Study on identically voided pervious concrete made with different sized aggregates

V. Kastro Kiran 1 and K. B. Anand 2
1 Post Graduate student, Department of Civil Engineering.
2 Professor, Department of Civil Engineering,
Amrita School of Engineering, Coimbatore, Amrita Vishwa Vidyapeetham, Amrita University, India.
Email: kastrokiran@gmail.com, kb_anand@amrita.edu (Corresponding Author)

Abstract. Pervious concrete (PC) is also known as no fines concrete and has been found to be a reliable stormwater management tool. As a substitution for conventional impervious pavement, PC usage has been increasing during recent years. PC made with different sized aggregate shows different void ratios and changed properties. As void ratio plays a notable role on strength and permeability of PC, this study aims to focus on properties of PC at identical void ratio of 20%, made using aggregates of three size ranges, viz., 4.75-6mm, 10-12.5mm, and 10-20mm. Appropriate alternatives were used to maintain the identical void ratio.

As the permeation capacity of PC gets reduced due to the clogging tendency, the life of PC will also get reduced. Hence, to make the PC to sustain for a long time it is necessary to study the clogging behavior. This study investigates the tendency of PC for clogging and the potential for regaining the permeability through de-clogging methods. Clogging tendency of PC is studied by using two sizes (coarse and fine) of clog particles and the changes in permeability are observed. Efficiency of de-clogging methods like pressure washing and vacuum suction on PC with different sized aggregates are also evaluated.

1. Introduction

Pervious concrete (PC) is also known as porous, no fines, permeable, or gap graded concrete has been found to be a reliable stormwater management tool. The texture of PC is rough and the honeycombed surface structure of PC allow water to channel through the pavement surfaces into the deeper layers of soil during periods of heavy rainfall. Pervious concrete is generally used in parking lots, low volume traffic zones, swimming pool decks, and walkways. Cement, coarse aggregate, water, and little to no fine aggregate are the major ingredients of a PC mix. Controlled amount of water and cementitious materials are used to provide a thick paste to bind and aggregates help to maintain a system of interconnected voids which allow water and air to pass through. The paste acts as a good binding agent which helps in the enhancement of strength. When contrasted with conventional concrete, PC has lower compressive strength and unit weight (approximately 70% by weight of conventional concrete). PC mix design is different from conventional concrete mix design. The primary difference is the little to no use of fine aggregate and usage of uniformly graded coarse aggregate. These two characteristics create large and continuous voids. Generally, PC mix
[1] consists of 270–415 kg/m³ of cement, 1190–1480 kg/m³ of aggregate and w/c ratio ranging between 0.28 to 0.40. The 28th day compressive strength (depending on the mix proportion) ranges from 3.5 to 28.0 MPa and the void ratio in the range 15-30% is normally adopted.

Earlier studies indicate that compressive strength and hydraulic parameters of PC change is dependent on the design void ratio and also on size of aggregate used. Therefore, the present study was conducted to investigate the strength and clogging behavior of identically voided PC made with different sizes of aggregates. The objectives of this study are:

a) Mix proportioning for constant void ratio using different sizes of aggregates
b) Studying the strength and permeability properties
c) Investigating the clogging behavior with different clog materials
d) Examining the effectiveness of de-clogging procedures.

2. Background literature

Size and quantity of aggregates play an imperative part in determining the binding property, strength, and permeability of PC. Dang Hanh Nguyen et al. [1] proposed a modified mix design for pervious concrete based on the layer quantification of cement paste coating the gravel and on the hypothesis that the cementitious paste acts only as a coating. Coarse aggregates of 4-6.3mm size and alluvial quartz sand of 0-4mm was used as 7% replacement of coarse aggregate. The highest compressive strength was observed as 28.6 MPa with a water-cement ratio of 0.37. S.O. Ajamu et al. [2] evaluated the structural performance of pervious concrete by using coarse aggregate sizes of 9.375mm and 18.75mm with three ranges of aggregate-cement ratios (6:1, 8:1 and 10:1). It was observed that the lowest aggregate to cement ratio gave the highest compressive strength whereas the highest aggregate to cement ratio gave higher permeability.

