Study on pervious concrete pavement mix designs

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Abstract. Increased precipitation in recent years due to the effect of climate change is leading to increased surface runoff and water logging in urban areas while impervious concrete or asphalt covering of urban lands hinders groundwater recharge. However, Pervious Concrete Pavements have the capacity of functioning as a Sustainable Urban Drainage System (SUDS) by allowing surface water to infiltrate downwards through the porous structure of the pavements, thereby minimizing flooding risks, recharging ground water, reducing run off and peak flows, alleviating the precipitation load on overstressed drainage systems, and improving water quality by capturing pollutants. This research provides an overview on pervious concrete mix designs and their effect on strength and permeability. Materials of pervious concrete include those used in conventional concrete, however eliminating the fine aggregate content. Different mix designs have been prepared and tested to understand the behavior of Pervious Concrete and recommend an ideal mix. The findings from the Compressive Strength Test and Standard Test Method for Infiltration Rate of in place Pervious Concrete, investigate the gradually varying properties of pervious concrete with changes in the mix which are reported and discussed. Results indicate that a fine balance between compressive strength and permeability is not possible however pervious concrete pavements can be an acceptable alternative when used in low volume and low impact areas.

1. Introduction

The natural processes of the water cycle have been fundamentally altered by human development and construction practices. In the natural state, rainwater falls to the earth and gets absorbed into the soil and vegetation where it is filtered, stored, evaporated, and re-dispersed into the ever-flowing cycle [1]. However continuous urbanization driven by increasing motor vehicles is leading to the impervious covering of the earth’s surface with bituminous or concrete pavements. By sealing the earth’s natural filter, potential for excess runoff is increased which can lead to a number of problems such as downstream flooding, bank erosion and possibly transport of pollutants into potable water supplies.

The problems associated with impermeable surfaces are:

- **Pollution of surface water:** When stormwater runs off impermeable surfaces, it picks up pollutants as it flows into storm drains. The contaminated water then flows directly into rivers, lakes, wetlands and oceans, generating problems for biodiversity as well as public health [2].

- **Flooding of surface water and erosion of stream banks:** During periods of heavy rainfall, large amounts of impermeable surfaces generate large amounts of runoff. This sudden influx of runoff into rivers can cause flash flooding and erosion of stream banks. Excess runoff also contributes to the rate of deterioration of pavements [2].
• **Lowering of Ground Water Table:** Impermeable surfaces send rainwater into storm drains rather than allowing it to percolate down to aquifers. Scientific studies on the groundwater revealed that excessive exploitation has been lowering the aquifer level, thus limiting natural recharge [3-4]. Additionally, overexploitation for longer periods may account for several natural hazards such as unexpected landslides, sustained water logging, reduction in soil moisture, and changes in natural vegetation [5-6].

• **Water Logging:** On impermeable surfaces where runoff has no drainage route, stormwater can puddle for long periods of time, causing water logging. Stagnate puddles can become breeding places for undesirable insects such as mosquitoes [2].

• **Heat island effect:** Due to the heat-absorbing quality of asphalt and other paving materials, sites with high ratios of impermeable surfaces increase ambient air temperatures and require more energy for cooling [2]. Unlike the rural countryside, cities are largely paved-over or built on, so there is no vegetation or moisture to absorb heat and cool the landscape; asphalt, concrete and rooftops simply absorb the sun’s energy during the day and re-release it at night. According to a 2009 American Meteorological Study, nighttime temperatures can be as much as 14 degrees hotter in built up urban areas than in rural areas[7].

Pervious concrete pavement systems are claimed to allow recharge of groundwater through infiltration, thus reducing or eliminating runoff, and help control the amount of contaminants in waterways. Such treatment occurs as a result of capturing initial rainfall and allowing it to percolate into the ground, thus allowing soil chemistry and biology to “treat” the polluted water naturally. It is also claimed that through collecting rainfall and allowing it to infiltrate, pervious pavements allows increased groundwater and aquifer recharge, reduction of peak water flow through drainage channels, and minimization of flooding [8]. A pervious pavement and its sub-base may provide enough water storage capacity to eliminate the need for retention ponds, swales, and other precipitation runoff containment strategies, thus serving as a mean of Sustainable Urban Drainage System (SUDS) [8].

