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Pervious concrete: a state-of-the-art review

Mudasir NAZEER [a],*, Kanish KAPOOR [a], S P SINGH [a]

[a] *Department of Civil Engineering, Dr. B R Ambedkar National Institute of Technology, Jalandhar, Punjab, India-144011*

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ABSTRACT

Pervious concrete is a special type of concrete, achieved by either minimizing or excluding the sand from the normal concrete mix. In recent years, the practice of pervious concrete as a pavement material in small volume roads and parking lots has added much significance due to its constructive and eco-friendly characteristics. It is used to lessen the problem of local flooding in municipal areas and is significant tool to lessen the burden of municipal drainage system. This paper reviews the various properties, factors controlling the performance of pervious concrete, clogging mechanism and de-clogging techniques and lastly the factors that enhance the life span and properties of durability of pervious concrete are discussed. Durability tests of pervious concrete like, permeability, surface abrasion, freeze thaw and thermal conductivity are discussed. Furthermore, controlling factors such as water to cement ratio, aggregates, admixtures, compaction and curing are also discussed in this review. There occurs an expensive range for future research to recognize the better material that will make it a favorable ecological roadway material for high speed and high-volume traffic in coming times.

1 Introduction

Concrete is an amalgamated substantial, mainly comprising of diverse components such as binding material (cement), water, coarse aggregates, fine aggregates and admixtures. Amongst these constituents, aggregates (coarse and fine) play a pivotal role in concrete work and occupy 60-75% of over-all volume of concrete [1, 2]. Pervious concrete is prepared by neglecting most of the fine aggregates from ordinary conventional concrete and by cautious regulation of the fraction of cement paste. This special concrete is a distinct kind of concrete with comparatively higher percentage void content and higher penetrability of water to that of normal concrete. It is an eco-friendly substantial and provide number of purposes of civil and architectural related engineering aspects. Due to high development in urban areas, impervious surfaces such as road surface and buildings decrease the percentage of water infiltration to the ground strata and thus raise the volume of runoff [3]. Pervious concrete is used to lessen the local flooding in municipal areas as it permits water to flow through normally impervious structure [4, 5]. Pervious concrete is generally used in pedestrian footpaths, car parks, sidewalks and other low traffic areas [6]. Neglecting fine aggregates from pervious concrete elevates the range of porosity between 15-40% thus

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* *Corresponding author. Tel.: +91 7889570255.*
E-mail address: mudasirn.ce.18@nitj.ac.in

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provides better permeability and noise absorption properties [7-9]. The compressive strength of this holey material is predominantly found by using the relation of total porosity of concrete, which further depends on a number of host factors i.e. binder content, ratio of water to cement, properties of aggregate and compaction during placement of this concrete [10, 11]. The compressive strength of pervious concrete at 28 days of curing ranges from 5 to 28 MPa but can be increased to higher grades upto 46 *MPa* with insertion of some mineral admixtures, fine aggregates and special chemical admixtures [11-13].

ACI committee 522 suggests 0.26-0.40 water cement ratio to create worthy aggregate coating and paste stability of concrete. Pervious concrete is a high penetrable material, having a water flow rate normally around 0.34 *cm/s* [11]. Besides many benefits, pervious concrete is unavoidably vulnerable to clogging that leads early degradation and serviceability complications. Physical clogging is caused because of the sediments of sand, clay and debris built upon surface, while biological clogging is caused due to Algae, Bacteria and plant root penetration [12]. The clogging potential is likely to be maximum when the sediment particle size is near or equal to the size of pore of this special porous concrete [5]. The main aim and objective of this review is to gather different studies about concrete of high permeability and to analyse its different properties and factors governing the life span of this unique concrete. The structure of the paper follows the various properties of pervious concrete and different factors that manipulate the performance. Moreover, clogging mechanism and de-clogging methods of pervious concrete are addressed. Finally, the techniques improving durability properties of pervious concrete are discussed.

Overall environmental benefits of pervious concrete

There are number of benefits that can proof pervious concrete as a sustainable and green environmental material.

Pervious concrete eliminates the problem of surface runoff during heavy monsoon and rainy season.

It recharges the groundwater, thereby making the vegetation happy with air and water.

It eliminating/ reduces the size of storm sewers.

It eliminating the need of 2 to 3% slope to prevent ponding.

Pervious concrete used in pavement, makes the potholes visible.

It minimizes the heat island effect by passive cooling of air voids (good thermal insulation).

Pervious concrete pavement produces less traffic noise than asphalt pavement.

Thermal conductivity of pervious concrete is approximately half that of dense concrete.

2 Properties of Pervious Concrete

The performance of pervious concrete depends upon the various mechanical and durability properties like compressive strength, permeability, Porosity and pore structure, Surface Abrasion Resistance, Freeze thaw Resistance and Thermal conductivity. Previous literature of pervious concrete has been studied and brief discussions of these properties from are given in this section of review article.

2.1 Composition and Mix Design

Pervious concrete, also known as gap graded concrete because of having high porosity, like 15% of porosity is considered as minimum. Therefore, in order to preserve voids in the material, it is generally developed by using coarse aggregates of size 19.00-19.50 *mm* [2, 5, 10]. However, many researchers have used aggregate size in the range of 2.36-9.50 *mm* to develop superior properties of pervious concrete [5, 14]. ASTM C33 / C33M – 13 discuss the limiting percentage of inert materials like clay and chert which otherwise deteriorates the bonding of aggregates with binding materials if present in higher percentage. Further suggests that the physical properties of aggregates used for pervious concrete should alike as that of normal concrete [15]. The physical properties like shape and size of aggregates plays an essential role to preserve permeability, durability and mechanical characteristics of pervious concrete used for pavements [13, 16]. It has also been observed that granite aggregate based pervious concrete shows good freeze-thaw resistance than limestone and river gravel aggregate based pervious concretes. Water absorption and abrasion resistance of aggregates play a vital role in controlling the freeze and thaw damage of pervious concrete [17]. Ordinary Portland cement (OPC-Type 1) has been used as binding material in the preparation of pervious concrete [18]. Maintaining abundant mortar coating around the aggregates enhances the durability of pervious concrete. The basic aim and objective in pervious concrete mix design is to attain good balance between the parameters like voids, cement paste, workability and strength [16]. ACI 2010 suggested trial and error method of mix design and field testing in order to get desired properties. Furthermore, design mix methods established on excess paste theory and volumetric ratio of paste, inter particle voids are proposed to get close-fitting mix design [13]. The mix proportions of various researches are shown in Table 1.

Table 1 - Mix proportions

Author	**Water to cement ratio**	**Aggregate to cement ratio**	**Aggregate *Kg/m³***	**Cement *Kg/m³***	**Water *Kg/m³***
Kevern et al.[14].	0.24	4.70:1	1600	340	80
	0.26	5.2:1	1620	310	80
	0.26	3.97:1	1510	380	100
	0.27	6.5:1	1700	260	70
	0.27	4.78:1	1580	330	90
	0.28	10:1	1820	180	100
	0.30	4.75:1	1570	330	100
	0.30	4.72:1	1560	330	100
Huang et al.[19].	0.35	4.5:1	1440.80	320.20	112.10
	0.35	4.5:1	1486.90	330.40	115.60
	0.35	4.5:1	1586.90	352.60	123.40
Ibrahim et al.[20].	0.35	8:1	1600	200	70
	0.35	12:1	1800	150	52.85
Lim et al. [15].	0.30	4.25:1	1560	367	110.10
	0.30	6.44:1	1560	242	72.96
	0.20	4.25:1	1560	367	73.40
	0.30	4.25:1	1560	387	110.1
	0.26	3.62:1	1560	430	110.10
	0.30	3.15:1	1560	495	148.50