M. Aamer Rafique Bhutta et al. [4] studied compressive strength variation of pervious concrete using admixtures with three size ranges of coarse aggregates, (13-20mm, 5-13mm and 2.5-5mm) with different water-cement ratios. It was observed that when PC is made with a combination of cohesive and high water reducing agents (SP) it could produce an acceptable High Performance Pervious Concrete with good workability and strength properties. Usage of smaller size aggregates showed higher compressive and flexural strengths whereas the larger size aggregates resulted in high void ratio and greater permeability. Specifically, aggregate sizes ranging between 2.5-5mm had the highest compressive strength of 18-30MPa and at lowest water-cement ratio (0.26-0.32) highest compressive strength (20-30MPa) could be attained. Studies [5, 6, 7] are also reported on strength and porosity of PC utilizing different sizes of aggregates. Ammar Yahia, et al [15] proposed a new method based on paste volume to inter-particle void ratio for different sizes of aggregates and the results showed the beneficial effect of fine particles on strength development.

Addition of small percentage of fine aggregates helps to increase the compressive strength of PC utilized for pavements. However, reduction in permeability had been observed as the voids are gets occupied with fine aggregates. M. Uma Maguesvari et al. [8] studied on the characterization of pervious concrete, replacing fine aggregates by 0-50% by weight of coarse aggregates. At 50% and at 0% replacement, the compressive strengths were observed as 24.8MPa and 10.03MPa for aggregates of size 9-12.5mm. Qiao Dong et al. [9] also studied the strength property by varying the percentages of fine aggregates and at 10% replacement of fine aggregates with coarse aggregate, compressive strength was observed as 10MPa at a void ratio of 28%.

Addition of mineral admixtures in the PC mix has a profound improvement on strength of PC accompanied with reduction in permeability. Jing Yang et al. [10] studied the PC properties by replacing 6% of cement with Silica fume and it was observed that compressive strength was increased from 18MPa to 26.7MPa by using 3-5mm size aggregates at a water-cement ratio of 0.2. Ketan Brijesh Jihenkar, et al. [13] studied the effect of titanium dioxide on strength properties. A study [17] on the influence of ultrafine
slag addition on the properties of cement grout have shown reduction in shrinkage strain and a reasonable increase in compressive strength. It is observed that, by using admixtures like silica fume and fly ash, strength of PC can be increased to a greater extent.

Omkar Deo et al. [3] studied the clogging tendency of pervious concrete in which finer sand and coarse sand were used as a clog material. It is observed that with increasing amounts of finer sand, the permeability had reduced due to the clogging of pores and/or blocking of some of the high inter-connectivity voids. Coarser sand particle sizes ranging from 0.84 mm–1.8 mm which were used as the clogging material showed the decrease in permeability values due to the blocking of pore structure. Liv M. Haselbach [11] studied clogging property using a natural red clay, and two commercial clays; kaolin and bentonite as clog particles. All the clog particles had shown high impact on porosity of the specimens. Bin Tong et.al [12] used clayey silty sand as blended clogging material which caused the most significant permeability reduction, and more than 90% of the initial permeability was reduced at the end of clogging test Nilesh Shirke, et al [14] described a potential process of removing clog particles by reverse flushing of water. However, this method is found to be difficult for pavement application. Percentage of voids in a sample of pervious concrete can vary significantly and is dependent on the quantity and size of aggregates used in a mix and also on the amount of fine aggregates. The inverse proportion of compressive strength to void ratio has a significant effect on density of the mix and a lower void ratio increases the potential for clogging.

