Technical Paper

ISSN 1997-1400 Int. J. Pavement Res. Technol. 4(2):104-110

Experimental Study on Properties of Pervious Concrete Made with Recycled Aggregate

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Abstract: This paper investigates recycled aggregate (RA) obtained from construction waste, with a particular focus the properties of pervious concrete. We reveal the mechanical performance and permeability of pervious concrete with regard to volume fraction of the binder (binder/ voids between aggregate), type of binder (cement paste and styrene-butadiene latex modified paste), particle size of aggregate and aggregate to cement ratio. The three nominal diameters of the aggregate were 3.6 mm, 7.2 mm and 11.1 mm. The volume fraction of the binder ranged between 0.3 and 0.5, by varying the nominal diameter of the aggregate. We designed and cast concrete specimens with water to binder ratios (w/b) of 0.35. We conducted laboratory testing of mixture proportions for various properties, such as workability, unit weight, compressive strength, flexural strength, porosity and permeability. The results show that mechanical strength decreases as permeability increases. Decreasing the aggregate to the cement ratio enhances mechanical strength but may reduce permeability, and styrene-butadiene latex greatly enhances flexural strength. From an economic point of view, our recommendation to achieve optimal strength and permeability in pervious concrete using recycled coarse aggregate is: w/b=0.35, nominal diameter of 11.1 *mm* for the recycled aggregate; the volume fraction of 0.5 for the binder; and aggregate to cement ratio of 3.9. The permeability coefficient for the above mentioned mix was 0.33 cm/sec with the 28-day compressive strength and flexural strength reaching 12.6 MPa and 2.1 MPa, respectively. The mixture for RA pervious concrete developed in this study satisfies the typical requirement for concrete sidewalks and is thus applicable for civic paving projects.

Key words: *Permeability; Pervious; Recycled aggregate; Styrene-butadiene latex.*

Introduction

Numerous sources have affirmed how population growth, urbanization and wasteful consumption of natural resources are leading to worldwide global warming. Due to a lack of permeability in common concrete pavement, storm water cannot easily penetrate through to the ground beneath. Over the past few decades, this has resulted in increased runoff and pollution from urban storm water. Groundwater is a natural thermostat, adjusting the heat and moisture in cities; and a lack of groundwater can lead to greenhouse and hot land effects. Several researchers [1, 2] have documented the negative impact that a lack of groundwater can have on streams. For over thirty years, in the US and Japan, pervious concrete has been used to reduce surface runoff by permitting rain water to drain into the ground [3]. The low strength of pervious concrete limits its uses to applications, such as sidewalks, parking lots, recreation squares and as a sub-base for conventional pavement [4, 5]. In addition to recycling old concrete pavement, many projects have demonstrated how buildings and other structures may provide an additional resource for recycled aggregate (RA) [6, 7]. The properties of pervious concrete depend on binder characteristics, aggregate volume, and the particle size of the aggregate [8, 9]. The proportion of mineral admixture, organic intensifiers and concrete mix are used to improve strength, and abrasion resistance [3]. However, the use of recycled aggregate for pervious concrete is still relatively new. In this study, we aim to quantify the effects of volume fraction of the binder (binder/voids between aggregate), the type of binder and variables in the aggregate on the properties of pervious concrete using recycled aggregate.

Experimental Details

Material Properties

Typical pervious concrete mix components include cement, natural and recycled aggregate, water. The experiment used Type I Portland cement conforming to ASTM C150 in all mixes. The fineness of cement was 345 m^2/kg. The recycled aggregate used in the research was taken from a construction waste recycling area, obtained by crushing waste concrete by a crusher. Three size ranges of aggregate were used with a diameter of 12.7-9.5 mm (A), 9.5-4.8 mm (B) and 4.8-2.4 mm (C), respectively. Nominal diameters of aggregate represent the average size ranges of aggregate mentioned above and can be expressed as 11.1 mm, 7.2 mm and 3.6 mm, respectively. Table 1 presents the physical properties of aggregate. The styrene-butadiene latex (SBL) is to enhance the strength properties of pervious concrete. The SBL is a fluid, milk-white dispersion of copolymer of butadiene and styrene in water. The solid content of the SBL is 48.2% and the density is 1.05 g/cm^3.

