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Establishing a Balance Between Mechanical and Durability Properties of Pervious Concrete Pavement

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Abstract: The use of pervious concrete pavement (PCP) is significantly increasing due to reduction of road runoff and absorption of traffic noise. However, this type of pavement cannot be used for heavy traffic due to a high amount of voids and consequently low strength. This study focuses on the use of by-products as fine additives such as silica fume (SF) and fly ash (FA) for evaluating their effect on the mechanical and durability properties of PCP as an attempt to establish a balance between permeability and strength properties. The effect of coarse aggregate size, ratio of fine aggregate, specimen's size and curing periods were investigated. The results indicate that PCP provided acceptable permeability of 3.6 mm/s and 28 day compressive strength reaching to 33.0 MPa through the combination of FA and SF.

Keywords: Pervious Concrete, Compressive Strength, Void Ratio, Permeability, Silica Fume, Fly Ash

1. Introduction

With population growth, continual urbanization has led to an increase of impervious surface areas, which block the percolation of precipitation from rainfall and snow down through the ground. This increases the potential for excess surface runoff, which can lead to downstream flooding, bank erosion and possibly transport of pollutants into potable water supplies. At the same time, there is a public concern about the conservation of water resources and quality. Conventional concrete pavement has lack of water and air permeability which had a negative impact on environment. The conventional concrete cannot capture stormwater and also cannot allow it to be filtered underground, causing some problem such as the phenomenon of urban heat island in city, water erosion and degradation in the quality of water. Utilization of conventional concrete in pavement construction consumes more efficient land use by need retention ponds, swales and other stormwater management devices [1- 2].

Pervious concrete pavement (PCP) is a mixture of Portland cement, uniform coarse aggregate, with either a small amount of or without fine aggregate, or water. Appropriate amounts of water and cementitious material are employed to create a paste that forms a thin coat around aggregate particles but leaves free spaces between them forming pores. The increasing interest in pervious concrete is due to the Environmental Protection Agency regulations, which require decreasing the amount of water runoff and initially treating the runoff. By allowing stormwater runoff to infiltrate, pervious concrete filters sediment and other contaminants that would otherwise make their way to waterways.

The advantages of using pervious concrete also include providing better road safety through improving skid resistance by removing water during rainy days, reducing traffic noise, minimizing the heat island effect in large cities and preserving native ecosystems. In general, initial costs for pervious concrete pavements are higher than those for conventional concrete or asphalt paving due to its thicker designed thickness especially above weaker subgrade. However, overall total system costs can be substantially lower due to: (1) Reducing installation costs where installing traditional curbs, gutters, storm drain inlets, piping, and retention basins can cost two to three times more than low-impact strategies for handling water runoff, such as pervious concrete. (2) Increasing land utilization where the pervious concrete pavement doubles as a stormwater management system, there is no need to additional land for installing large retention ponds and other water-retention and filtering systems [3, 4].

Pervious concrete pavement also has several potential disadvantages which considered advantages for ordinary concrete pavement. Those of most concern include perceived cold weather problems, the potential of clogged void spaces, historical high construction failure rates, and the potential to contaminate ground water. High construction failure rates are often associated with poor design and contractors who lack sufficient knowledge for proper installation of the product. Generally, relatively low strength is usually associated with the high porosity in PCP. Unlike other pavement systems, the low strength of pervious concrete not only limits its application in heavy traffic highways but also influences the stability and durability of the structures resulted in failures at an early stage of pavement life, because of, for example, susceptibility to frost damage and low resistance to chemicals. Therefore, PCP with low strength can only be utilized in some applications, such as sidewalks, parking lots, recreation squares and subbases for conventional pavement. And with some effective improvement in strength and using smaller size aggregate and fine additives, PCP could be applied in pavement shoulder and local roads. On another side, the disadvantages of pervious concrete compared with ordinary concrete pavement include yearly or bi-yearly maintenance to unclog voids and restore permeability and the possibility of contaminating the groundwater, depending on the soil conditions [5, 7].

Generally, the sizes of connected pore in pervious concrete range from 2 to 8 mm in diameter with void content between 15% and 35% by volume with permeability of 0.25–6.1 mm/s depending on the type of compaction and the type of the aggregates. Traditional concrete has compressive strength ranging from 24 to 34 MPa and tensile strength ranging from 2.4 to 4.1 MPa, while pervious concrete has compressive strength ranging typically from 2.8 to 28.0 MPa and tensile strength ranging from 1.0 to 3.4 MPa. Moreover, PCP has a unit weight of as low as 70% of the conventional concrete [4, 6]. Normally, the water cement ratio is one of the important factors for the compressive strength of cement concrete. The water-to-cement (w/c) ratio is typically between 0.27–0.33. Pervious concrete pavement has been used for over 30 years in England and the United States and Japan when the construction industry briefly considered reducing energy costs and exploring alternatives to building with non-renewable mineral resources [8 to 10].

When traditional concrete is compared to pervious concrete across criteria of cost, availability of contractors and future outcomes such as durability, maintenance, and long term savings, pervious concrete is almost equal to traditional concrete where it is appropriate to be used. In many situations, it comes out ahead. In addition, when factors such as long-term impact on the environment are considered, pervious concrete proves superior. The infiltration properties of the material - the ability to remove pollutants from storm water – show far greater effectiveness than some of the most popular storm water management systems. This demonstrates that a paving system which is nearly equal in cost to traditional concrete actually pays for itself over the long term, with a more effective storm water infiltration system than commonly used traditional storm water systems. It is therefore possible to employ an environmentally sound pavement solution while saving money [11].

2. Research Approach and Objectives

Several studies have been carried out on mechanical properties of pervious concrete such as Crouch et al. (2007) [12], Lian et al. (2011) [13] and Agar-Ozbek et al. (2013) [14]. While several studies have reported the results of mechanical and functional performance of pervious concretes, the material design has largely been based on trial and-error or empirical procedures. A few studies such as Deo et al. (2010) [15], Lian et al. (2010) [16] and Neithalath et al. (2010) [17] have reported methods to improve the compressive strength and freeze–thaw durability of pervious concretes. The objective of this study is to establish a new methodology to facilitate design of PCP mixtures with targeted mechanical and durability properties. The study consists in using the inter-particle void of aggregate as a design factor to achieve good balance between permeability and strength given the application on hand. The proposed approach aims to simplify the design procedure to optimize a given PCP formulation to obtain a freeze-thaw durable, permeable and high strength pervious concrete that can be used reliably in a paving system. This investigation has been achieved using industrial by-products such as silica fume and fly ash to enhance the performance of PCP. The utilization of these industrial by products is becoming popular throughout the world because of the minimization of their potential hazardous effects on environment and increasing the cost saving of pavement construction.