2.2 Compressive strength

It is observed from the previous studies that hardened properties of pervious concrete show great dependence on aggregate to cement ratio in addition of water to cement ratio [9]. Type of aggregate shows direct relation with the development of compressive strength, for example granite aggregate based concrete shows better results than limestone and other aggregates [21]. Pervious concrete mix made with insertion of 20% of fine aggregates along with 100% of coarse aggregates yields a compressive strength of 12.64 *MPa* [21]. Zaetang et al. made pervious concrete mix using OPC, Natural limestone aggregates, Recycled coarse aggregates (RCA) and super-plasticizer with water to cement ratio of 0.24. It was observed that using recycled aggregates in pervious concrete, a maximum compressive strength of 15 *MPa* was obtained against 60% replacement of RCA with natural aggregate [22]. A. Solomon used two types of aggregates of the size of 9.375 *mm* and 18.75 *mm* to made optimum mix design of pervious concrete regarding strength and permeability. Pervious concrete having maximum compressive strength of 8.20 *MPa* was witnessed at cement to aggregate ratio of 1:6 [23]. The strength of pervious concrete can range from 3.50 *MPa* to 28.00 *MPa* after 28 day curing age and can be further increased to 46 *MPa* with the addition of admixtures and superplastsizers [20]. Pervious concrete Pavements and footpaths not exposed to vehicular movement requires compressive strength of more than 13.80 *MPa* [24]. However, limited speed and infrequent usage pavements require minimum strength of 20.70 *MPa* [13]. P. designed M20 pervious concrete mix according to ACI-522R-10 using fly ash as replacement for cement, maximum compressive strength was obtained against 20% replacement of cement with fly ash at 0.38 *w/c* ratio [16]. The 7 and 28 day compressive strength of pervious concrete was observed and presented in Table 2. It is observed here that the 7 day compressive strength was found to be 70-90% as that of 28 day compressive strength of pervious concrete, also the rate of attaining 7 day strength of pervious concrete was higher than that of 7 day strength of normal concrete [25]. A maximum Compressive strength of 35 *MPa* was observed with the insertion of electric arc furnace slag (EAFS) in pervious concrete mix [26].

Table 2 - Compressive strength of pervious concrete.

S No.	Cement to aggregate ratio	Water to cement ratio	Fly ash (%)	Compressive strength (7 day)	Compressive strength (28 days)
1	1:4.41	0.38	20	16.52	21.40
2	1:4.41	0.38	40	13.20	17.80
3	1:4.41	0.38	60	6.66	11.20
4	1:4.41	0.38	80	5.02	8.40
5	1:4.41	0.38	100	Not workable	-

To assess the compressive strength and flexural strength of pervious concrete, there is no availability of standard test method at present. However, ASTM Subcommittee C09.49 has recommended a test method under following guidelines.

- The specimen for the test purpose should be cylindrical in shape and of the size of 101.60 mm and 203.20 mm.
- The cylindrical specimen is compacted through standard proctor hammer and filling of specimen is to be completed in two layers against 20 blows in each layer.
- After 24 hours of casting, curing of pervious concrete is done through covering the watered surface with polythene sheets or thick gunny bags as per ASTM C31.
- Compressive strength of pervious concrete is done as per ASTM C39 and flexural strength test is done as per ASTM C78. Moreover, freeze-thaw, sulphate and acid attack test are done as per ASTM C666-03 and ASTM C1012.

The dramatic effect of compaction on strength of concrete may be clearly seen from the Fig. 1. For example, the concrete containing 10% of voids have the strength drop of 50% as compared to fully compacted concrete. Compaction, in addition to expelling of entrapped air, promotes a more even distribution of pores within the concrete and thus reduces the flow path (tortuosity) in case of permeability of pervious concrete.

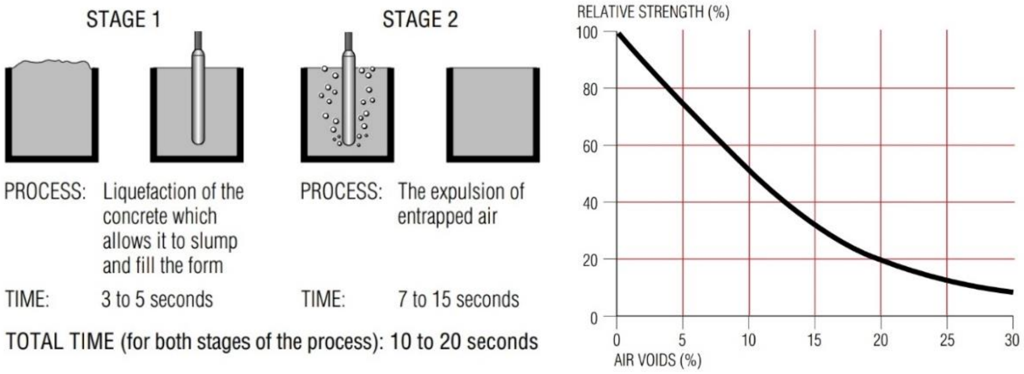

Fig. 1 - Loss of strength through incomplete compaction

2.3 Permeability

It is the property that states the ease with which permeable medium permits liquid under definite hydraulic gradient. Permeability is one of the pore structure dependent properties that also depend on aggregate size, compaction level, gradation and cement content. Permeability of pervious concrete fluctuates widely from 0.003 to 3.30 *cm/s* [18, 27, 28]. Y. Qin et al. observed that range of permeability varies between 0.100 to 2.00 *cm/s* [29]. It depends upon host of properties like distribution of size of aggregates, shape of aggregates, and degree of connectivity and tortuosity of pores [4]. Permeability can be determined easily by falling head permeability cell apparatus (Fig. 2) [30]. Hydraulic gradient of 2.00 is generally used in standard falling head permeability apparatus while 2.00 to 7.30 is used as modified hydraulic gradient [4]. The permeability of 2.67 *cm/s* was observed as highest values of permeability under falling head test when natural aggregate of 20 *mm* was used. These highest values of permeability were due to the higher porosity values of 35.9% [31].

Permeability decreases with the increase in the amount of glass fibres in Pervious concrete. At 0% fibre inception, permeability of pervious concrete was 150 $l/m^2/minute$ (0.25 *cm/s*). While an insertion of 0.10 % of fibre, permeability of concrete was 143 $l/m^2/minute$ (0.238 *cm/s*) [32]. The permeability of pervious concrete mix having cement to aggregate ratio 1:4 and water to cement ratio between 0.23 to 0.25 ranged between 0.05 to 4 *cm/s* [29]. Maguesvari and Narasimha observed the coefficient of permeability of pervious concrete mix at water cement ratio of 0.34 and cement to aggregate ratio 1:4.5. It was observed that aggregates having high angularity number show high permeability and aggregates with low angularity number show low permeability. Results confirm that the permeability range of pervious concrete was between 0.76 *cm/s* to 2.03 *cm/s* [21]. Huang et al studied the permeability of pervious concrete at 0.35 *w/c* ratio and 1:4.5 cement to aggregate ratio. It was observed that the permeability was within the range of 1.00 to 2.00 *cm/s* [33]. Kevern et al. study the effect of fly ash in pervious concrete and observed that upto 20 % of replacement of cement with fly ash, permeability gets decreased but as the percentage of fly ash was increased beyond 20 %, permeability goes on increasing. Further at 50% replacement, permeability was observed same as that of the control mix (0% fly ash) [34].

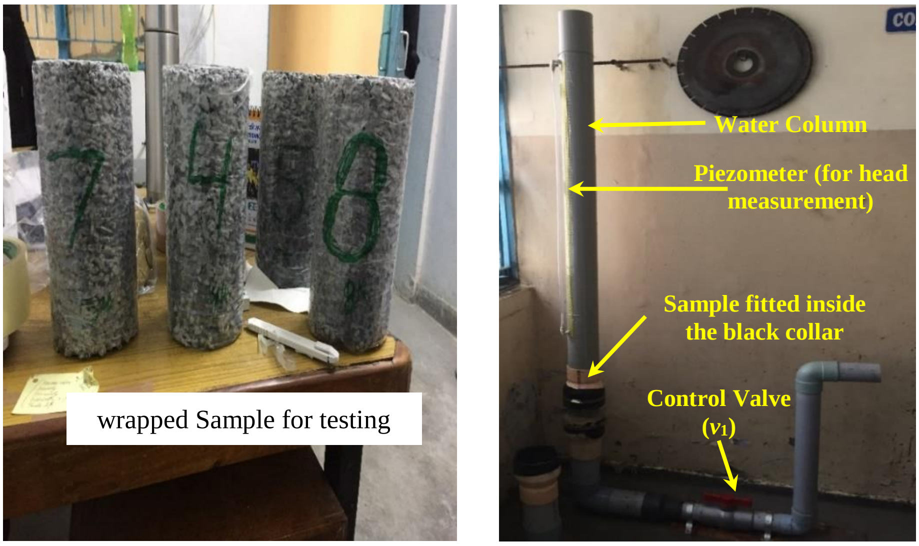

Fig. 2- Permeability Apparatus

The simple and accurate values of permeability are determined by falling head permeability cell. The apparatus used to determine the permeability of pervious concrete was prepared in accordance to permeability setup used in permeability of soil sample (IS:2720-1986). The procedure of this test simply starts by closing the valve (v_1) until the cylindrical tank is filled with water. Time (t) is recorded when Valve (v_1) is opened to make the water head fall from initial head h1 (1000 *m*) to a final head h_2 (250 *mm*). The Valve 2 of the apparatus is used at the end of each test to drain the cell of permeability and to clean the rig after the clogging test. This procedure is repeated three times for each sample and the average time (t) is used to determine permeability (*m/s*) according to Darcy's equation.

$$K = (A_1/A_2)\frac{L}{t}\ln(h_1/h_2)$$

Or this equation can also be presented as,

$$K = (A_1/A_2)\frac{L}{t}2.303\log(h_1/h_2) \tag{1}$$

Where A_1 cross-sectional area of water column pipe, used as water tank, A_2 is the cross-sectional area of sample which is cylindrical in shape and L is the length of cylindrical sample which is wrapped with adhesive to stop the lateral movement of water, h_1 and h_2 are top and bottom water heads.