3. Experimental programme

3.1 Materials used

Ordinary Portland Cement of 53 grade confirming to IS 12269: 1987 with specific gravity of 2.98 was used in the preparation of pervious concrete. A controlled mixture of pervious concrete can be made by using single sized coarse aggregate with necessary adjustments in quantities of cement and water. In this study, three sizes of aggregates are used, 4.75-6mm, 10-12.5mm, and 10-20mm confirming to IS 2386: 1963 and fine aggregate passing through 4.75mm sieve are used. The properties of materials used are shown in table 1.

| Materials    | Size of aggregate | Specific gravity | Bulk density | Water absorption |
|--------------|------------------|------------------|--------------|-----------------|
| Coarse aggregate | 4.75-6mm          | 2.85             | 1462 kg/m³  | 0.40%           |
|               | 10-12.5mm         | 2.82             | 1539 kg/m³  | 0.51%           |
|               | 10-20mm           | 2.82             | 1482 kg/m³  | 0.52%           |
| Fine aggregate | 4.75mm            | 2.66             | 1620 kg/m³  | 0.49%           |

4. Mix details

4.1 Procedure for mix proportioning of pervious concrete

The steps involved in the mix proportioning are:

a) Selection of appropriate sizes of coarse aggregates and determination of properties.
b) Selection of appropriate void ratio, Vv.
c) Determination of appropriate w/c ratio by using binder drainage test.
d) Calculation - volume of aggregates, cement and water content.
e) Preparation of PC and determination of fresh and hardened state properties.

In general, PC has the void ratio ranging in between 15%-30% [1]. In this investigation, a constant void ratio of 20% is chosen for the three sizes of aggregates and the fresh and hardened properties are determined at this void ratio.
4.2 Determination of w/c ratio
Quantity of water plays a paramount in deciding the strength, permeability and other properties of PC. Binder drainage test [1] is a sieve test which is used to determine the w/c ratio and is one of the effective methods.

Methodology followed: After a detailed study of the literature on aggregate to cement and water to cement ratios, in this study, for initial trail A/C ratio was taken as 4 and w/c taken as 0.32 and for every next trail A/C was increased by 0.125 and w/c increased by 0.02. 1000g of coarse aggregate was taken as fixed quantity for each trial. The amount of materials required were calculated and mixed thoroughly, the mix then placed on a sieve which was smaller than the size of aggregates used for the test. The sieve with collection tray was placed on a vibrating table, vibrated for 15s and the bottom of the sieve was observed. Paste content in excess and flowing through the sieve, indicates that the mix has a high water content. The procedure was repeated by adjusting the A/C ratio and w/c ratio until the amount of paste passing through the sieve gets controlled. Figure 1(a) and 1(b) shows the amount of liquid cement paste passing through the bottom of the sieve for an uncontrolled mix and hence the mix is considered as a poor mix. Figure 2(a) and 2(b) shows the w/c ratio of a good mix for which the amount of cement paste flowing through the sieve is controlled by adjusting the A/C ratio and w/c ratio. Care was taken that the mix was neither too dry or too wet.

![Figure 1](image1.png) **Typical poor mix (a):** Excess paste at bottom of sieve

![Figure 1](image2.png) **Typical good mix (b):** Aggregate without proper binder coating

![Figure 2](image3.png) **Typical good mix (a):** No Excess paste at bottom of sieve

![Figure 2](image4.png) **Typical good mix (b):** Aggregate with proper binder coating

After performing various trials of binder drainage test on three sizes of aggregates, proper ratios were arrived at Table 2 shows the results of binder drainage test for three sizes of aggregates. The w/c ratio adopted is highlighted in bold.

| Aggregate sizes | A/C ratio | w/c ratio | Coarse aggregate(g) | Cement(g) | Water(g) | Inference |
|-----------------|-----------|-----------|----------------------|-----------|----------|-----------|
| 4.75-6mm        | 4         | 0.32      | 1000                 | 250       | 80       | Poor mix  |
|                 | 4.125     | 0.34      | 1000                 | 242.4     | 82.41    | Dry mix   |
|                 | **4.25**  | **0.36**  | **1000**             | **235.2** | **84.6** | **Good mix** |
|                 | 4.75      | 0.38      | 1000                 | 228.5     | 86.83    | Liquid mix |
|                 | 4         | 0.32      | 1000                 | 250       | 80       | Poor mix  |
| 10-12.5mm       | 4.125     | 0.34      | 1000                 | 242.4     | 82.41    | Dry mix   |
|                 | **4.25**  | **0.36**  | **1000**             | **235.2** | **84.6** | **Good mix** |