3. Literature Review

Pervious concrete pavement (PCP) is a special type of concrete characterized by an interconnected pore structure and high void content/porosity typically, thus allowing direct infiltration of water through its structure. While its constituent materials are similar to that of normal concrete, PCP contains little or no fine aggregate. It is also known as no-fines concrete, permeable concrete, porous concrete and enhanced porosity concrete. High penetration velocity of water into pervious concrete has led into using this kind of pavement in other cases such as hydraulic structures, tennis courts, greenhouses and as a base course of heavy traffic pavements. However, because of lower durability and strength of pervious concrete, compared to ordinary concrete, its application is only in regions with low traffic congestion such as parking lots, sidewalks, road shoulders, streets and local roads [12]. Because of its environmental benefits, pervious concrete is increasingly used to a variety of infrastructures, including the pavements and overlays that may be subjected to fairly heavy traffic. These extended applications have demanded pervious concrete have superior strength and durability. Unfortunately, due to its high porosity and low cement/mortar content, pervious concrete generally has significantly reduced strength when compared with conventional concrete [13, 17].

Research has shown that the major factors that affect pervious concrete strength include the concrete porosity, water-to-cementitious material ratio, paste haracteristic, and size and volume content of coarse aggregates [18, 19]. The mechanical properties of pervious concrete can be greatly improved by using proper concrete materials and mix proportions [20]. Wang (1997) [21] used river sand to replace approximate 7% (by weight) coarse aggregate. Their results indicated that the 7-day compressive strength increases from 9.6–14.5 MPa to 22.2–22.7 MPa. Although the void content is reduced due to the fine sand in the mixtures, all void content values are still within an acceptable range (>15%) for PCP applications, and the permeability value is still higher than the minimum requirement to drain. Maguesvari et al. (2013) [22] observed that the increase in fine aggregate results in reduction of volume of voids which in turn increase of compressive strength, flexural strength and split tensile strength. Angularity number is more for higher size aggregate and which is reduced when size of aggregate reduces. The range of compressive strength varies between 10 N/mm^2 to 26 N/mm^2 when the angularity number varied from 8 to 4. Increasing the aggregate size increases angularity number. Coefficient of permeability increases from 0.4 cm/sec to 1.26 cm/sec when the angularity number is in the range of 4 to 8. These results agree with many researches such as [23, 24, 25, 26]. For PCP, the mass loss has been used as an indication of freeze-thaw durability. Beeldens (2001) [27] reported a mass loss of 0.25% after 25 cycles and reported a few key ways moisture conditions influence the freeze and thaw durability. Partially saturated pervious concrete exhibited high durability when it is frozen and thawed in air [28].

4. Experimental Design

4.1. Materials

4.1.1. Ordinary Portland Cement (OPC)

The mineralogical composition and physical properties of the cement used are shown in Table 1.

Table 1. *Chemical and physical composition of the cement.*

Properties	Value	Chemical Properties	Value
Specific gravity	3.15	CaO (%)	58.32
Initial setting time (min)	150	SiO_2 (%)	26.56
Final setting time (min)	185	MgO (%)	1.12
Volume expansion (mm)	2	Fe_2O_3 (%)	3.89
Compressive strength (MPa)			
2 days	22	Al_2O_3 (%)	6.58
7 days	38.7	SO_3 (%)	3.32
28 days	46.8	LOI (%)	1.25

4.1.2. By-Product Fine Additives Admixtures

Due to rapid industrialization throughout the world, significant amount of waste materials are being generated. This causes environmental hazard. So utilization of such waste material like fly ash, silica fume blast furnace slag, tire rubber-powder and rice husk ash as fine additives may be considered as one of the feasible solutions so as to improve the performance of PCP and to help in reducing the environmental pollution. In addition to the environmental effects, the improvement in strength and performance of PCP due to using waste and recycled fine additives may lead to reduce the designed pavement thickness and therefore increase the construction cost savings. The cost benefits of using these waste materials are not limited to reduce the materials quantities and construction costs but also the pavement maintenance costs [25, 28].

This study focuses on the use of fine additives such as silica fume (SF) and fly ash (FA) for supporting pozzolanic cement paste and evaluating their effect on the mechanical and durability properties of hardened concrete as an attempt to establish a balance between permeability and strength properties of PCP. Fly ash has particles of diameter about 10–25 μm. The particles are smooth and spherical. This improves fluidity of the pervious concrete mixture. Also, fly Ash has pozzolanic properties where it reacts with calcium hydroxide, to produce calcium silicate hydrate, which is the product formed during hydration of cement. This helps in strength gain at later ages of curing and reduces heat of hydration which in turn reduces free shrinkage of concrete, resulting in a reduction of thermal shrinkage cracking. Fly ash also refines the pore structure of pervious concrete, which has good implications on durability and long-term strength. Silica fume is also called micro silica or condensed silica fume. It is generally used as artificial pozzolonic admixture in concrete. It is a product obtained by reduction of high purity quartz with coal in an electric arc furnace in the manufacture of silicon or ferrosilicon alloy. Condensed silica fume is essentially silicon dioxide (more than 90%) which is present in non- crystalline form. It is extremely fine powder with particle size less than 1 micron and with an average diameter of about 0.1 micron, about 100 times smaller than average cement particles. Table 2 shows the properties of fly ash and silica fume [29, 30, 31].

Table 2. *Properties of fine additives.*

	Major chemical compositions (%)								Specific gravity (g/cm^3)	Ignition loss (%)
	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	K_2O	Na_2O		
Fly ash	61.8	26.4	5.0	1.10	0.40	0.42	0.80	0.54	2.37	2.07
Silica fume	98.2	-	-	-	-	-	-	-	1.89	0.61

4.1.3. Aggregate

Three gradations of sieved gravel are considered as coarse aggregate. The properties of coarse aggregate are measured according to ASTM C33 specifications and listed in Table 3. The sand from El-Suze city of diameter less than 3.0 mm is used as fine aggregate.

Table 3. *Properties of aggregate.*

Coarse aggregate	Coarse aggregate size ranges (mm)			Fine sand aggregate
	R1	R2	R3	
Gravel	25-16.0	16.0-9.5	9.5-4.75	<3.0
Unit weight (kg/m^3)	1536	1455	1427	1318
Bulk specific gravity	2.758	2.757	2.760	2.762

4.2. Mix Proportions

The mix design is conducted in two phases. Phase I investigates how aggregate size influences the mechanical and durability properties of pervious concrete, and Phase II investigates the effects of sand, fly ash, and silica fume on pervious concrete properties. The proportions of all prepared mixes are summarized in Table 4. Mix identification begins with a letter G that indicates the gravel aggregate type following that the range of the aggregate size. And then a number that indicating the ratio of fine mineral admixtures in the mix. The ratio of aggregate: cement: water is 4.5:1:0.3 by mass. These pervious concrete mixes have porosity ranging from 15% to 35% based on the recommendation provided by previous research.