2.4 Porosity and pore structure

The pore properties of pervious concrete play a vital role in characterising the material as viable pavement system. Pervious concrete comprises of large voids interconnected to each other, depends upon host of parameters like proportion of mix, aggregate used in concrete and degree of compaction etc. The pore size of pervious concrete generally ranges between 2 *mm* to 8 *mm* in fresh state [18, 28]. X. Kuang used the X- ray tomography technique to find the average effective pore size of pervious concrete and found it of the size of 3.425 *mm* [35]. The strength of pervious concrete decreases with increase in percentage of porosity for example, O. Deo and N. Neithalath performed experiment on pervious concrete samples having porosities in the order of 15%, 20% and 25% and the values of compressive strength have been found in the range of 38 to 44 *MPa*, 29 to 35 *MPa* and 15 to 22 *MPa* respectively. Thus, with each 10% increase in porosity, strength is reduced by 50% [36]. Tortuosity of pervious concrete is another key factor that governs the permeability, defined as the ratio of effective length to the total length of sample and is find out by using X-ray tomography technique (XRT) [37]. Besides large interconnected pores, pervious concrete also contains very fine capillary and gel pores having size range from several microns to nanometres. It is observed from the literature that the void content of pervious concrete is typically 15-35% and it depends on few properties like aggregate content, gradation, particle shape, and w/c ratio and compaction factor [24]. Percolation through pervious concrete can be low (percolation rate is < 15%) or high (percolation rate is > 35%), depends upon the host no of factors discussed as above [38]. Porosity of hardened pervious concrete can be determined by two densities, density free from voids and measured density of the concrete mix.

$$Porosity(\%) = 100 \times (T - D)/T \qquad (2)$$

Where T is the total compacted density of fresh pervious concrete and D is the normal density of hardened pervious concrete. Porosity can also be determined as per ASTM C1754, by calculating saturated surface dry sample mass in air and mass of the sample immersed in water for 24 *hours*. Porosity is then calculated in percent according the following equation.

$$\phi = \left[1 - \frac{w_3 - w_1}{V\rho_w}\right] \times 100\% \qquad (2)$$

Where, w_1 is the mass (kg) of sample in water, w_3 is mass (*kg*) of sample in air, V is the sample volume (m^3), ρ_w is the density of water (1000 kg/m^3).

2.5 Surface Abrasion Resistance

Abrasion (shown in Figure 3) is the process of wearing down or rubbing away the surface of the pavement. Resistance to abrasion is the most important factor that governs the long-term service and durability of pervious concrete. Abrasion resistance of pervious concrete is commonly found out by three different methods, Cantabro test, Loaded wheel Abrasion test and Surface Abrasion test [39]. ASTM C1747 is considered as the standard to gauge the degradation of pervious concrete due to impact and abrasive loadings. After 500 revolutions of Cantabro method, the mass lost from hardened pervious concrete is collected and is expressed as percentage of initial mass [40]. Pervious concrete having large amount of gravel aggregate had minimum abrasion resistance as the bond is not so strong between aggregate and cement paste. However, pervious concrete made with recycled coarse aggregates (RCA) shows enhanced resistance against abrasion, which was due to more roughness (friction) of adhered mortar [41]. J. Yang and G. Jiang conducted the study of abrasion on diverse mix samples of recycled coarse aggregate pervious concrete (RCAPC) and recycled block aggregate pervious concrete (RBAPC). It was observed that the weight loss of 100% natural aggregate based concrete was 8.2 *grams* that was much more as compared to RCA and RBA based concrete. The abrasion resistance of RBA pervious concrete gets amplified upto 20% replacement level. This enhancement of abrasion resistance of RBA based concrete was due to superior bond between aggregate and cement paste [42]. The weight loss of RBA based concrete was 52% which is slightly higher than acceptable value of 50% according to ASTM C33-03 [43]. Moreover, RCA based pervious concrete sample shows better abrasion resistance at all replacement levels. The lowermost weight loss in abrasion was 5.30 *grams* for 40% replacement of RCA which is significantly lower than 8.20 *grams* of 100% natural aggregate mix. However, the weight loss of pervious concrete with 100% RCA was still lesser than that with natural aggregate. The use of RCA based concrete thus show better abrasion resistance and improved strength than that of concrete prepared with natural aggregate.

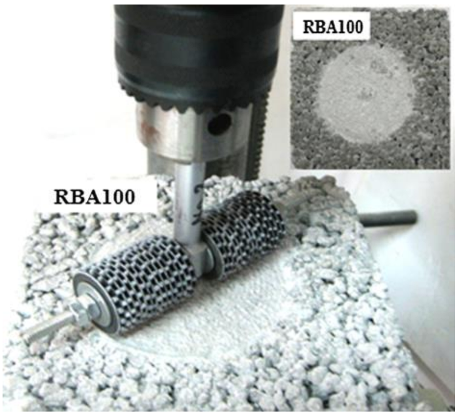

Fig. 3 - Surface abrasion testing.

2.6 Freeze thaw Resistance

Pervious concrete consisting of large macro pores (2-8 mm) which generally stores water and during freeze thaw cause the deterioration of material. Freeze thaw resistance is generally measured as the quantity of mass lost in successive freeze thaw cycles [44]. ASTM C666/C666M - 03 describes the standard freeze thaw test evaluation, which is same as that for conventional concrete [45]. Voids in pervious concrete can provides good resistance to freeze thaw degradation if these voids get empty before the freezing during cold weather conditions and thus make it de-icer resistant if drainable sub-base is recommended under pervious concrete pavement [23]. Similar to conventional concrete, the freeze thaw damage of pervious concrete rises at higher degree of saturation [42]. Experimental study shows that among two samples of mix, granite aggregate based concrete shows good resistance against freeze thaw rather than river gravel or limestone aggregate based concrete. The physical properties of aggregates like water absorption and abrasion resistance plays significant role against freeze thaw resistance. Paste coating of aggregates is also an important factor, thin paste coating allows water to easily pass through into the pore of aggregate and leads to early possibility of freeze thaw damage [46]. Moreover, particles trapped within the pores of pervious concrete may turn into saturated material and expands 2-3% under conditions of cold freezing. Additions of additives like Air Entrants, polypropylene fibres and addition of fines enhance the resistance of freeze thaw degradation [47]. Addition of silica fume with super-plasticizer can improve good freeze thaw resistance. Factors, such as improper placement and curing, reduced uniformity of void content, reduced air entrainment, scaling etc. cause rapid deterioration of pervious concrete [4].

2.7 Thermal conductivity

Thermal conductivity is the ratio of heat flux to the temperature gradient of material and it measures the capacity of material to pass heat through it. Thermal conductivity of pervious concrete has been observed low as compared to the thermal conductivity of normal concrete. Thermal conductivity and diffusivity are responsible for the development of thermal strains, warping and cracking at very initial age of concrete. The conductivity of ordinary concrete at saturated stage ranges between 1.4 and 3.6 $J/m^2s\ c°/m$ and it depends upon on the composition of concrete [48]. It has been studied that mineralogical composition of aggregates highly affects the conductivity of concrete. The thermal conductivities of different type of aggregates are given in Table 3 and it clear from the table that it varies from material to material, for example: Quartzite aggregate shows highest conductivity while shale aggregate shows lowest conductivity of 0.85 $J/m^2s\ c°/m$.

Table 3 - Thermal conductivity of aggregates.

