregate sizes, therefore resulting in higher void content. Incorporation of aggregates with wide range of sizes tends to decrease voids by effective packing of voids present in between larger aggregates. Use of aggregates of size 9.5 to 19 mm [20] tends to increase the voids sufficiently, whereas the 2.36 to 9.5 mm size increases the strength considerably [2, 61]. Yang et al. [40] show that strength parameters are improved, and that adequate permeability is ensured, in the case of incorporation of approximately 20 % of coarse aggregates of size 4.75-9.5 mm. Smaller aggregate size negatively impacts porosity by filling up pores, but is beneficial in increasing the unit weight of concrete. Based on the nature of aggregates and the method of compaction, the size of pores varies from 2 to 8 mm [6]. Larger-size pores and higher porosity can be obtained by using larger-size aggregates [16] whereas smaller-size aggregates engender smaller sizes of pores [6]. However, the size of pores is also influenced by the gradation of aggregates and the thickness of aggregate paste, and is not chiefly influenced by the size of coarse aggregate [17].

The presence of higher proportion of small-size aggregates in the gradation results in denser concrete [59]. According to Grubesa et al. [62], sharp grain edges of diabase even allow movement of water through the pores, and are hence considered as an optimum aggregate type for pervious concrete. Larger-size aggregates possess larger-size internal pores [53]. Fine grained dolomite results in higher compressive strength, whereas coarse grained diabase and steel slag result in higher compressive strength [62]. Use of small-size aggregates can lead to a homogeneous mix, whereas larger-size aggregates result in heterogeneous mix [22]. Energy dissipation in pervious concrete is significantly influenced by the number, spacing, shape, and size of pores. Larger pores increase the stress concentration with decreased toughness [5], which causes high rate of distress propagation [28]. The freeze-thaw damage of pervious concrete is largely affected by the size of coarse aggregates [32]. Smaller-size aggregates help in improving the freeze-thaw durability of pervious concrete and other properties [32].

4. Method of compaction and compaction energy

Compaction method plays a predominant role in influencing properties of pervious concrete. An increase in compaction energy influences volumetric properties of concrete by increasing the bulk density, while also reducing the permeability of concrete by decreasing void content [41]. Compaction by hand results in heterogeneous mix due to differential aggregate packing resulting in low mechanical strengths. Compared to hand compaction, compaction using an impact hammer results in higher mechanical strength [29]. However, Mulyono and Anisah [63] suggest the use of lower impact energy to ensure that aggregates are not crushed during compaction. Kevern et al. [64] make use of gyratory compaction whereas Putman and Neptune [65] and Li et al. [48] suggest heavy metal compaction for simulating site compaction. Compaction by means of vibration methods suitable for conventional concrete is not appropriate in the case of pervious concrete as such compaction affects distribution of voids [62]. Voids ratio decreases with an increase in vibration energy [51]. Yang et al. make use of vibrating table for 40 seconds with 5 kg load on the top. Zhu et al. [57] recommend vibration time of eight to twelve seconds to attain a good trade-off between permeability and strength. Chindaprasirt et al. [49] use similar vibrational surface compaction by applying vibrational energy of 90 kNm/m^2 for ten seconds.

Connectivity of pores can be negatively affected by the compaction method and energy due to its effect in the orientation and packing of ingredients and, hence, restriction of compaction is essential [29]. Impulsive compaction methods such as proctor hammer [17, 28, 67-69] or Marshall hammer [41, 66] are quite often used to compact porous concrete specimens for testing purposes. In the case of pavement application, pervious concrete is compacted using hand steel rollers with low compaction energy [66]. The cement paste thickness will be minimal in the case of uncompacted samples, whereas it increases with an increase in compaction levels leading to formation of cement paste bridge between aggregates [17]. An increase in compaction effort tends to result in close packing of aggregates, which reduces the number and size of voids [38]. An increase in the duration of vibration or repetition of compaction increases the compressive strength significantly [57]. Calibration of lab compaction with respect to field compaction is essential to ensure appropriate durability [66].