Table 4. *Designed pervious concrete mixtures proportions.*

Mix ID	Aggregate proportion				Cementitious materials proportion					
	Gravel		Sand		OPC (%)		CFA (%)		SF (%)	
	range	(kg/m^3)	(%)	(kg/m^3)	(%)	(kg/m^3)	(%)	(kg/m^3)	(%)	(kg/m^3)
GR1-100	R1	1203.5	15	212.4	100	314.6	0	0	0	0
GR1-80	R1	1367.1	15	241.2	80	285.9	20	71.5	0	0
GR1-70	R1	1432.4	15	252.7	70	262.1	20	74.9	10	37.4
GR2-100	R2	1222	15	215.6	100	319.4	0	0	0	0
GR2-80	R2	1439.6	15	254	80	301.1	20	75.2	0	0
GR2-70	R2	1540.5	15	271.8	70	281.9	20	80.5	10	40.3
GR3-100	R3	1264.8	15	223.2	100	330.7	0	0	0	0
GR3-80	R3	1483.8	15	261.8	80	310.3	20	77.5	0	0
GR3-70	R3	1508.2	15	266.1	70	276	20	78.8	10	39.4
Gr3-100	r3	1199.1	20	299.8	100	333.1	0	0	0	0
Gr3-80	r3	1423.2	20	355.8	80	316.2	20	79	0	0
Gr3-70	r3	1451.1	20	362.8	70	282.1	20	80.6	10	40.3

4.3. Samples Specimen Preparation

Four control mixes corresponding to four aggregate sizes were designed as RG100. An attempt is made to quantify the effect of increasing the fine aggregate ratio and reducing the coarse aggregate size on the voids content in the aggregate matrix. Pervious concrete mixtures were mixed using a mechanical mixer; different sizes of specimens were prepared for the pervious concrete mixes. The specimens were demoded after 24 h, and subsequently stored in a water curing tank maintained at a temperature of 20±2°C until the time of testing. Each experimental parameter was determined by averaging the results of three samples. All of the tests were performed at the end of 28 day curing period. Table 5 lists the sizes of the specimens used for the different designed tests.

Table 5. *Specimen's sizes.*

Mix ID	Specimen size (mm^3)	Tests
GR1-100	150×150×150	Compressive strength at 3, 7, 14 and 28 days.
GR2-100	150×150×500	Flexural strength at 28 days.
GR3-100	150×150×60	Water penetration coefficient.
Gr3-100	300×150 mm diameter	Split tensile strength at 28 days.
GR1-80	150×150×150	Compressive strength at 3, 7, 14 and 28 days.
GR2-80	100×100×100	Compressive strength at 28 days.
GR3-80	200×200×200	Compressive strength at 28 days.
Gr3-80	150×150×500	Flexural strength at 28 days.
	150×150×60	Water penetration coefficient.
	300×150 mm diameter	Split tensile strength at 28 days.
GR1-70	150×150×150	Compressive strength at 3, 7, 14 and 28 days.
GR2-70	150×150×500	Flexural strength at 28 days.
GR3-70	150×150×60	Water penetration coefficient.
Gr3-70	300×150 mm diameter	Split tensile strength at 28 days.

4.4. Test Methods

4.4.1. Compressive Strength

Compressive strength test was carried out according to ASTM C39 [29] standard to evaluate the compressive strength after the desired curing period load is applied gradually at the rate of 0.3–0.5 MPa per second till the specimens fails. Load at the failure divided by area of specimen gives the compressive strength of concrete. The strength value was reported as the average of three samples.

4.4.2. Flexural Strength

For measuring flexural strength, normal standard size of specimens 150×150×500 mm is used. Equal loads were applied at the distance of one-third from both of the beam supports. The load rate was about 0.1–0.2 MPa/s. As loading increases, if fracture occurs within the middle one-third of the beam, the maximum tensile stress reached called "flexural strength" is computed from equation (1) [21]:

$$FS = \frac{pl}{bd^2} \quad (1)$$

Where L: beam span between supports; d: depth of beam; b: width of beam and p: rupture load.

4.4.3. Split Tensile Strength

Split tensile strength according to ASTM C-496 is conducted. A standard test cylinder specimen (300×150 mm diameter) was placed horizontally between the loading surfaces of compression testing machine after 28 days curing. Due to this compressive loading, an element lying along the vertical diameter is subjected to a vertical compressive stress which acting for about 1/6 depth. The larger portion of cylinder is subjected to uniform tensile stress acting horizontally which acting for about 5/6 depth. The split tensile strength (STS) can be calculated from the equation (2) [22]:

$$STS = \frac{2P}{\pi DL} \quad (2)$$

Where L: length of cylinder; D: diameter of cylinder and P: compressive load at failure.

4.4.4. Water Penetration Coefficient

Water penetration coefficient (K) of pervious mixes is an important parameter of pervious concrete since the material is designed to perform as drainage layer in pavement structures. It was determined by using the idea of falling head permeability method based on earlier study [10, 27, 32, 33]. K value was measured after 28 days of curing with the device consists of a glass pane open in both ends of size 150×150×400 mm. The surface of sample was covered with wax before measuring. The device was put on the sample. The warm wax was used to cover the space between the device and sample. After wax hardening, water was injected into the device to reach to a specific height. The time required for decreasing the water head line by about 20 mm was recorded. The water penetration coefficient (K) can be calculated out by equation (3).

$$K = H/t \quad (3)$$

Where K is the water penetration coefficient (mm/s), H is the decrease in the falling head (20 mm) during a period of time (t).

4.4.5. Freezing and Thawing Resistance

This study focuses on investigating the effects of moisture conditions on the damage development in PCP during cyclic freezing and thawing. Note that the porosity of pervious concrete from the large voids is distinctly different from the microscopic air voids that provide protection to the paste in conventional concrete in a freeze-thaw environment. When the large open voids are saturated, complete freezing can cause severe damage in only a few cycles. Standardized testing by ASTM C 666 may not represent field conditions fairly, as the large open voids are kept saturated in the test, and because the rate of freezing and thawing is rapid. Neithalath (2003) [34] and Paul et al. [35] found that even after 80 cycles of slow freezing and thawing (one cycle/day), pervious concrete mixtures maintained more than 95% of their relative dynamic modulus, while the same mixtures showed less than 50% when tested at a more rapid rate (five to six cycles/day). It was noted that better performance also could be expected in the field because of the rapid draining characteristics of pervious concrete.