Type of aggregate	Wet density of concrete Kg/m^3	Thermal conductivity $J/m^2s\ c°/m$
Quartzite	2440	3.50
Dolomite	2500	3.30
Limestone	2450	3.20
Sandstone	2400	2.90
Granite	2420	2.60
Basalt	2520	2.00
Shale	1590	0.85

Y. Zaetang et al. studied the thermal conductivity mechanism of 11 samples of recycled coarse aggregate concrete (RCAC) and recycled block aggregate concrete (RBAC). Thermal conductivity coefficient of 0.78 *w/mk* was observed for normal concrete mix while conductivity of RBA and RCA based concrete varied in a fine range of 0.78 – 0.91 *w/mk* [22].

3 Factors controlling the performance of pervious concrete

3.1 Water Cement Ratio

Ordinary Portland cement (type 1) is usually used as binder to prepare pervious concrete mix. The basic purpose of this binding material in concrete is to bond the aggregate integrity and strengthen the concrete by providing sufficient coating around the aggregates. Aggregate size distribution is important factor to find the optimum cement content [17]. It is evident that strength of concrete has a direct relation with water to cement and water cement ratio of 0.26 to 0.45 was found optimal from the previous studies [4]. G. Background observed that pervious concrete prepared with water cement ratio of 0.37 to 0.42 provides good workable and uniform mix of concrete [18]. Dang Hanh Nguyen et al. observed the higher values of compressive strength (28.60 MPa for cube) at w/c ratio of 0.37 which was determined from the binder drainage test [16]. Furthermore, American Concrete Institute (ACI) suggested water cement ratio of 0.26-0.40 for pervious concrete to get stable paste and proper coating of aggregates [17]. Water cement ratio should be maintained at proper ratio as low water cement ratio may cause balling and sticking effects during of pervious concrete and high w/c ratio produces watery thin paste and cause blocking of pores [13].

3.2 Aggregates

Pervious concrete is commonly made up of aggregate size in the range of 19 *mm* to 9.5 *mm* to maintain sufficient interconnected voids [17]. However other studied has suggested the coarse aggregate size of 2.36-9.5 *mm* to rise the strength properties of pervious concrete [34, 36, 49]. Narrow grading and large particle size of aggregates provides sufficient pores to improve permeability. Round aggregates such as gravel shows good compressive strength but lowers the rate of infiltration due to low void ratio. Flaky and elongated aggregates are avoided in pervious concrete as it does not make proper bond and contact between aggregates and cement paste [23]. Utilisation of fine aggregates upto 7% weight of coarse aggregate can enhance strength and durability properties of pervious concrete and maintains good infiltration rate [13]. Workability and paste draw down like factors are directly governed by moisture content of aggregates, dry aggregate reduces workability while wet aggregates cause paste drain which reduces voids which in turn reduces permeability rate of pervious concrete [17]. J. T. Kevern et al. observed the effect of aggregate on freeze thaw resistance. It was found that granite aggregate based pervious concrete shows superior resistance against freeze and thaw. However, limestone and river gravel based pervious concrete show low resistance against freeze and thaw property of concrete [22].

3.3 Compaction and curing

It is obvious that freshly prepared concrete consists of very less amount of excess water content, thus quickly after mixing it should be placed at the final site to prevent drying and shrinkage. Sometimes a short delay between mixing and placing may cause surface ravelling, which leads to low strength of pervious concrete. The strength of concrete also depends on the factor of compaction. Compaction must be done in balanced manner, Inadequate compaction of pervious concrete offers low strength and surface ravelling and over compaction diminishes void content, causes bleeding and low efficient pervious concrete [19, 31]. Sometimes problem of drain down of paste may persist with small amount of over compaction of rolling crusher, which may further cause severe problem of void collapse. Finishing methods of floating and trowelling are not preferably used for pervious concrete as it causes void closing at the surface [28, 49]. Curing of pervious concrete is as important as curing of normal concrete and should be initiated at early stages of hardening. The basic aim of the curing is to keep concrete saturated for long time. Curing of pervious concrete is a bit different from normal concrete because it is not possible to maintain a certain level of water in pervious concrete unlike normal concrete. It is usually done by covering concrete either with plastic sheets (Fig. 4) or with wet gunny bags. The period of curing required depends on the factors of severity of the drying condition and the expected durability requirements. Curing of pervious concrete starts early from 20 minutes of placing and should last for 7 days in temperate areas and for more than 10 days in cold regions. European standard ENV-206:1992 provides the guidelines (Table 4) for minimum period of curing for various external exposure conditions.

Fig. 4 - Curing of pervious concrete by plastic sheet covering.

Table 4 - Curing period of concrete.

Rate of gain of strength of concrete	Rapid			Medium			Slow		
Temperature of Concrete, °*C*	5	10	15	5	10	15	5	10	15
Ambient Conditions during Curing									
No sun, $rh \geq 80$	2	2	1	3	3	2	3	3	2
Medium sun or medium wind or $rh \geq 50$	4	3	2	6	4	3	8	5	4
Strong sun or high wind or $rh < 50$	4	3	2	8	6	5	10	8	5

rh is relative humidity, rapid means rapid hardened concrete

4 Clogging mechanism

4.1 Clogging potential

Pervious concrete also known as permeable concrete is used to improve local flooding during heavy monsoons in municipal areas. Maintaining porosity throughout the life decides the lifespan of pervious concrete, Pervious concrete is having 15- 30% voids, permitting water to flow through and recharge the groundwater level. However, it may lose the full functional performance over some time period due to blockage of pores, which is commonly known as clogging. The accumulation or built up of sediment particles on the surface of pervious concrete or within the pore structure is known as clogging [50, 51]. Clogging of pervious concrete (pavement material) is classified into two categories. Accumulation of dirt and debris on the surface or within the pore is known as physical clogging. Biological clogging is caused due to living creatures like bacteria, algae and penetration of plant roots [10, 52]. Materials that cause clogging of the pervious concrete pavement include sediments of sand, silt, clay that are mostly eroded or deteriorated from surrounding areas of pavement, carried and deposited by wind or vehicular movement. Sometimes it may be due to wear or less abrasion resistance of pavement gets broken easily due to heavy traffic movement and gets accumulate into the pores and causes blockage or clogging [24]. A lot of works has been carried out on pervious concrete pavement to observe the effect of various sediments and clogging potential. The work of M. Kamali et al. confirmed that the majority of sediments removed from the pores of pervious concrete include particles having size greater than 38µm that was mostly vegetative in nature [3]. J. P. Coughlin et al. observed that among all the sediments of clogging, clay caused highest effect in clogging and are 10 times more than clogging caused by sand. Due to large size of coarse sand particles they are not able to enter the pore and thus significantly not make any prominent effect of clogging [25]. However, B. Tong and B. Tong found that sand significantly performs clogging problem in pervious pavement while as fine-grained silty clay shows very less effect. Moreover it was observed that combinations of sand and silty clay shows worst permeability reductions due to complete clogging after very less number of cycles [28]. American Concrete Institute (ACI) Suggested that the clogging potential is highest where there is no prominent difference between pore size and particle size in pervious concrete [17]. The summary of numerous studies that have been studied on clogging potential in pervious concrete in recent year are tabulated in Table 5.

Table 5 - Literature review of clogging in pervious concrete.

Author and year	Conclusion of the paper
Nguyen et, al. [21].	Performed the artificial clogging mechanism with total loading of 253 grams of sediments. The sediments include silty clay (75%) and sand (25%). It was mixed with water and poured on sample surface in 5 cycles. After each cycle permeability of the pervious concrete sample was measured. It was observed that permeability was reduced to 95% at initial stage and after few cycles it was completely clogged.
Kayhanian et, al. [29].	Worked on the depth of damage due to clogging of pervious concrete pavement. He observed that the sediments that were present inside the voids were range of 1-3.80 mm. it was concluded from the image analysis and porosity profile study that only top surface up to few centimetres of depth shows critical damage due to clogging.
Winston et, al. [30].	Worked on de-clogging mechanism of pervious concrete. Sample of pervious concrete were subjected to storm water run-off containing silt clay and organics. Falling head apparatus were used to check the infiltration rate, the initial infiltration rate of the sample slab (6×18 m) was 5.639 mm/s. Results show that vacuuming followed by pressure washing was most successful technique in recovery of pervious concrete sample.
Welker et al. [31].	Collected the samples of clogged material from permeable concrete pavement and permeable asphalt pavement laid for car parking purpose. The porosities of the pavements wire 27 and 25% for permeable concrete and pervious asphalt pavement respectively. Particle analysis shows that the most of the clogged material were particles of deteriorated pavement which is due to the surface ravelling effect. It was also observed that out of the total collected material 66% was of the concrete based pavement and 34% was of the asphalt-based pavement.
Couglin et al. [24].	Studied the effect of sand and clay on the performance and life span of pervious concrete. Infiltration rate and head-loss were recorded of 8 runs (i.e. on 8 samples with different conditions). • In case of first sample infiltration was calculated without any sediment load. • 3 samples having sediment load of sand between 20 to 140 grams. • 3 samples with sediment load of clay between 2 to 14 grams. • 1 sample after pressure washing was tested for infiltration. It was concluded from the above experiment that clay causes 10 times more clogging than sand.
Scheafer et al. [32].	Studied clogging mechanism of pervious pavement through 20 clogging cycles. The sediment load used for clogging was sand and silty clay (5 gram/cycle). It was observed that silty clay and sand cause the highest reductions in infiltration (93 to 96%) due to wide particle size distribution and corrosive nature of clay.
Tong [28].	Performed clogging mechanism of pervious concrete using sediment load of 0.82 kg in the form of sand, clayey silty sand. It was observed that samples with higher initial porosity achieved higher recovery after vacuum swept.