The voids between the aggregate were part filled with the binder.

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Note: Submitted June 10, 2010; Revised August 21, 2010; September 1, 2010.

Table 1. Properties of Recycled and Natural Aggregate with Different Size.

Type of Aggregate	Size Range of Aggregate (mm)	Aggregate Nominal Diameter (mm)	Specific Gravity		Absorption (%)	Los Angeles Test (%)	Bulk Density of Dry-rodded Aggregate (kg/m^3)
RA	9.5-12.7	11.1	SSD	2.47	4.72	28.0	1367
			OD	2.36			
	4.8-9.5	7.2	SSD	2.43	5.31	31.6	1385
			OD	2.32			
	4.8-2.4	3.6	SSD	2.36	8.26	33.8	1288
			OD	2.18			
NA	9.5-12.7	11.1	SSD	2.67	0.91	21.8	1591
			OD	2.63			

Note: NA = Natural Aggregate; SSD = Saturated-Surface-Dry; OD = Oven-Dry.

Table 2. Mix Design for Pervious Concrete (kg/m^3).

Series No.	Mix No.	Water	Cement	Volume Fraction of the Binder (V_f)	RA	NA	SBL
I	A3MR	77	220	0.3	1432	-	-
	A4MR	103	294	0.4	1432	-	-
	A5MR	129	367	0.5	1432	-	-
	B3MR	73	208	0.3	1459	-	-
	B4MR	97	277	0.4	1459	-	-
	B5MR	121	346	0.5	1459	-	-
	C3MR	69	198	0.3	1394	-	-
	C4MR	93	264	0.4	1394	-	-
	C5MR	116	330	0.5	1394	-	-
	A3MN	82	234	0.3	-	1606	-
	A4MN	109	313	0.4	-	1606	-
	A5MN	137	391	0.5	-	1606	-
II	A3PR	32	220	0.3	1432	-	45
	A4PR	42	294	0.4	1432	-	61
	A5PR	53	367	0.5	1432	-	76

The volume fraction of the binder (V_f) ranged from 0.3 to 0.5 by varying the aggregate diameter. Series I and II pervious concrete mixes were prepared with aggregates from different binders. In all the mixes, the water to binder ratio was kept at 0.35. Table 2 presents the preparation and details in each series of mixes.

Preparation and Testing Procedure

Abrasion resistance of aggregates was measured by the Los Angeles (LA) abrasion test in accordance with ASTM C131. Ten steel balls were added in the drum, and the drum was rotated at a rate of 30 rpm. After 500 revolutions, the diameter of particles less than 1.7 mm was calculated as the abrasion mass loss of aggregate. The procedure evaluated workability using the V. Bahrner denseness measurement in accordance with ACI 211.3. Workability of concrete was achieved using a glass plate on a vibrating table with an eccentric mass rotating at 50 Hz. Vebe time was defined that the glass plate was completely covered with concrete and no cavities in the surface of concrete. To avoid unhydrated cement mixing with SBL, the RA were pre-wet with water and mixed with cement for 2 min, then added to the SBL mixture. Compressive strength tests were conducted in accordance with ASTM C39 to evaluate the strength development of pervious concrete at 28 days. Twenty 100×200 mm cylindrical specimens were cast for each batch following ASTM C39 specifications. After 24-hours, the specimens were de-molded and cured in water (23℃) until testing. The strength values were calculated from five samples from each group.

Flexural strength was obtained from the three-point method according to ASTM C78. The test was carried out on a sample of 150×150×530 mm beams after 28 days of wet curing. Flexural strength was calculated based of the ordinary elastic theory, and is thus equal to

$$R = \frac{PL}{bd^2} \tag{1}$$

where P is the maximum load on the beam, L is the span, b is the width of the beam, and d is the depth of the beam.