After 28 days of curing, the specimens were soaked in water with a temperature of 10–30°C for 48 h. The freezing and thawing durability test was then started. After freezing in air with a temperature of -15°C for 5 h, the specimens was put into water 20–25°C to thaw for 5 hours. This process represented one cycle of Freezing and thawing. After completing 15 cycles of Freezing and thawing, the specimens were tested for compressive strength. The compressive strength loss (CSL) according to equation (4) and mass loss (ML) according to equation (5) were measured [20].

$$CSL = \frac{CS2 - CS1}{CS1} \times 100 \quad (4)$$

$$ML = \frac{B - A}{B} \times 100 \quad (5)$$

Where: CS2 is the compressive strength after 15 cycles of freezing and thawing, and CS1 is the control calculated compressive strength (i.e., before freezing–thawing cycles), A is the oven-dry mass after 15 cycles of freezing and thawing, and B is the original calculated oven-dry mass (i.e., before freezing–thawing cycles).

To better understand the effect of fine additives admixtures on the durability of PCP specimens according to compressive strength performance after Freezing and thawing cycles, the durability index (DI) was calculated according to equation (6) [20].

$$DI = CSFA/CS \quad (6)$$

Where: CSFA is the compressive strength of a specimen containing fine additives admixtures after the desired number of freezing and thawing cycles and CS is the compressive strength of specimen of the same aggregate size after the same cycle number.

4.4.6. Void Ratio Measurement

The porosity of the specimens was measured accordance to ASTM C29 by calculating the difference between dry and weight under water as illustrated in equation (7) [30].

$$Vr = [1 - \frac{W2 - W1}{\rho w * Vol}] \times 100 \quad (7)$$

Where, Vr: total void ratio (%), W1: weight under water, W2: oven dry weight, Vol: volume of sample, ρw: density of water.

5. Results and Discussions

5.1. Effect of the Aggregate Size

Table 6 shows the measured properties of all PCP mixes. It is obvious that the pervious concrete strength is relatively low due to its high porosity. When the mix proportion of the concrete are approximately same, the smaller the coarse aggregate size (GR3), the lower void ratio, the higher unit weight, the higher the compressive strength, flexural strength and split tensile strength. With increasing the sand ratio from 15 to 20% in mixtures Gr3, the compressive strength increases by 43%, the flexural strength increases by 46% and split tensile strength increases by 64%. The addition of natural sand increases the amount of cement mortar and thus increases the contact area between neighboring aggregate particles. Subsequently, the increased contact area will result in strength improvement. Moreover, Table 6 illustrates that the ratios of flexural to compressive strength (FS/CS) of the finer mixes are much higher than those of the coarser mixes at 28 days. So it suggests that the FS of pervious concrete may be more sensitive to aggregate size decreasing compared with the CS. In addition, the ratio of split tensile strength to compressive strength at 28 days (STS/CS) of the smaller aggregate size mixes, especially with increasing the sand ratio (Gr3), are higher than those of the coarser mixes. So it suggests that the STS of PCP may be more sensitive to sand amount change compared to the compressive strength.

Table 6. *Mechanical properties of PCP mix.*

Mix ID	Void ratio (%)	Unit weight (kg/m^3)	CS (MPa) at 28 days (150 mm)	CS (MPa) at 28 days (100 mm)	CS (MPa) at 28 days (200 mm)	FS at 28 days (MPa)	STS (MPa) at 28 days	FS/CS at 28 days (%)	STS/CS at 28 days (%)
GR1-100	36.6	1825	9.5	12.2	7.4	1.029	0.338	10.8	3.559
GR2-100	33.7	1853	10.1	13.7	8.5	1.2	0.437	11.9	4.33
GR3-100	28.8	1918	13.6	16.5	12	1.686	0.688	12.4	5.06
Gr3-100	26.3	1932	19.5	22.8	17.7	2.476	1.13	12.7	5.796
GR1-80	24.8	2073	9.9			1.126	0.414	11.4	4.803
GR2-80	20.2	2183	14.8			2.027	0.824	13.7	5.571
GR3-80	16.2	2250	17.1			2.377	1.128	13.9	6.597
Gr3-80	13.6	2293	24.5			3.479	2.05	14.2	8.376
GR1-70	20.7	2172	18			2.628	1.282	14.6	7.123
GR2-70	17.5	2236	23.2			3.433	1.901	14.8	8.194
GR3-70	15	2287	28.5			4.246	2.687	14.9	9.429
Gr3-70	12.6	2338	33			4.983	3.521	15.1	10.655

5.2. Effect of Fine Additives

As shown in Table 6, the compressive strength of control PCP mixtures (GR-100) is normally less than 20 MPa, due to high porosity. The average unit weight of pervious concrete is approximately 1870, 2170 and 2270 kg/m3 for each mixes GR100, GR80 and GR70 respectively. According to relevant researches that discussed the pervious concrete pavement [20-25], the diameter of the pores in the cement paste is mostly between 4.5 and 45 µm. While after incorporating the fine mineral admixture, that diameter is reduced to about 0.1–0.2 µm, these superfine particles can fill in the pores and increase the density of cement paste binder. It also reduced the thickness of the transition zone between the aggregate and cement paste. For each studied aggregate size, when 20% FA is used, the compressive strength increases more than the control mixtures by about 30%, but it is still at a low level of 20 MPa because of the poor dispersion of the FA particles. However, the silica fume appears to fill more voids in concrete. Thus, the concrete becomes close-grained and the compressive strength greatly increases by about 80-90% in the case of GR-70 mixtures. For flexural strength, the use of fly ash in GR-80 mixtures improves the Flexural strength by about 50%. While, with more addition of silica fume in GR-70 mixtures, the Flexural strength obviously increases by about 150-160%. A possible reason is that the addition of silica fume strengthens both the interfacial transition zone between the paste and aggregate and the matrix microstructure of pervious concrete, and makes the concrete less brittle, thus having excellent resistance to flexural damage.

According to Table 6, it is seen that the effect of fine additives on split tensile strength is similar to the effect on compressive strength and flexural strength. The addition of FA leads to a significant increase in the STS reached to 100% compared to the control mix. However, the effect of combining of FA and SF is especially significant improvement in the STS of pervious concrete that increases by about 250%. The split tensile strength of PCP equals about 32 to 45% of the flexural strength for control mixes with decreasing the aggregate size as shown in Fig. 1. While equals about 37 to 59% in case of adding 20% fly ash and about 50 to 70% for mixes containing 20% fly ash and 10% silica fume. Table 6 as well as Fig. 2 exemplifies that addition of FA and SF to PCP mix, increases the ratio of (FS/CS) by about 15% while addition of FA only increases this ratio to 11-14% compared to the control mixes where the ratio of (FS/CS) is about 10.8-12.7%. Moreover, Table 6 shows that the combination of FA and SF increases the ratio of (STS/CS) to about 7-11% while addition of FA only increases this ratio to 4-8% compared to the control mixes where the ratio of (STS/CS) is about 3.5-5.8%.