Table 2: Results of Binder drainage test
4.3 Mix proportioning

For mix proportioning of PC there are no standard methods proposed. Different studies include different concepts in mix proportion of PC. Most of the pervious concrete mixes are accomplished by adopting trial mixes upon requirement. After doing the review of literature, [1] is found to be one of the best methods of proportioning a PC mix and this method was based on the assumption that layer quantification of cementitious glue act just as a covering to the aggregates. The mix proportioning of PC is adopted from [1] in which volume of aggregate is calculated based on void ratio, and a scaling factor which depends on water absorption of coarse aggregate. Cement and water quantities were calculated based on the volume of cement paste. Void content and Bulk density of PC mix were obtained according to ASTM C1688 [16]. Table 3 shows the preliminary mix details, bulk density and void ratio of three sizes of aggregates.

Table 3: Preliminary mix details

| Aggregate sizes | Cement(kg/m³) | Coarse aggregate(kg/m³) | Water(kg/m³) | Bulk density(kg/m³) | Void content(%) |
|----------------|--------------|-------------------------|-------------|--------------------|-----------------|
| 4.75-6mm       | 321.31       | 1635.6                  | 115.67      | 2000               | 23.09           |
| 10-12.5mm      | 325.71       | 1617.17                 | 113.99      | 1860               | 28              |
| 10-20mm        | 321.03       | 1616.98                 | 115.57      | 2025               | 19.98           |

4.3.1 Corrections to preliminary mix

The void content obtained for the preliminary mix was 28% for 10-12.5mm size aggregates and 23.09% for 4.75-6mm size aggregates. To bring down the void content to 20%, trail mixes were prepared based on three alternatives: case 1) replacement of coarse aggregate with fine aggregate in coarse aggregate volume; case 2) using fine aggregate in the whole volume of mix; case 3) adding extra percentage of cement in the initial cement content.

For 10-12.5mm size aggregates, it was observed that the void content is 8% extra to the adopted void content, 20%. Therefore, trail mixes were prepared for 10-12.5mm size aggregates based on the above three alternatives. For case 1, coarse aggregate is replaced with 8% of fine aggregate. For case 2, 8% of fine aggregate is used in the whole volume of mix; for case 3, 8% of extra cement is added to the initial cement content.

After performing density and void content tests, it is observed that replacement of 8% of coarse aggregate with fine aggregate gave the 20% void content. This is because of the extra void content is occupied by the fine aggregate content. The same correction is also adopted for 4.75-6mm size aggregates. The corrected mix proportion for 4.75-6mm and 10-12.5mm size aggregates are shown in Table 4. For 10-20mm size aggregates no correction is done as the void ratio is approximately 20%. This is due to dense arrangement of different particle sizes of coarse aggregate which are ranging in between 10-20mm.

Table 4: Corrected mix proportion

| Aggregate size | Cement(kg/m³) | Coarse aggregate(kg/m³) | Fine aggregate(kg/m³) | Water(kg/m³) |
|----------------|--------------|-------------------------|-----------------------|--------------|
| 4.75-6mm       | 321.31       | 1635.6                  | 115.67                | 79.8         |
| 10-12.5mm      | 325.71       | 1487.79                 | 129.37                | 113.99       |
5. Experimental details

5.1 Influence of Compaction effort
As compaction effort plays an important role in determining the properties of PC, it is important to study the effect of compaction, especially on special concretes like PC. A detailed study on two compaction methods viz. hand compaction and machine compaction were studied on the PC specimens.