Permeability test was measured with the constant head device as shown in Fig. 1. The water supply at the inlet was adjusted in such a way that the inlet and outlet difference remained constant during the test period. After establishing a constant flow rate, water was collected in a graduated flask for a known duration. The permeability (k) can be expressed as

$$k = \frac{QL}{Aht} \tag{2}$$

where Q is the total volume of water, L is the length of specimens,

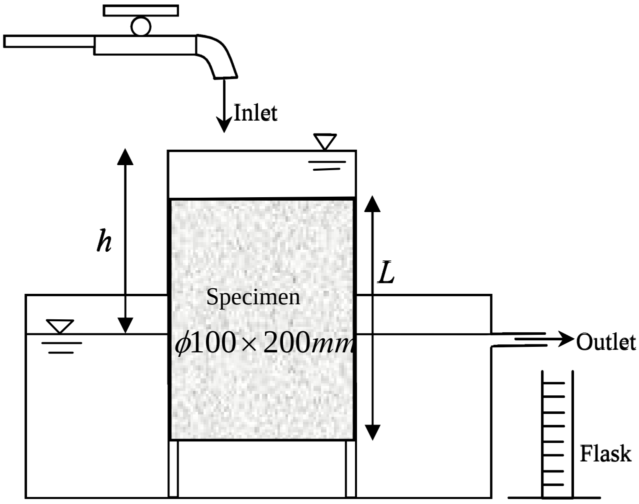


Fig. 1. Schematic Diagram of Permeability Test.

A is the area cross section of specimens, *h* is the total head of water, and *t* is the time.

Overall porosity was measured based on the water displacement in a specific gravity tank. The porosity (p) of the pervious concrete can be represented by the following equation:

$$p = 1 - \frac{(W_2 - W_1)\rho}{V_1} \times 100\% \tag{3}$$

where V_1 is the volume of the specimens, W_1 is the weight of the specimens immersed in water, W_2 is the weight of specimens in surface saturated dry condition, and ρ is the water density.

Results and Discussion

Unit Weight and Vebe Time

Table 3 presents the test results of unit weight and Vebe time of all pervious concrete mixtures. The table shows that the unit weight of pervious concrete mixtures ranged from 1500 kg/m^3 to 1900 kg/m^3. The unit weight in both RA and NA increased with increased volume fraction of the binder. The unit weight of RA concrete was less than the NA concrete. The decrease in unit weight may be because RA density is less than NA. This may be attributed to light adherence and the porous nature of old cement mortar to the recycled aggregate, as shown in SEM microscopy (Fig. 2(a)). The results of the Vebe time are given in Table 3, showing that Vebe time increased with increased volume fraction of the binder. Introducing more binder resulted in an apparent increase in mix stiffness. The aggregate to cement ratio has significant influence on the workability of RA fresh mix. A lower aggregate to cement ratio resulted in higher Vebe time. The Vebe time of RA concrete was lower than the NA concrete mixture with the same particle size and volume fraction of the binder. This increase in concrete workability is due to the spherical particles of RA.

Compressive Strength

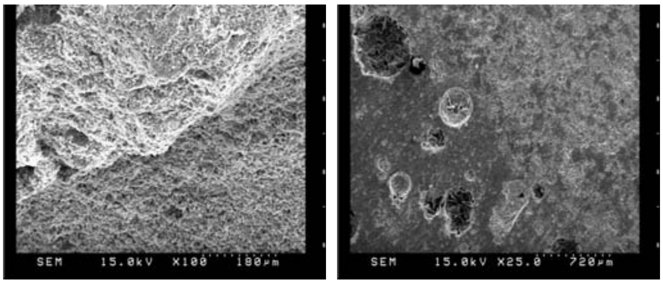
Fig. 3 shows the effects of volume fraction and particle size of RA on compressive strength. At a fixed volume fraction of the binder, the smaller nominal diameter of RA had higher compressive strength. This may be due to the paste lightly-adhered to RA and the round texture of RA that decreased the binding and interlocking characteristic between the paste and the RA interface zone. The smaller RA particles increased more weakness binder/aggregate interface, resulting in lower strength. As expected, an increase in the volume fraction of the binder generally results in an increase in compressive strength. The aggregate to cement ratio (*Cc*) has an important factor effect on compressive strength of RA pervious concrete. Fig. 4 shows the relationship between *Cc* and compressive strength. Findings show that the *Cc* and compressive strength are linear with r^2 equal to 0.85, and the function can be written as