4.2 De-clogging Techniques

There are different techniques to rehabilitate the clogged pervious concrete pavement that may include, pressure or power washing, vacuuming, combined pressure and vacuuming, sweeping etc. Pressure washing helps to maintain the infiltration of pervious concrete pavement under drainage limit. It generally makes dislodgment of sediment particles present at the top portion of pavement and finally flush them out. Moreover, vacuuming shown in Fig. 5 is the best effective technique to push out sediment within the top 25.40 *mm* of pavement surface [33].

Fig. 5 - Vacuuming of pervious concrete pavement.

Further more sweeping comes under daily maintenance cleaning method and it include riding sweepers, truck mounted sweepers, walk-behind sweeper depends upon area to be cleaned. Pressure washing is high effective technique than power-blowing but there was not a significant impact attained by combining the both methods at one time [24]. R. J. Winston et al. suggested that vacuum-sweeping technique performs well if used recurringly within 6 months period of duration. Others observed that pressure washing is less effective than other techniques in order to restore infiltration capacity of pervious pavement. Infiltration recovery of 49.4% was observed when operation of pressure washing was used while recovery of only 2.4 to 9.6% was observed when cleaned by vacuum swept in pervious concrete sample having porosities between 15 to 25% and sediment removed was only sand [30]. A. L. Welker et al. Studied pervious concrete sidewalk and found surface infiltration rate (SIR) through pressure washing and pressure washing with power blowing. SIR rates of 85 *mm*/*min* and 110 *mm*/min are obtained when operations of pressure washing and pressure washing with power blowing are used respectively [31]. Among these two methods of de-clogging washing with power blowing was found more effective in in rejuvenating pavement permeability. J. P. Coughlin et al. conducted a laboratory study of pervious concrete sample in which clay laden runoff was allowed to pass through. It was observed that after four cycles of flow process, SIR reduction factors were measured as 5 (minimum) and 95 (maximum). Surface sweeping followed by washing shows better results to gain good surface infiltration rate, although SIR cannot be rejuvenating to its original position [24].

5 Techniques for improving properties of pervious concrete

5.1 Understanding Cement and Concrete at Nano level as Nanotechnology

Concrete science is a multidisciplinary area of research where nanotechnology potentially offers the opportunity to enhance the understanding of concrete behaviour, to engineer its properties and to lower production and ecological cost of construction materials. The complex chemistry and physical structure of cement hydrates in concrete however mean that issues of fundamental science still need to be resolved. Analysis at the nanoscale may provide further insight into the nature of hydrated cement phases and their interaction with admixtures, nanofillers and nanofibers. These interactions offer the possibility of modifying cement reactions, creating new surface chemistries (referred to as nanoscience), developing new products for the concrete industry (referred to as nanotechnology), and allowing a more controlled and ecologically friendly manufacturing route to cement and concrete.

The most widely conducted studies on the use of nanoparticles in cement and concrete have been on nano-oxides, especially SiO_2 and Fe_2O_3. The addition of these nanoparticles to cement paste containing high volumes of fly ash and to sludge ash concrete mortars resulted in an increase in compressive strength. Nano-Fe_2O_3 and nano-SiO_2 were also used to increase the abrasion resistance of concrete for pavement [34]. Nano-$Ca(OH)_2$ particles have been prepared and their thermal properties were characterized to study the anomalous behaviours of $Ca(OH)_2$ in cement paste [35]. Also, other nano to sub-micro inorganic particles, such as zeolite, have been added to cement systems with the goal to improve the overall microstructure. Another nanosize oxide of interest to construction is TiO_2. It has recently been reported that the TiO_2 nanoparticles accelerated the rate of hydration and increased the degree of hydration [36].

5.1.1 C-S-H and C-S-H Composites

The main product of the hydration of Portland cement is a nearly amorphous material − Calcium Silicate Hydrate (C-S-H) − that forms up to about 60% by volume of the paste. In cement chemistry, CaO, SiO_2, and H_2O are represented by C, S, and H respectively. The hyphens in C-S-H indicate indefinite stoichiometry and the hydrate is sometimes referred to as "C-S-H gel". C-S-H is produced along with calcium hydroxide in the chemical reaction of the silicate phases (*i.e.* β-C_2S and C_3S) with water. C-S-H is the principal binding agent in the cement paste and is responsible for its important properties such as strength and shrinkage. The molar ratio of CaO to SiO_2 (C/S ratio) in C-S-H is one of the main parameters in defining and controlling the properties of a calcium silicate hydrate system. This value varies from 1.2 to 2.1 in hydrated silicate phases and has an average of about 1.75 [39]. Water molecules can also be physically adsorbed on the surface of solid phases. Finally, the capillary pores (10–50 nm in diameter in well hydrated pastes and as large as 3–5 micrometres at early ages) between C-S-H clusters can contain free water. Distinction of water states is not simple as the energy by which the water molecules are held in C-S-H varies over a wide range and may overlap for different locations [40].

Study of the structure of C-S-H in Portland cement systems using X-ray diffraction is limited due to its poorly crystalline nature. Early research investigations were conducted using mainly surface area and density measurements, and, weight and length change isotherms in order to characterize this material [41]. In the last few decades, many new aspects of the C-S-H have been revealed with the advancements in the analytical techniques and application of new methods such as nuclear magnetic resonance (NMR) spectroscopy. The nanostructure of C-S-H has been the subject of much research, yet is still not clearly understood with suggested models ranging from colloidal to "layer-like". One of the first physical models was proposed by Powers and Brownyard [42]. It describes C-S-H as a colloidal material. In this model the gel particles are held together mainly by van der Waals' forces and the space between them is called "gel porosity" which is accessible only by water molecules. A more comprehensive model was developed later by Feldman and Sereda based on extensive experimental studies of hydrated cement systems [43]. The role of water in this model is explained in more detail and the changes in the mechanical properties of C-S-H related to water content can be easily described. The main feature of their model (shown in Figure 6) is concerned with the layered nature of the C-S-H. Structural roles that are assigned to the interlayer water of the C-S-H, exhibit irreversible behaviour during the adsorption and desorption processes.

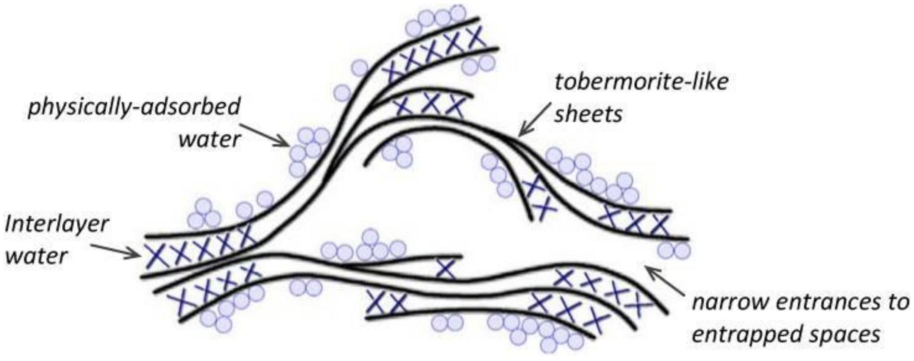

Fig. 6- Simplified physical model for hydrated Portland cement

5.1.2 CaCO3 as Nanoparticle

The use of $CaCO_3$ was first considered as a filler in cement to replace OPC. However, the results from a number of studies have shown positive effects of $CaCO_3$ additions in terms of strength and acceleration of hydration rate. A study on the accelerating effect of finely ground $CaCO_3$ addition on the hydration of C_3S showed that the higher the $CaCO_3$ addition, the greater was the accelerating effect [44]. The accelerating effect of the finely ground $CaCO_3$ addition on the hydration of cement paste was also observed [45].

