Investigating the Relationship between Porosity and Compressive Strength for Porous Concrete as a Sustainable Pavement

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Abstract: In this study, the relationship between porosity and compressive strength for porous concrete (PC) was investigated. The effect of mixture design parameters particularly, water-to-cement ratio (W/C) and size of aggregate on the porosity and compressive strength of PC was evaluated. To investigate the role of W/C and aggregate size on this testing procedure, the experiments were performed on specimens of two aggregates size and four range of W/C. The PC mixtures were made with W/C in the range of 0.28-0.34, 350kg/m^3 cement content and 19.5mm and 9.5 maximum size of aggregate. PC mixes were made from each aggregate and were tested. The results showed that the W/C and aggregate size are key parameters which significantly affect the porosity of PC. Investigation of compressive strength and porosity for the various mix designs showed a clear dependence on these parameters. The measured values fall within the expected range obtained from a review of the literature. Compressive strength of coarse porous concrete (CPC) is smaller than compressive strength of fine porous concrete (FPC) and the porosity of CPC are bigger than porosity of FPC. In general, increased W/C yields a smaller porosity and higher compressive strength. This approach can reduce the number of trial batches needs for target performance of PC samples.

Keywords: Porous concrete, W/C, porosity, compressive strength.

1. INTRODUCTION

Porous concrete (PC) is constructed in a similar fashion to traditional concrete, by mixing cement, water, and aggregates. The primary goal of any PC system is to achieve adequate porosity so that water can readily pass through the system and into the sub base. The creation of air voids is achieved by limiting or completely eliminating fine aggregate such as fine sand from the mix design, and using well-sorted coarse aggregate. With no fine in the mix, the coarse aggregate is bound together only by a thin layer of cement creating air voids. The use of a uniform coarse aggregate ensures the smaller pieces do not settle in the pore spaces decreasing the porosity of concrete [1].

A special type of concrete characterized by an interconnected pore structure and high void content in the range of 15-35% is PC, thus allowing infiltration of water through its structure [2]. While its constituent materials are similar to that of normal concrete, PC contains little or no fine aggregate. It is also known as permeable concrete and no-fine concrete. PC has been used in low-traffic pavements such as parking lots and sidewalks [3]. Permeability coefficient or hydraulic conductivity are the most important performance characteristic of PCs, and with any some material, transport properties are dependent on the pore structure features [4]. PC allows water to pass through its structure due to an increased air voids network. This open structure gives this concrete the added possibility to be applied in pavement engineering as a water drainage layer [5].

The disadvantages of a PC pavement are perceived to be the lower strength and durability that can sometimes occur in these systems, which may lead to a service life that is shorter than that of the designed life. However, several studies have shown that adequate strength can be achieved for a variety of applications in which PC pavements would be useful, specifically low-volume traffic areas such as parking lots. The low-volume areas have a smaller strength demand and act as point sources for storm water pollution [6].

Experimental studies have shown a wide range of values for 28-day Compressive Strength of PC. Some studies have reported that strengths of about 21 MPa (3000 PSI) or more are readily attainable with the proper porosity. Other studies have found compressive strength that range from about 4 MPa to 25 MPa. Several factors have attributed to this wide range of reported strengths. One of factors is porosity. It has been shown that in general, as the porosity of the sample decreases, there is a corresponding increase in the compressive strength of the sample [7].

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The costs of such asphalt pavements will grow the coming years due to the foreseeable increase in oil prices. PC is therefore a suitable material to be considered for increased usage in the developing sustainable pavement [8]. Natural Resources are increasingly consumed due to rapid urbanization and there after human construction activities, so that various strategies are being investigated by engineers to protect and restore natural ecosystems in the world PC pavement are termed as comprising materials that facilitate storm water infiltrate and transfer to the underlying subsoil [9]. The porosity is the ratio of the Volume of Voids to the total Volume of the Specimen. Some of the voids in PC are not effective in Carrying water through the material. The Voids that are frequently called the ‘effective void’ are important. Some methods for finding the porosity of PC only calculate the effective voids [10].