For hand compaction, 25 blows per each layer for all the three layers were given, and for machine compaction, after filling the mold with concrete, the mold is machine vibrated for 15s. Figure 3(a) and 3(b) shows the hand compacted and machine vibrated samples. For hand compacted sample it was observed that at the end of the test the paste content at the bottom of the sample accumulated is very less which is good for PC. On the other hand, for machine vibrated sample it was observed that the paste is accumulated at the bottom of the sample which could affect the permeability. Permeability tests were also conducted on both samples in which, hand compacted sample took 15s to allow 400ml of water, whereas machine vibrated sample took 28s to allow the same amount of water. Thus, keeping in mind on the importance of permeability factor, hand compaction is selected in this study.

Figure 3(a): Hand compacted specimen

Figure 3(b): Machine vibrated specimen

5.2 Density, Void ratio and Compressive strength
Fresh state density and void ratio of PC samples are evaluated according to ASTM C1688. Compressive strength of PC is evaluated by casting three cubic samples of 100×100×100mm for each size of aggregates and average compressive strength is recorded. PC cubes were tested to evaluate the compression strength at 28 days of time using Universal Testing Machine of 400 kN capacity. The test procedure followed was in accordance with IS 516-1959.

5.3 Permeability
Three cylindrical samples of 105×200mm are casted in PVC pipes to check the permeability and the efficiency of de-clogging. The permeability of PC specimens is evaluated using falling head permeability apparatus with an initial height of water level, h1=500mm and the final height of water level, h2=1mm. The time taken to fall the water level from h1 to h2 is recorded and the permeability is calculated by using permeability equation.

5.4 Clogging Characteristics
In real life, it is very common that the pores in the PC get clogged by fine dust and coarse particles. The fine dust particles are mostly either finer sand or organic matter and the coarser particles are mostly medium size sand particles and other dust. Due to these the pores get clogged and the efficiency of the pavement gets decrease. Therefore, it is very important to study the clogging behavior in the PC. In this study clogging of PC samples is done manually by using two sizes of fine clog particles viz, sandy soil (particle size in between 2.36mm-75µ) and fine soil (particle size in between 75µ-38µ) to understand the clogging behavior.
The pores are allowed to clog with sandy soil and fine soil because most of the pores in PC are affected due to smaller and medium sized grains.

5.4.1 Methodology adopted to clog and de-clog

One set of samples, three cylinders, are prepared for each size of aggregates for clogging and de-clogging tests. The clogging test is done in two phases, cyclic clogging phase and continuous clogging phase, to understand the permeability behavior of PC specimens. In the first phase i.e cyclic clogging, a total number of twenty cycles of clogging tests were conducted i.e the specimens are allowed to clog individually with sandy soil and fine sand. In each cycle, five grams of soil is allowed to pass through the specimen with 100ml of water, and the permeability value is recorded. For each cycle, a gap of 24 hours is given, this is because to allow the clog particles to dry in the specimen and the process was repeated.

In the second phase i.e continuous clogging, the specimens are clogged continuously for twenty cycles with the same charge of materials as explained in cyclic clogging phase and at the end of twenty cycles, the test for permeability is done. The basic aim of doing the clogging tests in two phases is to study the behavior of PC when clogged continuously due to dust and also when clogged during periodic occurrence of rain. During periodic rainfall, the pores which are already clogged with dust gets de-clogged due to the rain and at the same time there is also a chance of clogging the pores when the dust particles are mixed with rain water clogging the pores.

Due to the clogging of open pores, reduction in permeability occurs and it is necessary to clean or de-clog the PC for better efficiency. De-clogging methods like pressure washing, vacuum blowing, vacuum suction and reverse flushing are few options [14]. In this study, the cleaning or de-clogging technique used was water pressure washing at a rate of 2.2 kg/cm² followed by vacuum suction. In cyclic clogging, after every five cycles of clogging of PC specimens, de-clogging methods like water pressure washing was done for 15s and then the specimen is subjected to vacuum suction for 15s. Initially, it was observed that for the first two cycles there is a minor change in permeability, therefore it is decided that clogging of PC is possible only after particular number of cycles, for which in this study after five cycles de-clogging test is done and hence the clogging behavior is studied after every five cycles. The permeability values were again recorded after de-clogging is done. Figure 4 shows the typical specimen clogged with fine sand and Figure 5 shows the typical specimen after tested for pressure washing and vacuum suction. It was observed that, pressure washing followed by vacuum suction is the best method in cleaning the PC.