Although pervious concrete systems can effectively solve the problems of urban drainage, there are issues regarding is behavior and mix designs. Its performance relies on two key characteristics; ‘Strength’ and ‘Permeability’. The primary objective of this research is to understand the gradually varying properties of pervious concrete pavements by altering the mix design parameters. The lack of proper specifications and standard test methods make its design an arduous task, as different field conditions require different specifications. Therefore, a better understanding of the properties in order to determine an ideal mix design will ease the design and installation of pervious concrete pavements.

2. **Materials of Pervious Concrete Pavements**

Pervious Concrete pavements consist of the same materials as conventional concrete except fines; rather the mix consists of uniform graded coarse aggregates which allow a higher porosity and low inter particle connectivity [8]. By eliminating the fine aggregate content, we compromise with strength but this allows the infiltration of surface water downwards through the pores of the concrete structure. However the infiltration rate and strength both depend on parameters such as water content, size and gradation of aggregate, fines content, compaction energy etc.

Water and its application in pervious concrete are extremely critical. Since fines are eliminated from pervious concrete, strength relies on the bond of the cement paste and its interface with the aggregate. The correct amount of water will maximize the strength without compromising the permeability characteristics of the pervious concrete [9].

In pervious concrete the cement paste is limited and the aggregate rely on the contact surfaces between one another for strength. Typically aggregate within the range of 9.5mm and 19mm are used because of enhanced handling and placement. Anything larger would result in larger void spaces but would provide a rougher surface[9].

The amount of aggregate relative to the amount of cement is another important feature. The more cement paste available for compaction the higher the compressive strength. Again this will clog the pores and is detrimental to the function of the pervious concrete. Utilizing data obtained from prior
research, a suitable range of A:C ratios were used to create various mixtures of pervious concrete to be tested for compressive strength [9].

The degree of compaction and the compaction procedures/methods are two of the most important factors influencing the mechanical properties of pervious concrete [10]. It has been found that increasing the fresh concrete unit weight, increasing the amount of fine aggregates in the mixture, and applying a high compaction effort can improve such mechanical properties as compressive strength but decrease the hydraulic performance (permeability) and void ratio [11-12]. To get the best surface finish, required strength, and permeability, proper compaction is important. Too little compaction may not provide the required strength or a smooth surface, and it may also cause potential ravelling of the finished pavement. Too much compaction may cause a decrease in permeability by closing the voids. For a given mixture, the permeability can vary by as much as 25% for different compaction levels. As such, it is important to control the compaction energy accurately and quantitatively to obtain batches of pervious concrete with similar properties. In addition, a maximum thickness of 6 in. of pervious concrete is recommended because studies have shown that the concrete at the bottom quarter of a pervious concrete pavement often has a lower strength and/or lower porosity than the concrete at the top layer of the pavement [10].

Previous studies have indicated that employing fly ash can improve concrete performance, making it stronger, more durable, and more resistant to chemical attack. Fly ash use also creates significant benefits for the environment [13]. The significance of using fly ash is to minimize the use of environmentally unfriendly Portland cement in the production of pervious concrete, while meeting the specification requirements for pavement applications. To investigate the main properties of pervious concrete having fly ash used as a partial replacement for Portland cement, experimental research was conducted to determine the properties of various previous concrete specimens. The critical issue is the percentage of fly ash used to replace the cement. Researches have been conducted where up to 50% mix of fly ash was used [13].

3. Typical Cross Section of Pervious Concrete Pavements

The basic permeable concrete pavement system consists of a top layer of porous concrete covering a layer of gravel that consists of uniformly sized aggregate, which is placed on top of the existing soil sub-base often separated by a layer of Geotextile as shown in Figure 1. Storm water penetrates the porous concrete and is filtered through the first layer of gravel. The stored runoff gradually infiltrates into the underlying soil.

Figure 1. Typical section of a Pervious Concrete Pavement

The factors determining the design thickness of permeable concrete include its desired hydraulic (e.g. permeability and voids contents) and mechanical properties (e.g. strength and stiffness).
there is any concern about the possible migration of pollutants into the groundwater, Pervious Concrete Pavements should be constructed with an impermeable membrane, and the treated storm water should subsequently be discharged into a suitable drainage system [14].

4. Mix Design
One of the objectives of this research work was to determine the mix ratio that yields the perfect balance of compressive strength and permeability. For this study, the parameters changed in each mix design include, Cement : Aggregate ratio, Aggregate size, Water content & addition of Supplementary Cementitious material (SCM). SCMs are a sustainable alternative to ordinary Portland cement, which often includes recycled industrial by-products such as fly ash. A total of 14 mixes were selected to be tested including 42 standard cylindrical samples referring to sample A1-A42; 3 corresponding to each mix and 14 rectangular slabs referring to sample B1-B14 with the dimension 2’x2’x4”.