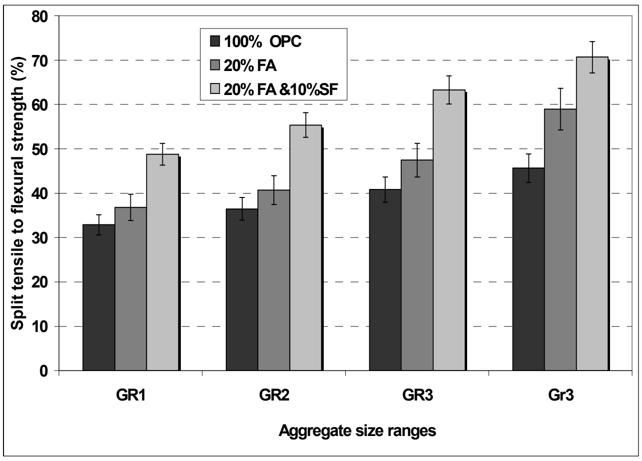

Figure 1. *Split tensile to flexural strengths of PCP.*

5.3. Relations Between Strengths

Fig. 3 shows the linear relationships between the compressive and flexural strengths, and between the compressive and the split tensile strength for all pervious concrete mixtures. The results showed acceptable trend as the compressive strength increases, the split and flexural strengths increase by a similar gradient. An approximate linear relationship between flexural and split tensile strengths at 28 day can be illustrated in Fig. 4. Equations (8 to 10) can be approved where the all strengths measured by MPa:

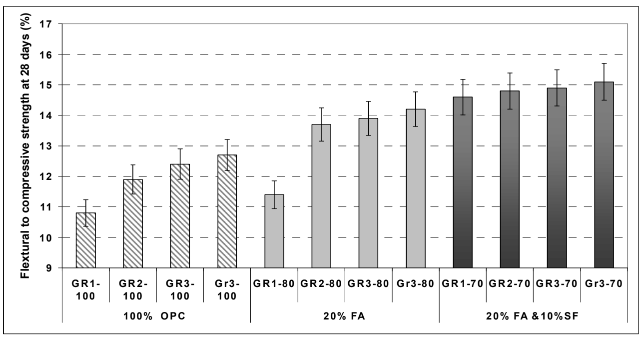

Figure 2. *Flexural tensile to compressive strengths of PCP.*

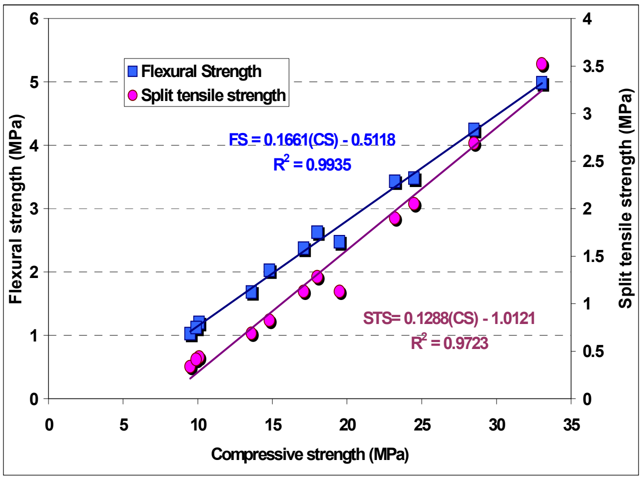

Figure 3. *Relation between compressive and tensile strengths.*

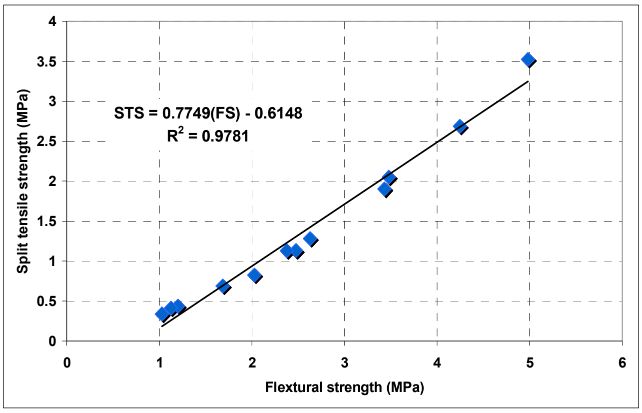

Figure 4. *Relation between split and flexural strengths.*

$$FS = 0.1661\ (CS) - 0.5118,\ (R^2 = 0.9935) \quad (8)$$

$$STS = 0.1288\ (CS) - 1.0121,\ (R^2 = 0.9723) \quad (9)$$

$$ITS = 0.7749\ (FS) - 0.6148,\ (R^2 = 0.9781) \quad (10)$$

5.4. Effect of Concrete Age on the Compressive Strength

The development of compressive strength as a function of time is shown in Fig. 5 for mixes GR1 and Gr3. The general trend is an increase in strength as a function of time. Figure 5 illustrates the difference in rates of the strength development where the mixes that contain fine additives have more rapid strength development at early ages but slower strength development at later ages compared with the control mixes.

The rapid strength development of these mixes at early ages may be contributed to the use of FA and SF where the aggregate particles are rapidly wrapped and cemented together by a stiff paste to form the skeleton-pore structure, obtaining quite strong resistance to the destructive load at early ages. However, due to the small amount of cementitious paste used and slow hydration process, there is no remarkable strength gain at later ages.

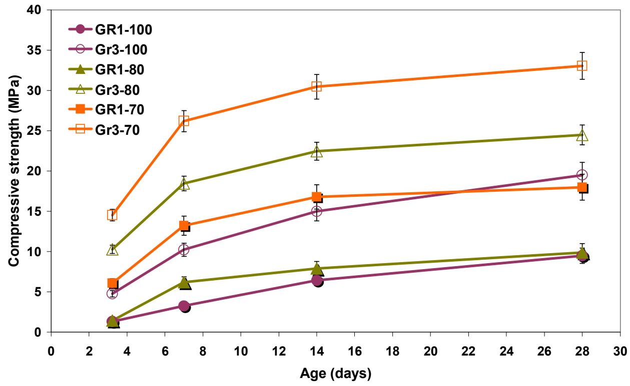

Figure 5. *Effect of concrete age on the compressive strength.*

5.5. Effect of Specimen Size on Compressive Strength

Test results of the 28-day compressive strength of cubic specimens with different sizes for mixtures GR-100 are presented in Table 6. A size conversion factor is calculated as the ratio of the compressive strength of the cube specimens with standard size (150 mm) to the compressive strength of the cube specimens with non-standard size (100 mm or 200 mm). For conventional concrete, the size conversion factors are 0.95 when 100 mm cube specimens are used and 1.05 when 200 mm cube specimens are used for compressive strength tests [7, 21, 36]. Fig. 6 evidences the clear size effect of pervious concrete on compressive strength because the size conversion factors of 100 mm specimens are all much lower than 0.95, while those of 200 mm specimens are all much higher than 1.05. Thus, pervious concrete has much more significant size effect than conventional concrete. Moreover, it can be concluded that with decreasing the aggregate size, the specimen size conversion factor increases for 100 mm cubic sample and decreases for 200 mm cubic sample.