Scanning electron microscope (SEM) images of both types of $CaCO_3$ particles are shown in Figure 7. The average particle size of the micro-$CaCO_3$ was approximately 5 to 20 *µm* whereas that of nano-$CaCO_3$ was about 50 to 120 *nm*. The surface area values of micro-and nano-$CaCO_3$ were 0.35 *m²/g* and 20 *m²/g*, respectively.

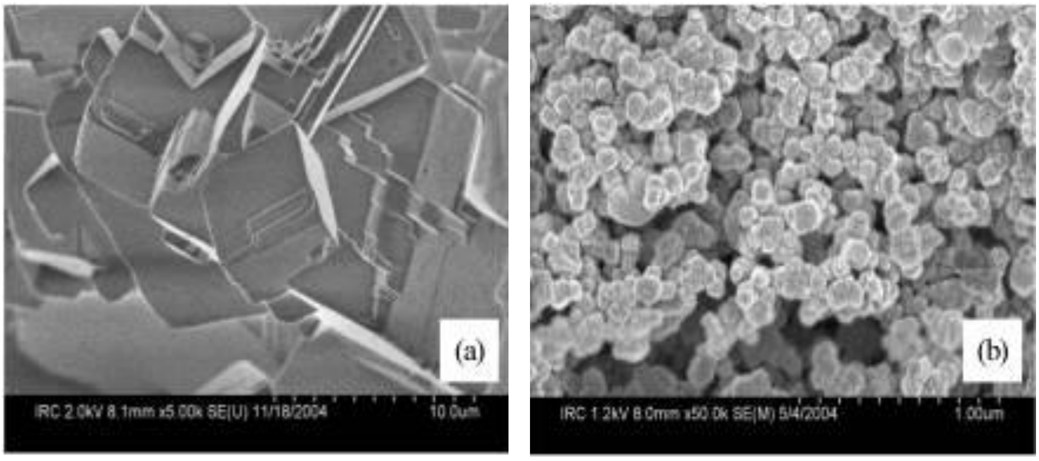

Fig. 7- Scanning electron microscope image of (a) micro-$CaCO_3$ and (b) nano-$CaCO_3$

Different cement pastes with variable additions of fly ash and nano-$CaCO_3$ were prepared and analyzed. Figure 8 illustrates the rate of heat development measured by the conduction calorimeter for four different samples. The rate of heat development of the 50% OPC and 50% fly ash blend is significantly lower than that of 100% OPC (sample 1). When micro-$CaCO_3$ was added to the OPC/fly ash blend (sample 3), a slight acceleration above that of sample 2 was observed. When nano-$CaCO_3$ particles were incorporated (sample 4), the rate of heat development was significantly accelerated.

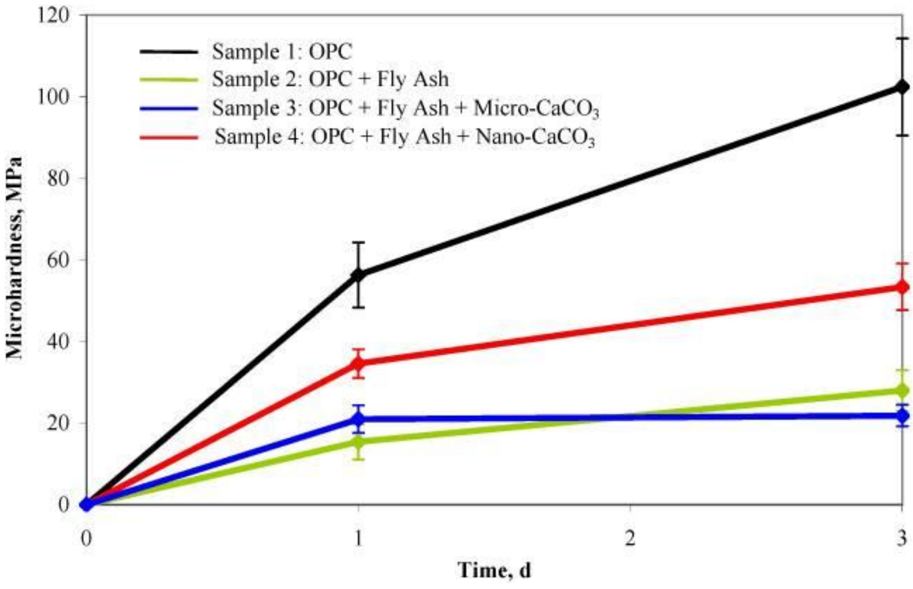

Fig. 8 - Rate of heat development measured by the conduction calorimeter

5.1.3 Subsurface cracks and surface ravelling

The frequency of cracking patterns and cracking direction were observed in the polished pervious concrete samples in different studies. Subsurface cracks appeared both parallel and vertical to the concrete's surface and also propagated around and radiated at different angles from aggregate particles (radial cracking). The crack propagation is either through the paste or inside the aggregate, and sometimes it propagates through interfacial transition zone (ITZ). The locations of the cracks in a majority of the samples were within 2 *in*. (50 *mm*) from the surface, which later on leads to the problem of surface ravelling (Fig. 9) and disintegration of aggregates.

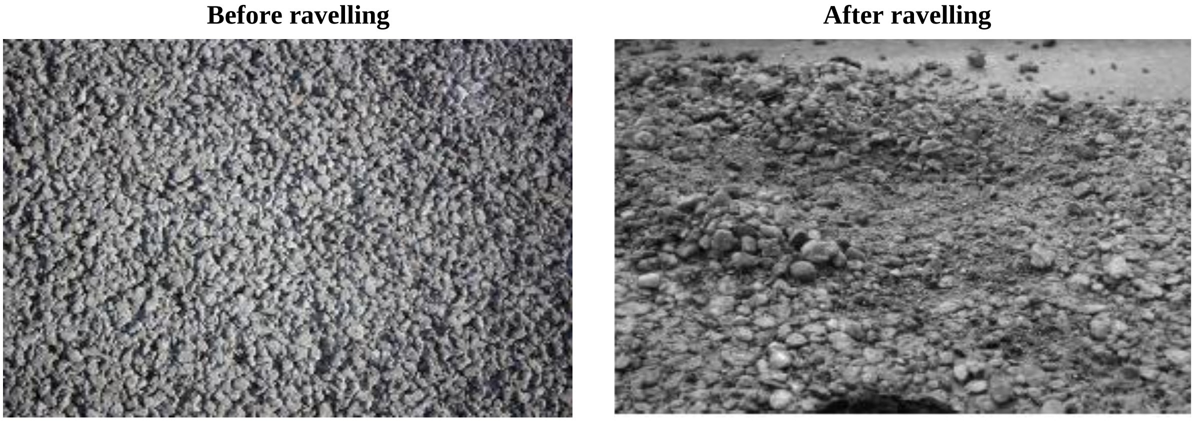
Before ravelling **After ravelling**

Fig. 9- Surface ravelling

One frequently observed cracking pattern in the pervious concrete cores was a pattern in which the cracks propagated in both the parallel and vertical directions of paste-aggregate interface. This pattern was observed in 11 of 33 cores [46]. This cracking pattern was observed to depths of the samples' top 50 mm to the full depth of the samples. An example of this cracking pattern is shown in Fig. 10. A second cracking pattern frequently observed in the pervious concrete cores was isolated incidences of cracking or cracking that was confined to one region of the sample. These cracks were either parallel to the surface or radial and occurred primarily through the paste and aggregate. This pattern was observed in seven of 33 pervious concrete cores. The cracks occurred from between 6 *mm* 45 *mm* below the concretes' surfaces. One examples of this cracking pattern are shown in Fig. 11.

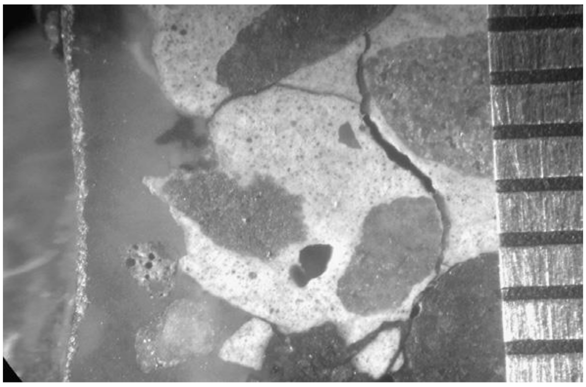
Fig. 10 - Cracks through the paste and around the ITZ.