6. Test results and discussions

6.1 Void ratio and Density

The fresh state properties like density and void ratio of PC specimens are calculated according to ASTM C1688 and the values are shown in table 5.

| Aggregate size | Void ratio(%) | Density (kg/m³) |
|----------------|--------------|-----------------|
| 4.75-6mm       | 20.8         | 2060            |

Figure 4: Typical specimen after clogging
Figure 5: Typical specimen after de-clogging
6.2 Compressive strength and Permeability
The compressive strength of 100×100×100mm cubic samples of pervious concrete is tested for three sizes of aggregate and the permeability of PC specimens are calculated using falling head permeability apparatus and the values are shown in table 6.

| Aggregate size | Average compressive strength (MPa) | Average permeability (mm/s) |
|----------------|-----------------------------------|-----------------------------|
| 4.75-6mm       | 13.12                             | 20.48                       |
| 10-12.5mm      | 8.82                              | 20.4                        |
| 10-20mm        | 11.88                             | 21.29                       |

From table 6 it is observed that, smaller size aggregates gave higher compressive strength compared to larger size aggregates, this is due to dense packing of smaller size aggregates. Also, as the void ratio of all the three sizes of aggregates is identical the permeability of all the three aggregate sizes are almost the same.

6.3 De-clogging
Figure 6, 7 and 8 shows the permeability values recorded for the three sizes of aggregates during clogging for fifteen cycles and de-clogging of specimens were done after every five cycles.

Figure 6: Permeability of 4.75-6mm size aggregates for clogging and de-clogging tests

Figure 7: Permeability of 10-12.5mm size aggregates for clogging and de-clogging tests
Figure 8: Permeability of 10-20mm size aggregates for clogging and de-clogging tests

From Figure 6,7 and 8 it is observed that for three sizes of aggregate the permeability values are gradually decreasing when the specimens are clogged with both types of clogging particles and under de-clogging, partial regain in permeability is noted. The effect of size of clog particles also plays a significant role in deciding the life of PC. PC made with 4.75-6mm size, under the influence of sandy soil major decrease in permeability value was observed. This is because in PC is made with smaller size aggregates, large size clog particles will clog the pores by blocking the pore structure. In PC made with 10-12.5mm size aggregates, fine clog material showed major reduction in permeability due to the accumulation of fine particles around the aggregates and in the pores. PC made with 10-20mm size aggregates and when clogged with both sizes of clog particles, for the first five cycles decrease in permeability was observed and after the five cycles, there is no much permeability reduction. This is because, as the pores are almost clogged in the first five cycles and hence as there are only little voids available for further clogging and as the number of cycles gets increased there are no voids available to further clog the pores and hence the drop in permeability is not much high after five cycles when compared to the other two sizes of aggregates.

From the three graphs it was observed that, PC made with smaller size aggregates (4.75-6mm) had shown greater permeability reduction when clogged with coarser sand particles and the cleaning efficiency had shown less impact in regaining the permeability. But, PC made with larger size aggregates (10-12.5 and 10-20mm) had shown almost equal ratios of permeability reduction when clogged with both sizes of clog particles. Also, the cleaning efficiency of PC made with 10-12.5mm size aggregate had shown the good results in re-gaining permeability when compared to other two sizes of aggregates.

It was observed that by adopting the efficient cleaning procedures the clogging of pores in PC can be reduced and hence the life of the PC can be increased.