It's believed that PC can effectively assist solving drainage problems and reducing the risk of flash flooding, resulting from continuous urban development [11]. Some researchers recommends to finding the total porosity of PC using a water displacement method [12]. The water displacement method is based on Archimedes principle of buoyancy, which states that the buoyancy force is equal to the weight of fluids displaced. The dry mass, the submerged mass and the total volume must be known to calculate the porosity using the displacement method [13]. Since the porosity of PC is the most important characteristic of PC, in this study, the characteristic of PC has been evaluated. The objective of this study was to evaluate compressive strength and porosity of PC specimens.

One of the most important parameter for PC that affected the performance is compressive strength. PC made with different porosity has different compressive strength. In this study the porosity and compressive strength of PCs are investigated. This approach leads to finding ideal mix design for making PCs with highest strength and durability.

2. EXPERIMENTAL PROGRAM

2.1. Materials and Mixtures

For this study, a total of 24 PC mixtures were prepared and tested. For each mixture, triplicates of 150mm cubic sample were prepared same to the one described in ASTM C192. Samples were filled in three layers. Each layer tamped 15 times using a standard compacting bar. Excessive tamping was avoided in order to prevent blockage of the PC open pore structure. Excess concrete above the upper edge of the mould was removed and a steel trowel was used to press on the surface for levelling.

The composition used to prepare PC samples consisted aggregates, ordinary Portland cement and water. All mixtures were designed with either single size of crushed silica aggregates. The single size of aggregate defined as the size of sieve on which, 100% of aggregate was passed but all retained the sieve under that. Crushed silica Aggregates with a size of 4.75-9.5mm and 9.5-19.5mm were used in this study. Aggregates with a size of 4.75-9.5mm were named fine and aggregates with a size of 9.5-19.5mm were named coarse. The engineering properties of used aggregates are shown in Table **1**.

Table 1: Engineering Properties of Aggregates

Flakiness Index (%)	Water absorption (%)	Los Angeles Abrasion (%)	Sand Equivalent (%)
10	3	13	70

Table 2: Chemical Contents of Type 2 Cement, According to ASTM C150 (Tehran Cement Company Laboratory)

Constituent Compounds	CaO,%	SiO_2,%	Al_2O_3,%	Fe_2O_3,%	MgO,%	SO_3,%	L.O.I,%	I.R,%
Measured value	63.35	21.45	4.61	3.3	2.26	2.05	2.00	0.57

Table 3: Properties of Type 2 Cement, According to ASTM C150 (Tehran Cement Company Laboratory)

	Chemical Properties			Blaine Specific Surfacec m^2/g	Autoclave Expansion,%	Physical Properties Setting Time		Compressive Strength MPa		
	MgO%	L.O.I%	I.R%			Initial Minutes	Final Hours	3-Day	At Least 7Days	At Last 28Days
Value	<6	<3	<0.75	>2800	<0.8	>45	<6	>10	>17	>21

The chemical properties of cement are shown in Table **2**. Type 2 Portland cement having a specific gravity of 3.15 and conforming to the requirements of ASTM C 150, was used for preparing all the PC mixtures. The properties of type 2 cement are shown in Table **3**.

PC mix design for achieving minimum 10 MPa (Mega Pascal) compressive strength is shown in Table **4**.

Table 4: Mix Design For 1 Cubic Meter PC Making

Ingredient	Cement	Water	Aggregate
Weight (kg)	350	98-120	1400

All mixtures were produced using single size aggregate and only Portland cement and water-to-cement ratio (W/C) of 0.28, 0.3, 0.32, and 0.34. 1400kg aggregates were used for making one cubic meter of PC mixes. The W/C was incrementally changed from 0.28 to 0.34. In this way, Samples of different porosity were obtained. PC mixes was made from fine aggregates was named fine porous concrete (FPC), and PC mixes was made from coarse aggregates was named coarse porous concrete (CPC). All Mixtures were proportioned to achieve appropriate permeability coefficient and porosity. Standard 150mm cubic sample were used for 28-day compressive strength tests on hardened PC. All specimens were de-moulded after 24h and stored in the curing room at approximately 95% relative humidity. The compressive strength was reported based on the average of three samples. Picture of FPC sample and CPC is shown in Figure **1**.