4.1. Aggregate Size
The aggregate sizes selected for this study are 25mm down grade, 19mm down grade and 12.5mm down grade. After acquiring aggregates, they were sieved to obtain a single sized gradation. A well graded mix results in decreased pore sizes and % void. Single sized gradation yields the maximum void ratio which means maximum permeability. Although the literature includes tests of aggregates of sizes between 9.5mm to 25mm, the smallest particles size chosen for our test was 12.5mm down grade, as smaller particles would yield lower permeability. To conduct the sieving, standard sieves of sizes 25mm, 19mm, 12.5mm and 9.5mm were used. The particles passing 25mm sieve but retained on 19mm sieve was stored, the particles passing 19mm but retained on 12.5mm sieves were stored, and finally the aggregated passing the 12.5mm sieve but retained on the 9.5mm sieve was stored. The rest of the aggregates were discarded for their small sizes.

4.2. Aggregate : Cement Ratio
Aggregate : Cement Ratio of 4, 5, & 6 were chosen for this study. Previous researches have tested Aggregate : Cement ratios of 7 and higher, but have yielded poor outcomes in terms of compressive strength. The mixes have no quantities of fine aggregates, but only coarse aggregates to allow prevent the blocking of pores and allow permeability by only coarse particle interlocking with the cementitious paste. Literature shows that addition of fines improves the strength of the samples, but lowers permeability. The aggregate : cement ratios were maintained on the basis of weight not volume. Appropriate weights were taken to the second decimal to determine the amount of cement and aggregate required for each mix.

4.3. Water Content
Varying water content of 0.36, 0.32 and 0.28; each at an interval of 0.4 was chosen for this study to understand the variation of strength properties of pervious water concrete with water. Water was added to various mixtures of aggregate and cement in experiments designed to maximize hydration and optimize compressive strength. The goal is to determine an appropriate range of W/C ratios that will yield high compressive strengths in the pervious concrete.

4.4. Addition of Fly Ash
Fly ash was added to mix 12, 13, 14 corresponding to aggregate to cement ratios of 4, 5, 6 with w/c 0.28 and aggregate size of 19mm down grade to analyze its effect on the physical properties. Fly ash was added on the basis of 20% replacement of the weight of cement.
Table 1. Mixtures and Corresponding Parameters

| Mix | Aggregate : Cement (4,5,6) | Aggregate Size (25mm, 19mm, 12.5mm) | W/C (.36, .32, .28) |
|-----|---------------------------|------------------------------------|-------------------|
| 1   | 4                         | 25.0mm                             | .36               |
| 2   | 4                         | 25.0mm                             | .32               |
| 3   | 4                         | 25.0mm                             | .28               |
| 4   | 4                         | 19.0mm                             | .36               |
| 5   | 4                         | 19.0mm                             | .32               |
| 6   | 4                         | 19.0mm                             | .28               |
| 7   | 4                         | 12.5mm                             | .36               |
| 8   | 4                         | 12.5mm                             | .32               |
| 9   | 4                         | 12.5mm                             | .28               |
| 10  | 5                         | 19.0mm                             | .28               |
| 11  | 6                         | 19.0mm                             | .28               |
| 12  | 4                         | 19.0mm                             | .28               |
| 13  | 5                         | 19.0mm                             | .28               |
| 14  | 6                         | 19.0mm                             | .28               |

5. Tests on pervious concrete samples

In order to understand the behavior of the pervious concrete samples, proper tests must be conducted. Therefore the two test parameters of the study were compressive strength and Permeability.

5.1. Visual Inspection

From a visual inspection of the samples it is evident that the top surfaces have sufficient pores for infiltration of water, whereas segregation led to the bottom surface to appear clogged and smooth (Fig 5-1). It was also observed that the top surfaces of samples B-1 B-2 & B-3 containing 25mm downgraded aggregates were rough and prone to abrasion due to large sized particles. The surface was uncomfortable for walking on barefoot and could lead to sustained pedestrian injuries from accident or impact. The mix containing 12.5mm downgraded aggregates provided a smooth surface suitable for walking and an aesthetic texture too.