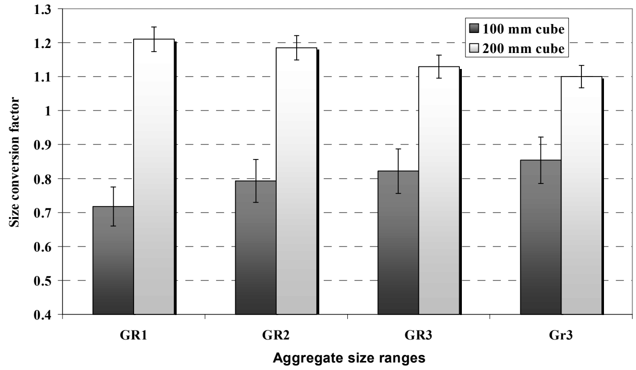

Figure 6. *Size conversion factors of PCP.*

5.6. Water Penetration Coefficient

Permeability is one of the major properties of PCP such that they are typically designed on the basis of permeability requirement. The water penetration coefficient (K) for each mixture is illustrated in Table 7 where all values still higher than the minimum requirement to drain (0.25 mm/s). It is obvious that the permeability of PCP is high (ranged between 7.0-9.0 mm/s) due to its high porosity. Smaller coarse aggregate size seems to decrease the penetration coefficient where adding 20% FA decreases the permeability by about 50% to range (3.5-5.0 mm/s). While adding SF and FA, decreases the permeability by about 62% to range (2.0-4.0 mm/s).

Table 7. *Durability properties of PPC mix.*

Mix ID	Void ratio (%)	Unit weight (kg/m^3)	Permeability (mm/s)	Mass loss (%)	Initial CS (MPa) at 28 days	CS (MPa) at 28 days after 15 cycles	Strength loss (CSL) (%)	Durability index (DI)
GR1-100	36.6	1825	8.8	0.33	9.5	7.2	23.8	1
GR2-100	33.7	1853	8.2	0.29	10.1	7.5	25.7	1
GR3-100	28.8	1918	7.6	0.23	13.6	9.7	28.6	1
Gr3-100	26.3	1932	7.3	0.22	19.5	15.1	22.3	1
GR1-80	24.8	2073	4.9	0.27	9.9	8.6	13.4	1.19
GR2-80	20.2	2183	4.5	0.24	14.8	12.3	17.2	1.64
GR3-80	16.2	2250	4.1	0.21	17.1	13.3	21.9	1.37
Gr3-80	13.6	2293	3.6	0.2	24.5	20.2	17.5	1.29
GR1-70	20.7	2172	3.7	0.21	18	16.9	6.3	2
GR2-70	17.5	2236	3.1	0.16	23.2	21	9.6	2.8
GR3-70	15	2287	2.8	0.12	28.5	24.5	13.8	2.5
Gr3-70	12.6	2338	2.4	0.11	33	29.6	10.2	2.1

5.7. Freezing and Thawing Resistance

5.7.1. Mass Loss

As shown in Fig. 7, it can be seen that the smaller course aggregate into PCP decreases the mass loss after the freezing–thawing cycles. The increasing of the sand ratio from 15 to 20% has a slight effect on reducing the mass loss value. At the end of the 15 freezing–thawing cycles, the most noteworthy effect of the fine additives is observed on the samples GR-70. In the literature it is reported that mass losses around 0.1-0.2% did not significantly affect the strength of PCP. In another meaning, a mass loss of 20% after freeze-thaw cycles represents the terminal serviceability acceptable level for pavement surfaces [37].

Hence, it can be concluded that the addition of 20% fly ash and 10% silica fume causes PCP to exhibit more resistance against the freezing–thawing period in seasonally frozen areas.

5.7.2. Compressive Strength Loss

As illustrated in Table 7 as well as in Fig. 8, decreasing of coarse aggregate size into PCP increases the compressive strength loss (CSL) after 15 freezing–thawing cycles.

However, the increasing of the sand ratio from 15 to 20% decreases CSL by about 21% to 26%. The addition of fine mineral additives has a great effect on decreasing the CSL especially at using SF and FA combination where it reduces CSL by about 50-70% compared to control mixtures.