Figure 1: Samples of FPC and CPC.

2.2. Testing Procedures

Prior to testing, the samples were weighted to determine the density. Compressive strength testing was performed in general accordance with ASTM C 39. The unconfined compressive strengths testing of PC specimens were carried out on the lab mixes. For this test, a concrete compression kit with the speed of 1.3mm/min was used. Picture of this jack was shown in Figure **2**.

The porosity test was carried out at 28 day of age. The effective porosity was measured as the percentage of pore volume or void space within the concrete that can contain water. The total porosity was measured by finding the difference of the PC sample weight submerged in the water and the weight after air drying for 24h. The sample was oven dried firstly and was left to cool for measurement the dimensions of the sample were measured in dry condition and the total volume of sample (v) including the solid and void component was determined. The difference in the measured weights was then divided by the sample volume (mm^3) as follow [14]:

$$P = 1 - \left(\frac{\frac{W_1 - W_2}{\rho_W}}{V} \right) * 100 \quad (1)$$

Where p is the total porosity of the PC (%), w_1 is the PC sample weight air-dried for 24h (kg), w_2 is the PC sample weight submerged under water (kg), v is the PC sample volume (mm^3), and ρ_w is density of water (kg/mm^3).

Figure 2: kit for compressive strength measurement.

3. RESULTS AND DISCUSSION

3.1. Effect of W/C and Aggregate Size

The W/C and aggregate size and their effects on PC mixes were evaluated in lab mixes FPC1-FPC4 and CPC1-CPC4. Table **5** shows the measured properties

Table 5: Measured Properties of All PC Mixes

Pc Mixtures	Size of Aggregates (mm)	w/c	Porosity	Compressive Strength (MPa)
FPC1	9.5	0.28	0.39	9.3
FPC2	9.5	0.3	0.386	15.5
FPC3	9.5	0.32	0.375	16.1
FPC4	9.5	0.34	0.35	18
CPC1	19.5	0.28	0.41	8
CPC2	19.5	0.3	0.405	11.8
CPC3	19.5	0.32	0.4	13
CPC4	19.5	0.34	0.39	13.5

of all PC mixes, including compressive strength and porosity. Average results from the experimental study were summarized in this table. The tests yielded a range of values from about 8MPa to 18MPa for compressive strength. In PC mixtures failure was predominantly observed between the cement-aggregate interfaces, resulting in the lower average compressive strength. Failure in PC mixtures was generally due to crumbling on the exterior of the PC sample. It can be seen from Table **5** that the highest compressive strength achieved in this study is 18MPa for mixture FPC4, which was produced from fine aggregate. Mixture CPC1 has the lowest compressive strength of 8MPa, which was produced from coarse aggregate. The density of PC is approximately 1800kg/m^3.

3.2. Porosity and Compressive Strength

Figure **3** illustrate the effect of porosity on compressive strength for CPC. The compressive strength generally decreases when the porosity increases. Figure **4** illustrate the effect of porosity on compressive strength for FPC. The highest compressive strength of around 18 MPa can be seen when the porosity is higher than 35%. The smallest compressive strength of around 8 MPa can be seen when the porosity is higher than 41%. Figure **3** and **4** shows that porosity played an important role in compressive strength of the PC specimens. These changes can be mainly attributed to the decrease in workability of the mix designs as the W/C is adjusted. Traditional methods of measuring the workability of a PC mix are not effective for mixes, as they generally have negligible slump even when the W/C is below the optimal level. With increased workability, greater densification occurs even when and porosity decreased. This greater densification led to increase in compressive strength that was observed for the various mix designs.

The low workability of this mix indicates that the cement paste may have been stiff, and therefore may not have readily coated the pore in the mix. This lower density resulted in a greater amount of pore space available for water to pass through. This would also have contributed to the lower compressive strength. The higher W/C would have contributed to an increased workability as well as made more water available for hydration of the cement paste, resulting in a stronger concrete specimen.