Fig 2: Visual Inspection of the samples

5.2. Compressive strength test

The 28-day average compressive strength of each of the 13 Mix Designs was determined by crushing 3 cylindrical samples corresponding to each mix. A total of 39 cylinders that were successfully recovered, were crushed using a Universal Testing Machine and the corresponding strengths have been complied into Table2. Mix 14 corresponding to an A/C Ratio of 6 and 20% fly ash was ostracized from the calculations as the samples were unsuccessfully recovered from the molds. It is
assumed that the lack of cement and slow nature of strength development of fly ash was responsible for the premature failure of the samples. This could have been prevented by prolonging the curing time. The results are consistent with visual observations where Mixture 11, provided the least compressive strength of about 457 psi owing to the lack of cement paste to bond the aggregate together. On the contrary, Mixtures 7, 8, 9 yielded the highest compressive strengths of 2732.06, 2949.64 and 3173.61 psi respectively in spite of their high standard deviations. Although a wide range of compressive strengths were obtained, none of the mixtures provide strength equal to that of conventional concrete. An inspection on the failure mode of samples show that none of the samples were actually crushed under the applied loads, rather exhibited shear failure initiating from the top surface. Due to the lack of binder in proportion to aggregates, the bond weakens before the structure fails.

When compared to previous studies, compressive strength of Pervious Concrete mixes can develop compressive strength in the range of 5 to 30 MPa (750 to 4350 psi), with typical values of about 17 MPa (2465 psi), which is suitable for a wide range of applications, such as light traffic pavements [8,15,16]

Table 2. Compressive strength and Infiltration Rates of Samples

| Mix no. | Avg compressive strength (psi) | Standard deviation, s | Prewetting time (3.6kg) | Wetting time (18kg or 3.6kg) | M (kg) | Infiltration Rate (mm/hr) |
|---------|-------------------------------|-----------------------|-------------------------|-----------------------------|--------|--------------------------|
| 1       | 787.73                        | 121.06                | 10.5                    | 13.4                        | 18     | 68412.92                 |
| 2       | 972.24                        | 116.93                | 9.0                     | 23.9                        | 18     | 38437.45                 |
| 3       | 1252.44                       | 159.53                | 4.4                     | 12.1                        | 18     | 75763.07                 |
| 4       | 968.18                        | 166.58                | 7.7                     | 38.0                        | 18     | 24124.55                 |
| 5       | 1153.27                       | 229.78                | 6.4                     | 18.8                        | 18     | 48840.34                 |
| 6       | 1517.07                       | 291.88                | 9.5                     | 16.5                        | 18     | 55728.46                 |
| 7       | 2732.06                       | 506.21                | 23.0                    | 123.9                       | 18     | 7398.97                  |
| 8       | 2949.64                       | 435.24                | 61.2                    | 53.6                        | 3.6    | 3420.64                  |
| 9       | 3173.61                       | 411.40                | 58.4                    | 56.7                        | 3.6    | 3233.62                  |
| 10      | 827.65                        | 102.76                | 6.1                     | 12.3                        | 18     | 74531.15                 |
| 11      | 456.95                        | 179.06                | 3.9                     | 9.8                         | 18     | 93544.28                 |
| 12      | 573.05                        | 81.46                 | 12.4                    | 13.7                        | 18     | 66914.83                 |
| 13      | 720.31                        | 35.19                 | 7.1                     | 10.6                        | 18     | 86484.26                 |

5.3. Permeability Test
Permeability test of the samples was conducted in accordance with ASTM 1701/C. According to this test method, an infiltration ring is temporarily sealed to the surface of a pervious pavement with seal putty to prevent the water from escaping. The ring is watertight, sufficiently rigid to retain its form when filled with water, and has a diameter of 300 ± 10 mm with a minimum height of 50 mm.

From Table 2, the results of the infiltration test show that sample B-11 corresponding to mixture 11 provided highest infiltration rate of 93544.2 mm/hr. However this mix also corresponds to the minimum compressive strength. On the contrary, Mixtures 7, 8 and 9 that exhibited maximum compressive strength corresponded to the least infiltration rates of 7398.97, 3420.64 and 3233.62 mm/hr respectively. The measurement of prewetting time and wetting time varied due to minor discrepancies of water pouring rate. A water head of 15mm was maintained at all time when pouring water. Another issue arose when measuring the permeability of mixtures 7, 8 and 9. As most of the pores were clogged due to segregation, the surface provided very little space for infiltration.
Previous studies indicate the variation of permeability of Pervious Concrete can range between 4,860 to 80,800 mm/hr, with a typical rate of 7,200 - 20,200 mm/hr, depending on compaction, void content, materials and sub-base infiltration rates [17].