5. Role of admixtures/replacement materials and fibres in pervious concrete

5.1. Mineral admixtures/replacement materials

Utilization of waste materials/industrial by-products in construction industry can potentially improve their effective management, and minimise in turn their ill-effects on the environment [1, 55]. Materials such as fly ash, metakaolin, silica fume, and ground granulated blast furnace slag, are also suggested for use as supplementary cementitious materials (SCM) in addition to cement [18]. The use of additives leads to high rate of strength development at an early age due to rapid cementing of the aggregate and paste [1]. The strength of cement matrix can be enhanced with the use of pozzolanic materials such as nano-silica which will produce more C-S-H gel due to the micro-filling effect resulting in higher strength values [26]. The effect of various types of materials on the properties of pervious concrete, along with proportions of addition or replacement, is presented in tables 2 and 3.

Replacement of aggregates in pervious concrete was researched using both low and high density materials. The most commonly used low density materials are recycled or waste materials, which contribute to an effective waste management. Though an increase in the recycled concrete aggregate content negatively impacts strength values of pervious concrete, it can be used in contents that yield required standard strength values. This can improve economy and reusability of aggregates [88]. These materials characterised by lesser density than conventional aggregates result in decreased strength parameter values, but those still remain within acceptable ranges. Incorporation of high-density aggregates such as copper slag yields higher compressive strengths, which is mostly due to their higher mechanical properties and denser transition zone [37]. The use of pozzolanic materials enhances the cement matrix and improves mechanical properties of pervious concrete [73]. Incorporation of waste materials in pervious concrete mixes leads to an improved sound absorption [55]. Split tensile strength of pervious concrete can be improved effectively with the use of fly ash and silica fume [1]. The use of fly ash, GGBS, and metakaolin improves durability of pervious concrete by increasing its resistance against sulphates and alkali-silica reaction [13]. The compressive strength develops at a faster rate during early ages of concrete containing metakaolin, resulting in a denser microstructure [76]. Wang et al. [21] recommend the use of 20 % fly ash for high strength pervious concrete.

Table 2. Cement replacement by supplementary cementitious materials (SCM)

References	SCM	Replacement range	Merits	Demerits
[13. 19. 30. 42. 52. 56. 70. 71]	GGBS	0 to 70 %	– Decreased albedo value – Densifies cement matrix – Improves strength and durability	– Reduces porosity
[1. 19. 23. 37. 42. 46. 61. 72. 73. 74. 75]	Silica fume	0 to 25 %	– Improves microstructure of cement paste – Improves mechanical strength – Improves fatigue property – Improves the durability and strength parameters – Substantial improvement in strength along with superplasticizers – Pozzolanic properties aids in additional C-S-H gel formation	– Decreases permeability
[1. 7. 11. 13. 14. 18. 21. 26. 36. 42. 51. 63. 68]	Fly ash	0 to 75 %	– Improves fatigue property – Improves freeze thaw resistance – Improves mechanical strength values – Micro-filler effect decreases porosity and permeability	– Decreases compressive strength at higher replacement levels
[13. 76]	Metakaolin	0 to 10 %	– Improves cement paste – Better early age compressive strength – Higher resistance to sulphate attack and abrasion	
[77]	Sorghum hush ash	0 to 25 %	– Improves compressive strength due to pozzolanic effect	
[58]	Rice husk ash	0 to 12 %	– Improves strength of cement paste – Optimum percentage – 8%	
[51]	Epoxy resin and hardeners	0 to 40 %	– Increases adherence between ingredients	
[72]	Styrene butadiene latex	10 to 20 %	– Improves internal cohesion between ingredients	
[29]	Micro-silica	15 %	– Effect of silica fume is significant in the case of finer aggregates compared to coarse aggregates	
[7]	Crumb rubber	0 to 5 %		– Decreases porosity and permeability due to filling of voids
[15]	Polyester resin	12 to 16 %	– Increases mechanical properties and durability properties	– Decreases permeability values
[15]	Epoxy resin	12 to 16 %	– Increases mechanical properties and durability properties	– Decreases permeability values