$$f_c = -2.0 \times Cc + 20.3 \tag{4}$$

where f_c is compressive strength of RA pervious concrete (MPa), *Cc* general ranged from 4 to 7 in this study. Higher *Cc* means the

Table 3. Effect of Aggregate Particle Diameter on Properties of Recycled Aggregate Pervious Concrete.

Type of Aggregate	Type of Binder	Aggregate Nominal Diameter (mm)	Aggregate to Cement Ratio	Vebe Time (s)	Volume Fraction of Binder (V_f)	Unit Weight (kg/m^3)
RA	Cement paste	11.1	6.51	3.9	0.3	1597
			4.87	4.3	0.4	1712
			3.90	5.7	0.5	1732
		7.2	6.88	3.9	0.3	1589
			5.17	4.3	0.4	1690
			4.14	4.5	0.5	1733
		3.6	7.23	3.3	0.3	1507
			5.42	4.2	0.4	1588
			4.34	5.3	0.5	1639
	SBL modified paste	11.1	6.51	2.9	0.3	1742
			4.87	3.2	0.4	1790
			3.90	3.1	0.5	1854
NA	Cement paste	11.1	6.86	4.2	0.3	1776
			5.13	4.7	0.4	1875
			4.11	5.9	0.5	1949



(a) (b)

Fig. 2. Interface of Recycled Aggregate.

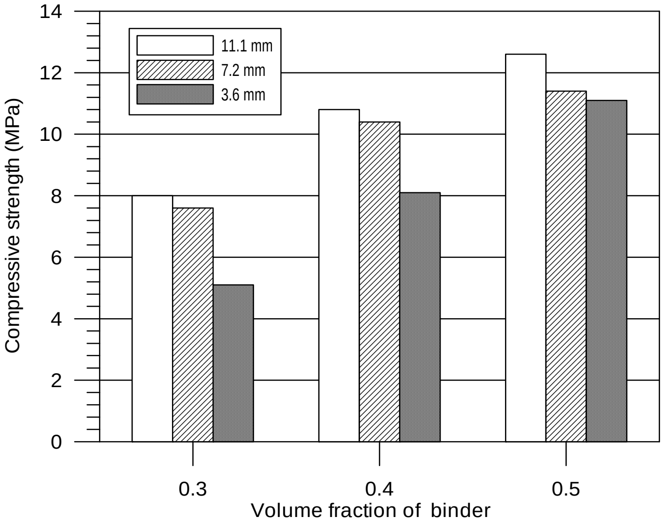


Fig. 3. Effect of Volume Fraction of the Binder on Compressive Strength.

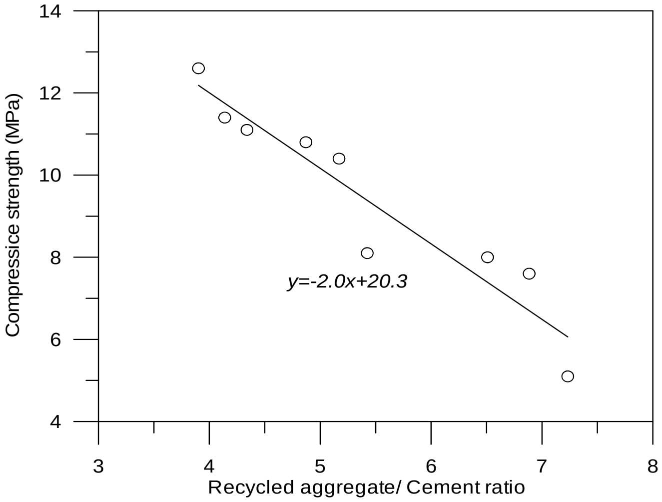


Fig. 4. Relationship between Recycled Aggregate/Cement Ratio and Compressive Strength.