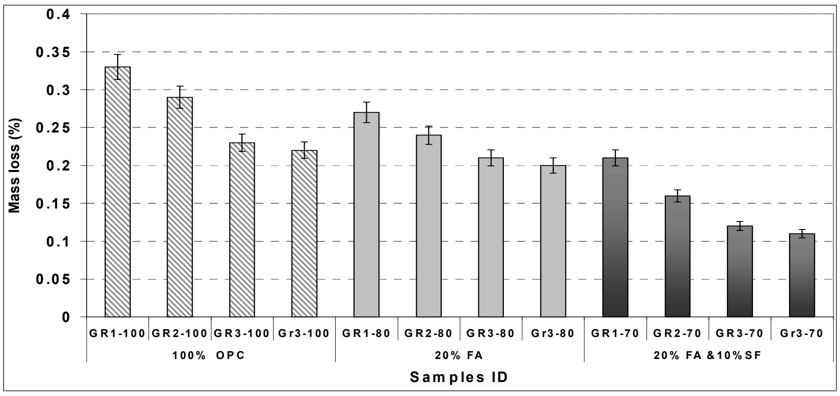

Figure 7. *Mass loss of PCP.*

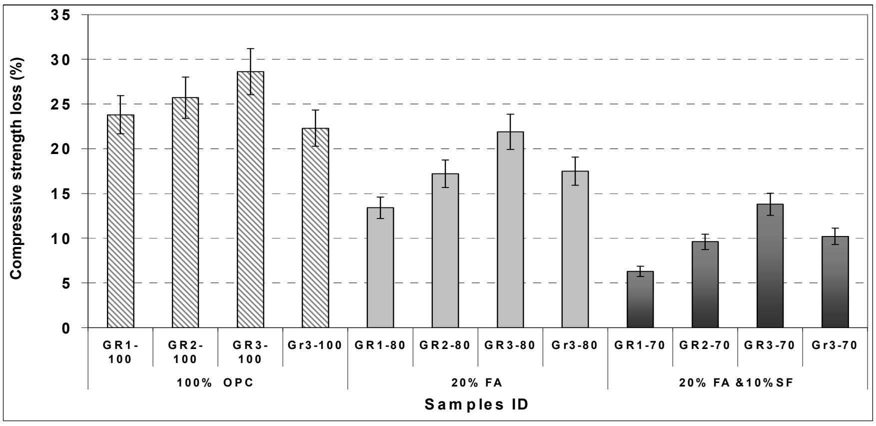

Figure 8. *Compressive strength loss of PCP.*

5.7.3. Durability Index

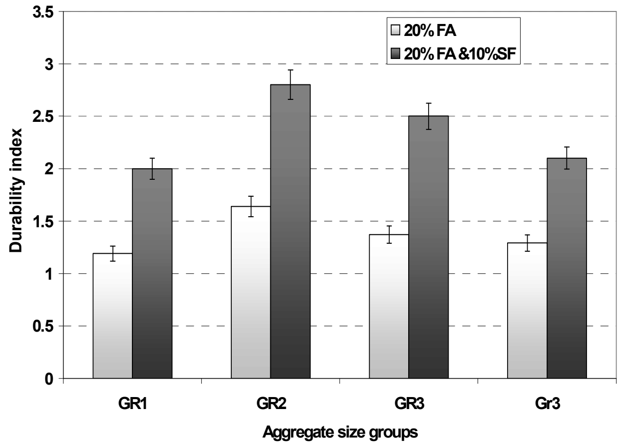

Figure 9. *Durability index of PCP mixtures.*

As shown in Fig. 9, mixes that contain FA and SF have better durability index (DI) than those contain FA only by about 50 to 100%. This result can probably be attributed to the sufficient hardening which develops for the samples. Subsequently, the samples can resist the actions of the freezing and thawing cycles. On another side, the coarse aggregate size of 16.0-9.5 mm achieves the highest DI. While with increasing the sand amount from 15 to 20%, the DI decreases to the lowest value.

5.8. Effect of Void Ratio

Fig. 10 shows the effect of aggregate size on total void ratio, it is seen that most of the porous concretes had total void ratio within the range from 12 to 37% regardless of aggregate size. The average void ratios tend to increase as the aggregate size increases. When fly ash is added, the void ratio is reduced by about 47.8% while the unit weight increases by about 21%. When both fly ash and silica fume are used, the decrease in the void ratio is about 41% and the increase in unit weight is about 16%. Increasing of natural sand ratio from 15 to 20% in mixes Gr3 reduces the void ratio by about 8.6% for control mixture and 16% for fine additives mixes. However, the void ratio for mixtures Gr3-70 and Gr3-80 is reduced due to the fine sand in the mixtures to become lower than the acceptable range% for PCP applications (according to the majority of researches >15% [8, 17, 26]). But according to Saeid et al. (2014) [38], the porosity of PCP is ranged between 9% and 29% to be appropriate for a drainage layer of pavement, thus the mixtures Gr3-70 and Gr3-80 are acceptable.

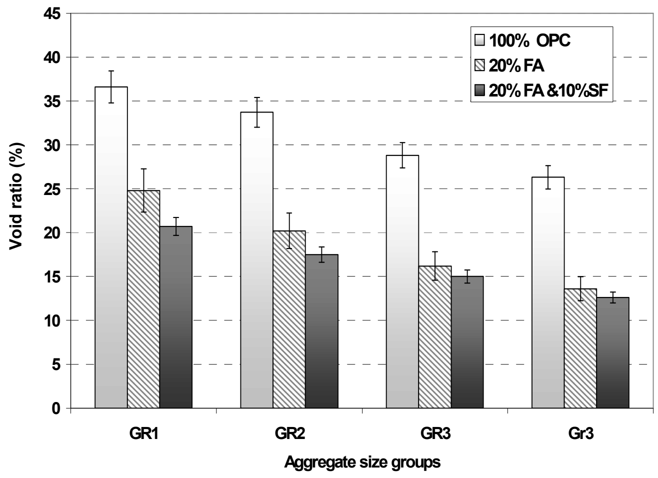

Figure 10. Effect of aggregate size on void ratio.

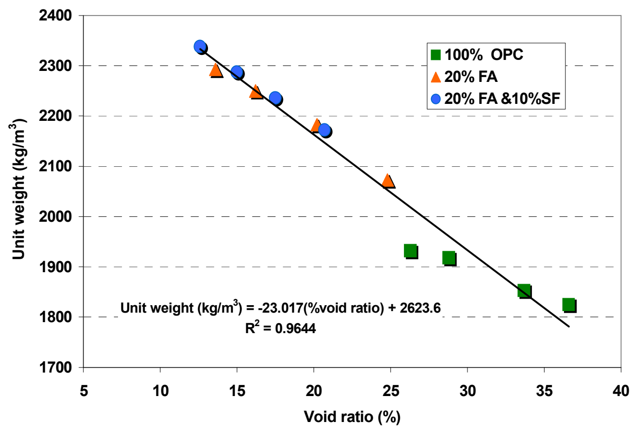

Figure 11. Relation between void ratio and unit weight.

The relationship between density and void content of PCP is shown in Fig. 11. The unit weight decreased linearly with an increase in the void content for all PCP. For example, the unit weight is 2338 kg/m^3 when the void content was 12.6%. While the void content increases to 36.6%, the density reduces to 1825 kg/m^3. A linear relationship with high R2 of 0.96 can be derived as given in equation (11).

The results show the same trend of relationship to that of the normal Portland cement pervious concrete [27, 30].

$$\text{Unit weight (kg/m}^3\text{)}=-23\ (\%\text{void ratio})+2623.6,\ (R^2=0.96) \quad (11)$$

5.9. Relations Between Void Ratio, Permeability and Strengths

As shown in Figs. 12 and 13, the compressive strength, flexural strength and split tensile strength decrease exponentially as the void ratio increases where there is a notable scatter in the plotted data, while the permeability moderately increases exponentially as the void ratio increases. The relationships between them are summarized in equation form as shown in the Figs. 12 and 13. The results signify the importance of void content present in aggregate and percentage of fine aggregate regardless of the size of aggregate and cement content.

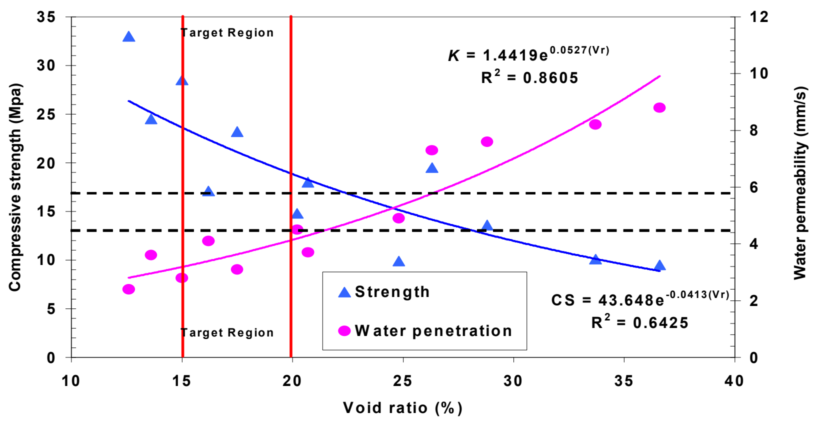

Figure 12. Optimization of mix based on void ratio, compressive strength and permeability.