5.4. Infiltration Rate vs Aggregate Size

Figure 3 shows the relation between Infiltration rates (mm/hr) and the Aggregate sizes (mm). The trend is an upward rising directly proportional curve that indicates infiltration rates increase with the increase in aggregate sizes. This is because larger aggregate sizes with single sized gradation means larger voids and more porosity which allows easier infiltration of water through the concrete matrix.

A typical relationship between the void ratio and permeability of Pervious Concrete has been previously researched [18] which shows a good association between the two properties with a coefficient of determination ($R^2$) of 0.82. The non-linear behavior is attributed to the dependence of the infiltration rate on the percentage of voids as well as their interconnectivity. The permeability of Pervious Concrete is also dependent upon pore-size distribution, pore roughness, and partitioning of the pore space [19]. Previous studies also indicate, a good correlation also exists between the fresh density and void ratio of Pervious Concrete, which suggests that the fresh density test can act as a viable quality control/performance measure for the acceptance of Pervious Concrete, which can be determined by ASTM C1688 [20].

5.5. Infiltration Rate vs Aggregate : Cement Ratio

Permeability is affected by the A/C ratio. As the amount of cement in a mixture decreases, which indicates an increase in the A/C ratio, the permeability of the pervious concrete increases. This relationship is shown in Figure 4, which shows a directly proportional relationship by an almost linear curve. A lower Aggregate : Cement ratio produces a higher volume of paste in excess of the amount needed to encapsulate the aggregate for bonding the pervious concrete matrix. Surplus paste clogs the open pore structure of pervious concrete, thus reducing the void ratio and increasing compressive strength [21]. Conversely, a very high A : C ratio can lead to reduced adhesion between aggregate particles and placement problems.

5.6. Selection of appropriate mix

By observing the relationship between compressive strength and permeability as shown in Figure 5, it is evident that there is no perfect mix that yields a balance between maximum strength and permeability. From Figure 5 we notice that the relation between the two varies inversely with a coefficient of determination ($R^2$) of 0.8856. It is evident that Mix 6 produces satisfactory results (1517 psi and 55728.46 mm/hr). However if high infiltration rates are not required, rather emphasis is given
on compressive strength, then mix 7 (2732 psi and 7399 mm/hr) could be selected. The respective key properties of mix 6 and 7 are exhibited in Table 3.

| Mix no. | 6   | 7   |
|---------|-----|-----|
| A/C ratio | 4   | 4   |
| Aggregate size | 19mm | 12.5mm |
| W/C ratio | 0.28 | 0.36 |
| Fly ash | None | None |
| Compressive strength (psi) | 1517 | 2732 |
| Infiltration Rate (mm/hr) | 55728.5 | 7399 |

**Figure 5.** Compressive strength (psi) vs Infiltration Rate (mm/hr)

### 6. Conclusion and Recommendation

Errors of the past will dictate designs of the future. Unfortunately there is not a precise recipe for pervious concrete that yields high compressive strength and porosity and neither do the existing test methods provide a clear understanding of the behavior of pervious concrete. Testing along with analysis of existing systems is the best method for developing a range of values which will lead to a functional design.

The compressive strength test performed on cylindrical samples does not provide an accurate measurement of the strength and durability of Pervious Concrete Pavements. Therefore other test parameters including flexural strength, splitting tensile strength, fresh density, and void ratio may provide a better understanding of the performance of pervious concrete pavements. Besides, the lack of standard procedures for compaction methods make it an arduous task to design pervious concrete pavements for field use.

Based on the finding of the study, Pervious concrete, although not as strong as conventional concrete, may provide an acceptable alternative when used in low volume and low impact areas. It is normally used without any reinforcement due to high risk of corrosion because of the open pores in its structure. It can be gainfully used to some extent to allow ground water recharging and to control intensity of urban flooding as well as to keep thermal balance in buildup areas. Some applications include pervious pavement for parking lots, rigid drainage layers under exterior areas, greenhouse floors to keep the floor free of standing water, structural wall applications where lightweight or better thermal insulation characteristics, or both are required, elements where better acoustic absorption characteristics are desired, base course for roads, surface course for parking lots, tennis courts, zoo areas, animal barns, swimming pool decks, beach structures, seawalls, embankments, etc. [8,22,23,24].
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