Table 3. Replacement materials in place of coarse aggregates

References	Material	Replacement range	Merits	Demerits
[30. 52. 70. 71. 72. 73. 78. 79. 80. 81]	Recycled aggregates	0 to 100 %	– Increases porosity and permeability – Splitting strength not affected by recycled aggregates	– Recycled aggregates affect total strength due to poor transition characteristics and poor aggregate paste bonding – Unit weight decreases with recycled aggregates – Decreases strength due to low bulk density and abrasion resistance
[72]	Fibre rubber	0. 5 to 3 %		– Lower compressive strength, splitting tensile strength, and modulus of elasticity
[59. 62]	Steel slag	0 to 100 %	– Higher density of concrete – Higher density concrete compared to other aggregates	
[82]	Tire chips	0 to 100 %		– Lower compressive strength, splitting tensile strength, and modulus of elasticity
[62]	Dolomite	0 to 100 %	– Improved compressive strength	
[62]	Diabase	0 to 100 %	– Optimal type from hydrologic point of view	
[35]	Volcanic pumice	0 to 100 %		– Modulus of elasticity decreases
[83]	Palm oil clinker	0 to 100 %	– Optimum replacement is 25 %	– Not suitable for structural applications
[55]	Oil palm kernel shell	0 to 75 %	– Sound absorption will be superior	– Compressive strength decreases with an increase in proportion
[55]	Cockle shell	0 to 75 %		– Fall in strength values with increase in proportion
[54. 84]	Incinerator bottom ash	0 to 100 %	– Satisfies requirement of pervious concrete – Higher porosity values	
[47]	Copper slag	0 to 100 %	– Optimum content of copper slag is 60 % based on compressive, split tensile, and flexural strength	
[85]	Crushed sea shell	0 to 60 %		– Lower mechanical strength – Weaker durability
[86]	Acidic pumice	0 to 50 %	– Increased porosity	– Decreased mechanical properties and density
[71. 80]	Ceramic waste	100 %		– 60 % decrease in compressive strength
[45. 80]	Electric furnace slag	0 to 100 %	– Improves mechanical properties better than normal aggregates – Higher permeability and compressive strength compared to gravel	
[87]	Engineered bio-mass	0 to 25 %	– Optimum percentage replacement is 20 %	

Table 4. Influence of fibres on properties of pervious concrete

Fibre type	References	Length [mm]	Dia [mm]	Proportion [mm]	Remarks
Polypropylene fibres	[72]	12		0.1 to 0.2 %	Compressive strength decreases Improves split and flexural strength
	[66]	19			No significant improvement in strength
	[66]	12			Decreases strength and stiffness
	[66]	18			Increase in fibre length improves mechanical properties
	[56]	18			No significant improvement in tensile strength
	[91]	38.56		0.16 to 0.49 %	56 mm and 0.16% is desirable
	[92]				Improved tensile strength
	[93]	19			No influence on horizontal and vertical strain
	[75]			0.025 to 0.1 %	-
Cured carbon fibre composite material	[67]	11.6		0.27 to 0.4 %	Enhances the flexural and tensile strength of PC
	[67]			0 to 1.5 %	Significant increase in mechanical and durability properties
	[90]	2 to 0.841		0 to 5 %	No significant improvement in compressive strength but the flexural and split tensile strength values increase Higher resistance to abrasion and impact
Glass fibres	[73]	12	0.1	0.05 to 0.2 %	Decreases compressive strength but improves flexural and split tensile strength
	[58]	12	0.1	0.2 %	Improves mechanical properties substantially
Steel fibres	[58]	36	0.7	0.5 %	Superior mechanical properties compared to glass fibres
Polyphenylene sulphide fibres	[58]	50 to 54	0.07	0.3 %	Good interlock between fibres and aggregates due to higher flexibility
Cellulose fibres	[94]			0.5 %	Improves the tensile strength and freeze-thaw resistance

5.2. Fibres

Fibres can be potentially incorporated in pervious concrete to improve its mechanical and durability properties [89]. Use of metallic fibres can be restricted in case of pervious concrete due to its direct contact with water [89]. Incorporation of polypropylene fibres improves flexural and split tensile properties of pervious concrete, just like in the case of conventional concrete [72]. However, the effect of fibres on the compressive strength of pervious concrete is negligible [67]. In some cases, it even leads to slight decrease in compressive strength [73, 90]. When low density fibres such as glass fibres are used, the density of pervious concrete has been found to decrease [73]. Emiko et al. [25] observed that steel fibres improve compressive strength more than flexural strength.