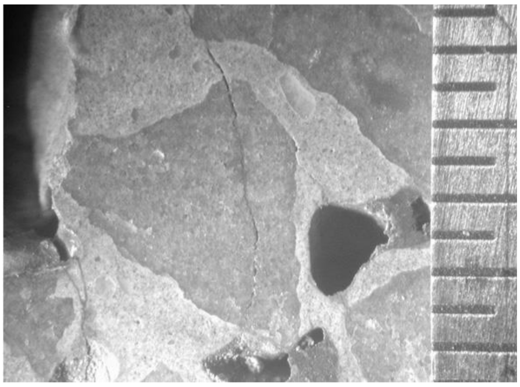
Fig. 11 - Cracks through aggregate and paste.

Surface ravelling and cracking of pervious concrete is a durability problem can be caused by lack of resistance to frost, sulfate, corrosion, and abrasion as well as alkali-silica reactivity. The cracks presented in above figures are attributable to one of the following expansive mechanisms [46].

i. Alkali-aggregate reaction
ii. Reformation of ettringite in situ
iii. Recrystallization of salts
iv. Corrosion of reinforcement
v. Surface cracks over an expanding core
vi. Thermal gradient from the environment
vii. Freeze/thaw attack

Stereomicroscopic observation revealed that the cracking in the pervious concrete samples was not caused by above three reactions (one through three) as there were no signs of alkali-aggregate reaction, reformation of ettringite in air voids, or salt recrystallization. Only two of the 33 pervious concrete samples showed subsurface distresses due to reactive aggregates, and the aggregate in both pervious concrete samples was traced to one aggregate source. Furthermore, no secondary products were observed within the microstructure. None of the pervious concrete pavements observed in this study were reinforced, which eliminates cracking due to reinforcement corrosion. This suggests that cracking in the pervious concrete samples could be attributable to mechanisms of surface cracks over an expanding core, Thermal gradient from the environment, or Freeze/thaw attack (five through seven).

Furthermore, the problem of cracking in pervious concrete may be nullified internally by using self-healing mechanism of concrete alike as self-healing of conventional concrete. Self-healing concrete is a result of biological reaction of non-reacted limestone and a calcium-based nutrient with the help of bacteria to heal the cracks appeared on the building. Special type of bacteria's known as Bacillus are used along with calcium nutrient known as Calcium Lactate. While preparation of concrete, these products are added in the wet concrete when the mixing is done. This bacteria's can be in dormant stage for around 200 years. When the cracks appear in the concrete, the water seeps in the cracks. The spores of the bacteria germinate and starts feeding on the calcium lactate consuming oxygen. The soluble calcium lactate is converted to insoluble limestone. The insoluble limestone starts to harden. Thus, filling the crack, automatically without any external aide [47]. The other advantage of this process is, as the oxygen is consumed by the bacteria to convert calcium into limestone, it helps in the prevention of corrosion of steel due to cracks. This improves the durability of steel reinforced concrete construction.

$$\begin{cases} CaO + H_2O & \rightarrow \quad Ca(OH)_2 \\ Ca(OH)_2 + CO_2 & \rightarrow \quad CaCO_3 + H_2O \end{cases} \tag{4}$$

When the water comes in contact with the unhydrated calcium in the concrete, calcium hydroxide is produced by the help of bacteria, which acts as a catalyst. This calcium hydroxide reacts with atmospheric carbon dioxide and forms limestone and water. The limestone then hardens itself and seals the cracks in the concrete.

5.2 Utilization of SCMs and fibers

Supplementary cementitious materials (SMCs) can be used to improve the performance of concrete in its fresh and hardened state. They are primarily used for improved workability, durability and strength. Concrete mixtures with high Portland cement contents are more susceptible to cracking and high generation of heat. These effects can be controlled to a certain degree by using supplementary cementitious materials. Furthermore, consumption of SCMs reduces the use of OPC, having high energy consumption and carbon emissions. Supplementary cementitious materials, also called as mineral admixtures that include number of by-products or end products of various industries include, Fly ash, Silica fume, Ground granulated blast furnace slag, Metakaolin and Rice husk ash Electric arc furnace slag (EAFS) and Alkali activated slag cement (AASC) etc.

Fly ash is a by-product of coal-fired furnaces at power generation facilities and is the non-combustible particulates removed from the flue gases, Fly ash used in concrete should conform to the standards specification, ASTM C618 [53]. The Amount of Fly ash in concrete can vary from 5% to 65% by mass of the cementitious materials, depending on the source of the fly ash and the performance requirements of the concrete. Characteristics of fly ash can vary significantly depending on the source of the coal being burnt. Class F Fly Ash is normally produced by burning anthracite or bituminous coal and generally has a low calcium content. Class C Fly ash is produced when subbituminous coal is burned and typically has cementitious and pozzolanic properties.

Ground Granulated Blast Furnace (GGBFS) is non-metallic manufactured by-product from a blast furnace when iron-ore if reduced to pig-Iron. The Liquid slag is rapidly cooled to form granules, which are then ground to a fineness similar to Portland cement. Ground granulated blast furnace slag used as cementitious material should conform to the standard specification, ASTM C 989 [54]. Three grades - 80, 100, and 120 are defined in C989, with the higher grade contributing more to the strength potential. GGBFS has cementitious properties by itself but these are enhanced it is used with Portland cement. Slag is used at 20% to 70% by mass of the cementitious materials.

Silica Fume is a highly reactive pozzolanic material and is a by-product from the manufacture of silicon or ferro-silicon metal. It is collected from the flue gases from electric arc furnaces. Silica fume is an extremely fine powder, with particles about 100 times smaller than an average cement grain. silica fume is available as a densified powder or in a water-slurry form. The standard specification for silica fume is ASTM C 1240 [49] it is generally used are 5 to 12 % by mass of cementitious materials for concrete structures that need high strength or significantly reduced permeability to water. Due to its extreme fineness special procedures are warranted when handling, placing and curing silica fume concrete

Natural Pozzolans Various naturally occurring materials possess, or can be processed to possess pozzolanic properties. These Materials are also covered under the standard specification. ASTM 618 [53]. Natural pozzolans generally derived from volcanic origins as these siliceous materials tend to be reactive if they are cooled rapidly. In the US, commercially available natural pozzolans include Metakaolin and Calcined Shale.

Metakaolin and Calcined Shale or clay: These materials are manufactured by controlled calcining (firing) of naturally occurring minerals. Metakaolin is produced from relatively pure kaolinite clay and it is used at 5 -15% by mass of the cementitious materials. Calcined shale or is used at higher percentages by mass, Other natural pozzolans include volcanic glass, zeolitic trass or tuffs, rice husk ash and diatomaceous earth.

Furthermore, pervious concrete can be made extra green by replacing OPC with geopolymers (sodium silicate and sodium hydroxide with fly ash). Cement manufacturing is a highly energy-intensive process and the production of 1 tonne of OPC releases about an equal amount of CO_2 in the atmosphere, making it one of the major contributors to global warming [55, 56]. Geopolymers binders are hardened compounds which attain their strength and other characteristics by a chemical reaction between alkaline solutions and aluminate silica-rich source materials. Geopolymer is inorganic alumina-silicate polymer structured around tetrahedral coordinated Si^{4+} and Al^{3+}, forming a polymer chain. These geopolymer precursors chemically bond and form oligomers leading to the formation of alumino-silicate polymers [19].

The effect of use of fibre in pervious concrete was investigated and it was studied that insertion of fibres in pervious concrete showed better results than normal pervious concrete. The various types of fibres (Fig.12) like polyphenylene sulphide (PPS), steel and glass fibres were used in concrete to gain better mechanical properties of concrete. Pervious concrete with insertion of these fibres along with Rice Husk Ash (RHA) was studied at variable percentage. The results showed good enhancement in mechanical properties, for example compressive strength was enhanced to 34%, 37% and 36% on insertion of glass, steel and PPS fibres respectively along with RHA of 8-10 % at water cement ratio of 0.33. Furthermore, tensile strength also showed better results with the insertion of these fibres, for example 31%, 30% and 28% of enhancement of tensile strength was observed on utilization of glass, steel and PPS fibres respectively. On performing the flexural test on fibre based pervious concrete, increment of flexural strength of 64%, 63% and 69% was observed for glass, steel and PPS fibre based pervious concrete [50]. J. J. Chang et al. study the effect of electric arc furnace slag (EAFS) and alkali activated slag cement (AASC) in pervious concrete. Observations showed better results of compressive strength as well as of permeability in concrete. A maximum Compressive strength of 35 *MPa* and 0.49 *cm*/*s* of coefficient of permeability were observed. This is because of the great knitting and permeable property of electric arc furnace slag; thus, it can show strong binding properties than ordinary Portland cement (OPC). Thus utilizing these materials in pervious concrete, it can be used for high speed traffic volumes even in harsh environmental conditions [51].