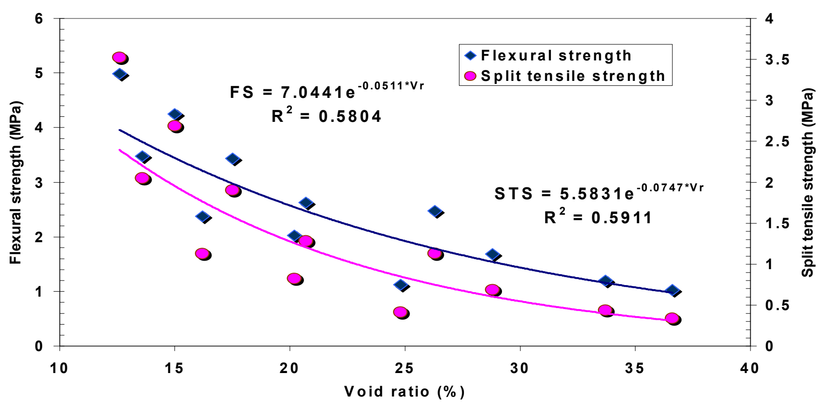

Figure 13. Relations between void ratio, flexural and split tensile strength.

5.10. The Optimum Mix

As shown in Fig. 12, balancing the compressive strength and permeability, optimum mix is determined. Compressive strength found to be lying between 13 to 17 MPa and permeability between 4.5 mm/sec and 6.0 mm/sec where the void ratio is about 25%. With reference to the above values the mix GR1-70 is identified as optimum mix. For all mixes, the coefficient of permeability ranges from 2.5 mm/s to 8.8 mm/s. Mixes with an optimum void ratio between 15% and 20% based on the recommendation provided by previous research [29, 30] achieve both an adequate 28-day compressive strength of about 19 MPa or more, flexural strength of 2.5-3.5 MPa, split tensile strength of about 1.25-2.0 MPa and a permeability value ranges between 3-4 mm/s, indicated in Fig. 13 as the limits of the target region. It has been observed that mixes that achieve both the required strength and adequate permeability have a unit weight ranging from 2170 kg/m^3 to 2270 kg/m^3. This value of PCP unit weight can be used as a quick quality control/quality assurance indicator at the time of placing pervious concrete.

6. Conclusions

Due to voids in pervious concrete, it is difficult to obtain high-strength materials by using the common material and proportion of mixture. A laboratory experiment was conducted to investigate the durability and mechanical properties of fine additives-modified pervious concrete. The effects of aggregate size, sand ratio specimen size and curing age were evaluated. Based on this study, the following conclusions can be drawn:

a) When the mix proportion of the concrete were approximately same, the smaller the coarse aggregate size (9.5-4.75 mm) provided lower void ratio, higher unit weight, higher compressive strength, higher flexural strength, higher split tensile strength lower mass loss and higher compressive strength loss after freezing and thawing cycles. While the medium size range of (16.0-9.5 mm) achieved the highest durability index. The average density of PCP was around 1870, 2170 and 2270 kg/m^3, with a porosity of 32.7%, 20.5% and 17.8% and average water permeability coefficient of 8.2, 4.5 and 3.25 mm/s for each control mixtures, 20% fly ash and combination of 20% fly ash and 10% silica fume mixtures respectively.

b) The increase in the dosage of sand from 15 to 20% in mixtures led to reducing the void and penetration ratios, increasing the strengths due increasing of unit weight and reducing each mass loss, compressive strength loss and durability index after freezing and thawing cycles. The compressive strength increased by 43%, the flexural strength increased by 46% and split tensile strength increased by 64%. The compressive strength of the samples containing 20% sand could reach 24.5 and 33 MPa instead of 19.5 MPa for control PCP mixtures and the flexural strength can reach 3.5 and 5.0 MPa by incorporating of only fly ash and both fly ash and silica fume respectively instead of 2.5 MPa for control PCP mixtures.

c) Generally, for each studied aggregate size, the addition of by-product fine improved both mechanical and durability properties of PCP mixtures, when 20% fly ash was used, the PCP mixtures provided higher density by about 16% and lower permeability coefficient by about 42%. Moreover, it improved the flexural strength and the split tensile strength by about 50% and 100% respectively and increased the compressive strength by about 30% but it was still at a low level of 20 MPa. After subjecting to 15 freezing and thawing cycles, the addition of fly ash reduced the mixtures mass loss and compressive strength loss by about 14% and 30% respectively while increased the durability index by about 36% compared with control PCP mixtures.

d) The addition of 10% silica fume to 20% fly ash established the best balance between mechanical and durability properties where the PCP mixtures provided highest density by about 21% and lowest permeability coefficient by about 60%. Moreover, the flexural strength, the split tensile strength and the compressive strength were obviously improved by about 155%, 250% and 85% respectively. Furthermore, the addition silica fume provided more resistance against the freezing–thawing period where the mixtures mass loss and compressive strength loss reduced by about 44% and 60% respectively while the durability index increased by about 130% compared with control PCP mixtures.

e) Mixes that contain fine additives had more rapid strength development at early ages but show slower development at later ages compared with control mixes. Moreover, PCP had much more significant specimen size effect than conventional concrete where the size conversion factors of 100 mm specimens were all much lower than 0.95, while those of 200 mm specimens were all much higher than 1.05. Moreover, with decreasing the aggregate size, the specimen size conversion factor increased for 100 mm cubic sample and decreased for 200 mm cubic sample.

f) Linear relationships between the compressive, flexural strengths, and split tensile strength for all pervious concrete mixtures were achieved with acceptable trend. Pervious concrete engineering properties varied as a function of void ratio. The compressive strength decreased exponentially, the unit weight decreased linearly and the permeability increases exponentially as the void ratio increases. For balancing the compressive strength and permeability, optimum mix was determined where compressive strength found to be lying between 13 to 17 MPa and permeability between 4.5 and 6.0 mm/sec whereas the void ratio was about 25%. The mixture GR1-70 was identified as optimum mix.

g) Mixes with an optimum void ratio between 15% and 20% achieved both an adequate 28-day compressive strength of about 19 MPa or more, flexural strength of 2.5-3.5 MPa, split tensile strength of about 1.25-2.0 MPa and a permeability value ranged between 3-4 mm/s. The mixes that achieved both the required strength and adequate permeability had a unit weight ranging from 2170 kg/m^3 to 2270 kg/m^3. This value of PCP unit weight can be used as a quick quality control/quality assurance indicator at the time of placing pervious concrete.

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