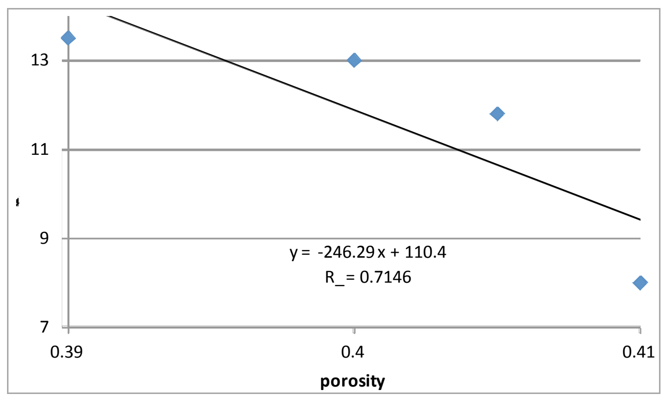

Figure 3: Effect of porosity on compressive strength for CPC.

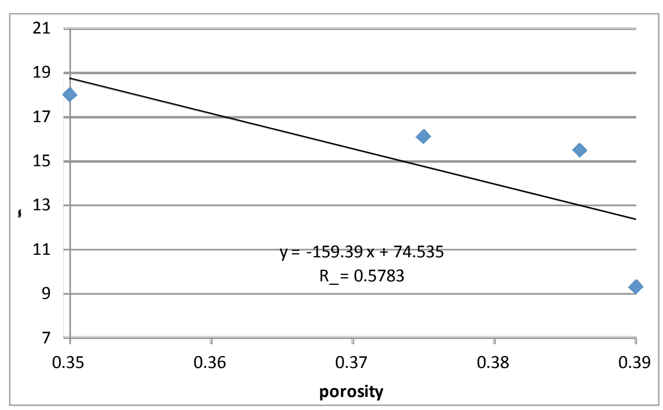

Figure 4: Effect of porosity on compressive strength for FPC.

4. STATISTICAL ANALYSIS OF THE RESULTS

Analysis of variance (ANOVA) was used to test the significance of regression models, and t-test were performed to identify the non-significant (NS) variables model coefficients by using linear regression analysis.

A Linear Regression Model (LRM) along with ANOVA was conducted to study the significance of porosity distribution on PC compressive strength as follow:

$$\text{Compressive strength} = \text{Constant} + A * \text{prosity} \quad (2)$$

Where, A is regression multiplier.

The statistical analysis parameters are shown in Table **6** and indicate that for compressive strength of PC samples, the porosity content of all samples included in this study are significant. The analysis also indicates that the increase of porosity content reduces the compressive strength, as the multiplier sign is negative. This model could be used to estimate the compressive strength for any porosity included in the regression model, however, it is limited to the specific size of aggregate used in this study.

Table 6: LRM Parameters for Permeability Coefficient

Factor	Sample Name	Multiplier Estimate	T Test	R Squared
Constant	FPC	-159.39	2.06	0.578
A		74.54	-1.66	
Constant	CPC	-246.29	2.50	0.715
A		110.4	-2.24	

5. SUMMARY AND CONCLUSIONS

In this study, the main property of PC containing two aggregate sizes was investigated. Twenty-four (24) different mixes of PC were tested. The experimental investigations included determining porosity, compressive strength, and relationships among them. The W/C and aggregate size had an effect on the mechanical properties like compressive strength and porosity. The main conclusion remarks are summarized below:

1. The average compressive strength of PC produced from single sizes aggregate is approximately 10mm/s for FPC and 14mm/s for CPC. These values depend on the mix design.

2. As expected, if the W/C of PC increased, the porosity decreases and compressive strength increases. W/C played a strong role in both the compressive strength and porosity of PC. Optimum W/C is 0.34, because the W/c bigger than this leads to closing the pores in PC.

3. Characteristics such as compressive strength and porosity showed clear dependence on the size of aggregates and mix design parameters. If the size of aggregate increased then the porosity increases and compressive strength decreases. PCs are made from fine aggregate have bigger compressive strength.

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