Fig. 12 - Different fibres used in pervious concrete.

5.3 Maintaining Tortuosity

Tortuosity is the property of pervious material and is defined as the ratio of actual path travelled by the liquid (flow path) to the straight distance between two ends of that path [4]. Pervious concrete must hold adequate porosity in order to maintain the good flow which indirectly defines the life span of pervious concrete. Pore channels inside the pervious concrete are too complex and torturous, having inconsistency in opening area of pore and are connected randomly. Tortuosity and connectivity are inversely related to each other, particle can get easily accumulated if the path of flow is more tortuous and heterogeneous in nature. Thus, to maintain the self-cleaning nature of pervious concrete, path length of the flow should be efficient. The variable nature of flow path is shown in Figure 14 below and thus maintaining the flow path (Tortuosity), life span of pervious concrete in terms of durability can be increased to good extent.

Pore tortuosity s is defined by Eq. (5) as the ratio of the effective path length (L_e) to the sample length (L) (Fig. 13).

$$\tau = \frac{L_e}{T} > 1 \tag{5}$$

A few studies [22, 52] has been carried out to quantifying the influence of pore tortuosity on hydraulic conductivity of PC. A parameter χ, defined as the ratio of effective electrical conductivity to solution electrical conductivity, was used to represent pore tortuosity [52]. By combining the Kozeny-Carman model and the modified parallel effective conductivity model, a hydraulic connectivity factor β_H was introduced by Neithalath et al. [8] to account for the influence of pore tortuosity. The Kozeny-Carman model can be represented by Eq. (6).

$$K = \frac{\phi^3}{c\tau^2 s^2 (1-\phi)^2} \tag{6}$$

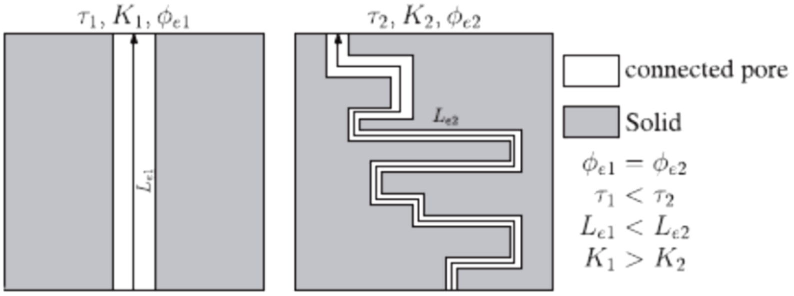

Fig. 13 - Schematic illustration of influence of pore tortuosity on hydraulic conductivity.

Where k is the intrinsic permeability, ϕ is total porosity, c, s and τ represent Kozeny constant, pore tortuosity and specific surface area, respectively. Hydraulic conductivity (K) is related to intrinsic permeability (k) as follows:

$$K = k\frac{\rho g}{\mu}$$

where g is the gravitational acceleration, ρ and g are the density and dynamic viscosity of fluid, respectively.

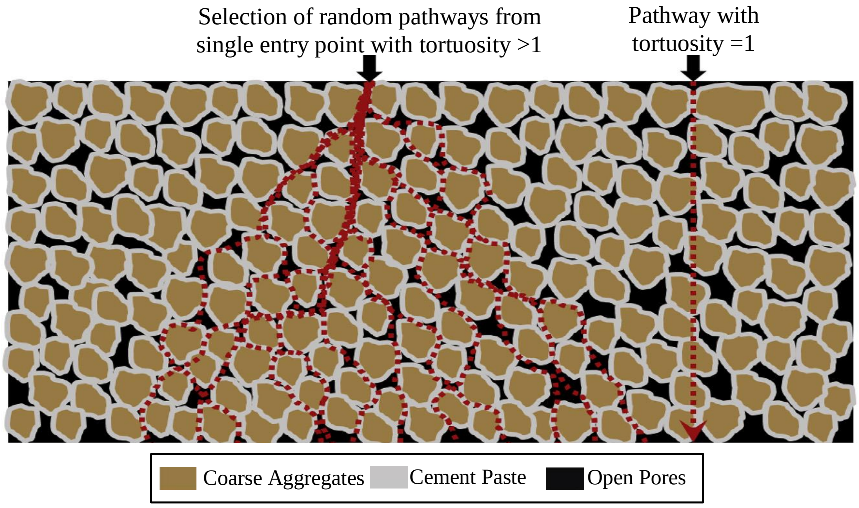

Fig. 14 - Tortuosity of pervious concrete.

5.4 Use of Recycled Coarse Aggregate

RCA provides excellent mechanical properties (e.g. lower specific gravity, higher resilient modulus, and freeze–thaw durability)

and is largely available for use as a base course in pavement structures. However, potential environmental risks associated with highly alkaline effluent and the leaching of heavy metals (aluminum (Al), arsenic (As), antimony (Sb), barium (Ba), calcium (Ca), cadmium (Cd), chromium (Cr), cobalt (Co), copper (Cu), iron (Fe), lead (Pb), magnesium (Mg), molybdenum (Mo), nickel (Ni), potassium (K), selenium (Se), sodium (Na), strontium (Sr), vanadium (V), and zinc (Zn)) from RCA have been reported by various state departments of transportation. Cement phases (e.g. calcium silicate hydrate, portlandite, and ettringite) in RCA have the potential to generate highly alkaline leachate (pH 12∼13) [57-59]. Thus, these metals may cross the maximum contaminant levels (MCLs) in surface runoff generated by rainwater wash through an RCA and cause ill effects to ground water as well as to soil profile and metal water pies passing beneath or nearby the RCA leachates. There are some mitigation techniques of the above problems that are present in literature, higher liquid to solid ratio (L/S) of leachate may lower the concentrations of Mo and Cr. Soil acidity also play an important role in neutralizing the high PH of RCA leachate at low L/S ratio [60-64]. Soil vapor CO_2 below the RCA base has combining effects of carbonating the RCA as well as lowering the leachate PH. However, the leaching problems of RCA can be minimized to a large extent by the process of beneficiation of RCA. The beneficiation technique may be chemical (using strong sulphuric acid), mechanical (high abrasion rotations) or both (chemco-mechanic) before using in concrete [11].

Some of the researchers has used the demolished waste that may include recycled concrete block aggregates (RBA) or recycled concrete aggregate (RCA) in pervious concrete with good results regarding strength parameter. Y. Zaetang et al. performed the study of pervious concrete with insertion of RBA and RCA at different replacement levels of coarse natural aggregates. Recycled concrete block aggregates based pervious concrete showed better results than virgin natural aggregate based pervious concrete. The compressive strength of 17.0 *MPa* was observed at 40% replacement of coarse aggregate with RCA, while compressive strength of only 13.4 *MPa* was observed for pervious concrete made with virgin coarse aggregate . The surface abrasion resistance of recycled aggregate based pervious concrete was better than virgin aggregate based pervious concrete, for example abrasion resistance was observed maximum at 20% level of replacement of RCA. This increase in compressive strength and abrasion resistance was due to the good bonding between RCA or RBA and cement paste.

6 Conclusion

This paper reviewed the various mechanical, hydrological and durability properties of pervious concrete. Awareness regarding the pervious concrete, its benefits and importance in the context of urbanization was the main purpose and objective of this paper. Furthermore, enough laboratory work has been done on pervious concrete in recent years, however yet it has not been used widely in the field of pavement construction because of its limited strength and low life span of permeability. Thus, materials that proved handy to eradicate these limitations of pervious concrete were also discussed. It acts as a sustainable drainage system in urban areas during heavy rains thus reduces local flooding that may prove sometimes fatal and may cause immense health and environmental problems if not treated soon. Earlier Studies show that there is no proper mix design and testing methods of this material and also it lacks long term performance. Thus, to eradicate these limitations of pervious materials, it can be used widely with great benefits and can be proved a better option for pavement construction. The review has also high-lightened the techniques through which the overall properties like strength, permeability and durability of pervious concrete can be enhanced in order to optimise the applications of this material. Overall, the past studies indicated that pervious concrete is a beneficial and versatile pavement material and can be used for high speed traffic pavement during harsh conditions of weather, if proper care and proper design of mix is prepared.

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