Clustering of fibres in the form of spheres should be avoided with the use of mixing methods other than rotary drum mixer [90]. Fibres reduce the void content of pervious concrete by closing up voids [66]. However, poor cohesive nature and balling effect of fibres leads to an increase in void ratio, which in turn increases permeability [73]. Permeability of pervious concrete is affected by the proportion of fibres [91].

An increase in compressive strength can be observed by incorporating fibres in low porosity pervious concrete, whereas it negatively influences the compressive strength of high porosity pervious concrete [56]. The durability of pervious concrete pertaining to abrasion and freeze-thaw can be improved by the use of fibres [91]. Fibres act as a bridge across cracks, which tends to improve the post crack strength by restraining their propagation [73]. The addition of fibres can improve the post peak loading providing higher toughness to the pervious concrete specimen [90]. The influence of various types of fibres, including their sizes and proportions, on the properties of pervious concrete is presented in Table 4.

6. Conclusion

The paper revealed various factors that influence the properties of pervious concrete, namely the compaction, ACR, w/cm, sand fraction, size of aggregates, and porosity. The importance of the above factors is stressed and their effect on the properties of pervious concrete is presented. Moreover, the use of replacement materials and fibres is discussed, which depicts the research gap related to the use of materials other than the ones discussed.

The influence of various parameters involved in the design of pervious concrete mixes, and the properties of ingredient materials, are extensively discussed in the above sections. Pervious concrete acts as an effective medium in promoting the sustainability of urban environments due to its multi-aspectual benefits. This article focuses on the use of the above summarized properties of the ingredients and the mix, the aim being to obtain a balance between the strength and permeability of pervious concrete based on local requirements. Important parameters discussed in the paper can be summarized as follows:

- *Cement Content:* Failure pattern varies with the cement content in the cement paste. The use of high cement content improves mechanical properties due to an increase in the paste coating thickness on the surface of aggregates.
- *ACR:* Decrease in ACR values leads to enhanced mechanical properties due to decreased void nature. Increase in ACR increases permeability due to an interconnected void structure.
- *w/cm:* This highly influences fresh properties compared to hardened properties. Higher w/cm values result in increased gravitational flow of cement paste, while also affecting permeability. The use of workability modifying agents is recommended to achieve desired mechanical properties.
- *Sand Fraction:* Mechanical and durability properties of pervious concrete can be gained with the addition of fine aggregates, but they influence the permeability as well.
- *Porosity or Void ratio:* Porosity has a greater effect on the properties of pervious concrete compared to other parameters. It emphasized the drainage nature of concrete, but acts as a defect with respect to mechanical properties of pervious concrete.
- *Size of Aggregates:* Single sized aggregates are recommended for achieving higher drainage efficiency. Graded aggregates can also be used for enhancing mechanical properties but they have a considerable effect on drainage properties. In both cases, aggregates of size not exceeding 19 mm are recommended.
- *Method of compaction:* It is recommended to use impact methods for compaction. Extensive care and vibration time measures should be taken if compacted by vibrational methods.
- *Effect of admixtures/replacement materials:* Replacement of cement by supplementary cementitious materials promises to improve mechanical and durability properties, which is further aided by their pozzolanic characteristics. Recycled/lower density aggregates decrease mechanical strength but can be used for less significant applications. Industrial by-products can be incorporated in pervious concrete, which is a good solution with respect to waste management.
- *Effect of fibres:* Fibres have a minimum effect on drainage properties of pervious concrete. With the addition of fibres, the efficiency of strength improvement is generally higher with respect to tensile and flexural strength compared to compressive strength. It is recommended to incorporate fibres in the pervious concrete mix used for paving applications.

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