7. Conclusion:

1) Size of aggregate used in the PC mix has an indirect relation with strength. Smaller sized aggregate showed higher strength compared to other two sizes of aggregates and this was observed due to the dense packing of aggregates. The mixes prepared with different aggregate sizes at identical void ratio showed similar permeability.

2) The clogging of PC majorly depends on the size of clog materials. It was observed that larger size clog particles have a greater impact in clogging the pores when PC is made with smaller sized aggregates. Smaller sized clog particles had shown minor effect in reducing the permeability. This was observed as the clog particles got drained off during permeability tests. Similar results were also observed in [14].
3) It was observed that smaller size clog particles took five to seven cycles to clog the pores and then major decrease in permeability was observed, whereas larger size particles took only three cycles for which significant drop in permeability was observed.

4) De-clogging of pervious concrete specimens is found efficient under pressure washing followed by vacuum suction. PC made with larger size aggregates showed higher efficiency to de-clogging procedure.

References:

[1] Dang Hanh Nguyen, Nassim Sebaibi, Mohamed Boutouil, Lydia Leleyter, Fabienne Baraud 2014 A modified method for the design of Pervious Concrete Mix Construction and Building Materials 73 pp 271–282.

[2] S.O. Ajamu, A.A. Jimoh, J.R. Oluremi 2012 Evaluation of Structural Performance of Pervious Concrete in Construction International Journal of Engineering and Technology 2.

[3] Omkar Deo, Milani Sumanasooriya, Narayanan Neithalath 2010 Permeability Reduction in Pervious Concretes due to Clogging: Experiments and Modeling Journal of materials in Civil Engineering 741.

[4] M. Aamer Rafique Bhutta, K. Tsuruta, J. Mirza 2012 Evaluation of high-performance porous concrete properties Construction and Building Materials 31 pp 67–73.

[5] Praveen Kumar Patil, Santosh M Murali 2014 Study on the Properties of Pervious Concrete International Journal of Engineering Research & Technology 3.

[6] Milani S. Sumana sooriya, Omkar Deo, Narayanan Neithalath 2012 Particle packing-based material design methodology for Pervious Concretes ACI Materials Journal 109.

[7] C. Lian, Y. Zhuge, S. Beecham 2011 The relationship between porosity and strength for porous concrete Construction and Building Materials 25 pp 4294–4298.

[8] M. Uma Maguesvari, V.L. Narasimha 2013 Studies on characterization of pervious concrete for pavement applications Procedia - Social and Behavioral Sciences 104 pp 198 - 207.

[9] Qiao Dong, Hao Wu, Baoshan Huang, Xiang Shu, and Kejin Wang 2010 Development of a simple and fast test method for measuring the durability of Portland cement Pervious Concrete Portland cement association.

[10] Jing Yang, Guoliang Jiang 2003 Experimental study on properties of Pervious Concrete pavement materials Cement and Concrete Research 33 pp 381–386.

[11] Liv M. Haselbach 2010 Potential for Clay Clogging of Pervious Concrete under Extreme Conditions Journal of hydrologic engineering.

[12] Bin Tong 2011 Clogging effects of Portland cement Pervious Concrete Report-Iowa State University.

[13] Ketan Brijesh Jibhenkar, V.D Vaidya, S.S Waghmare, D. P Singh 2015 Experimental Investigation of Pervious Concrete using Titanium Dioxide International Journal of Advance Research and Innovative Ideas in Education 1.

[14] Nilesh Shirke and Scott Shuler A solution to clogging of porous pavements Report-Colorado State University, Fort Collins, Colorado.

[15] Ammar Yahia, K. Daddy Kabagire 2014 New approach to proportion pervious concrete Construction and Building Materials 62 pp 38–46.

[16] ASTM C1688/ C1688M-10a - Standard Test Method for Density and Void Content of Freshly Mixed Pervious Concrete.

[17] Sowmini Gopinathan, K B Anand. Properties of cement grout modified with ultra-fine slag, Frontiers of Structural and Civil engineering, DOI 10.1007/s11709-017-0383-0.