specimens have less binder around the aggregate, resulting in more voids in the concrete, which reduces compressive strength and increases permeability. Fig. 5 shows the test results of the NA and SBL modified paste for compressive strength. The addition of NA or SBL modified paste increased the compressive strength of the concrete mixture. The rougher and more angular particle shape of NA compared to the RA increased the bond between the cement paste and the aggregate. Other reasons for the reduced compressive strength of RA were that the Los Angeles test values of NA in this study were lower than RA, as shown in Table 1. Adding SBL into the RA concrete mix significantly increased compressive strength. The SBL modified paste combined cement hydration and polymer adhesion, resulting in improved strength close to the NA concrete mix.

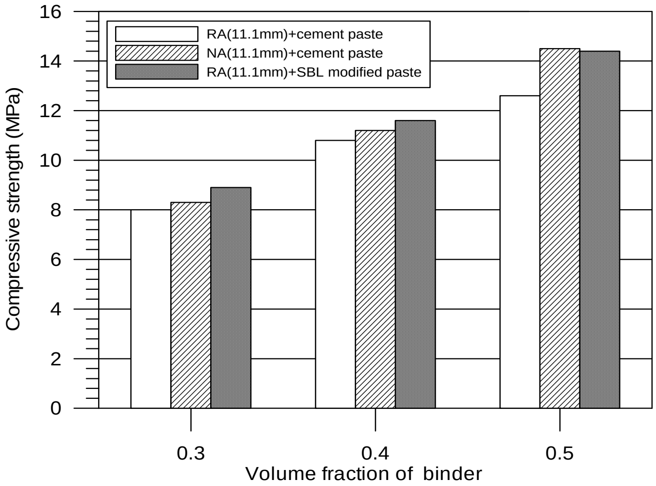


Fig. 5. Effect of SBL and NA on Compressive Strength.

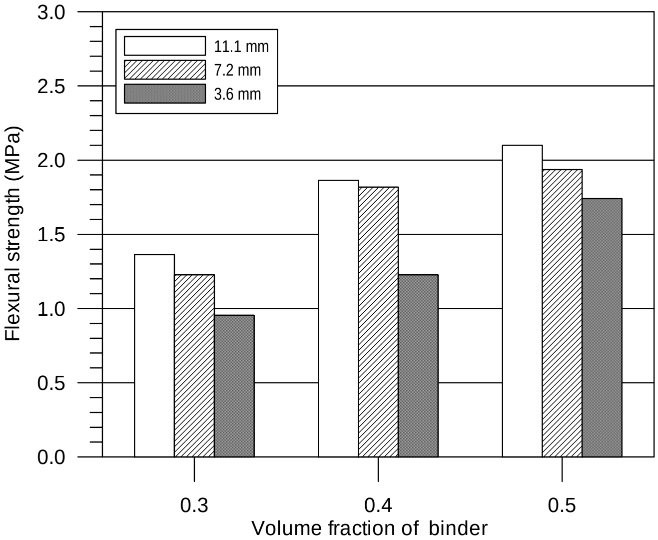


Fig. 6. Effect of Volume Fraction of the Binder on Flexural Strength.

Flexural Strength

Fig. 6 presents the static flexural strength test results for various mixes with different particle sizes of RA corresponding to different volume fractions of the binder used in this investigation. The test result shows the same tendency as compressive strength. The flexural strength SBL modified paste concrete is higher than other unreinforced epoxy polymer concretes, as shown in Fig. 7. Test results showed similar flexural properties for the polymer composite [10]. Increased flexural strength corresponding to ultimate load was observed to vary from 37% to 123% for RA concrete mixes having an SBL binder. This is attributed to the latex composites formed during the mixing and inter-hydration of the latex and cement

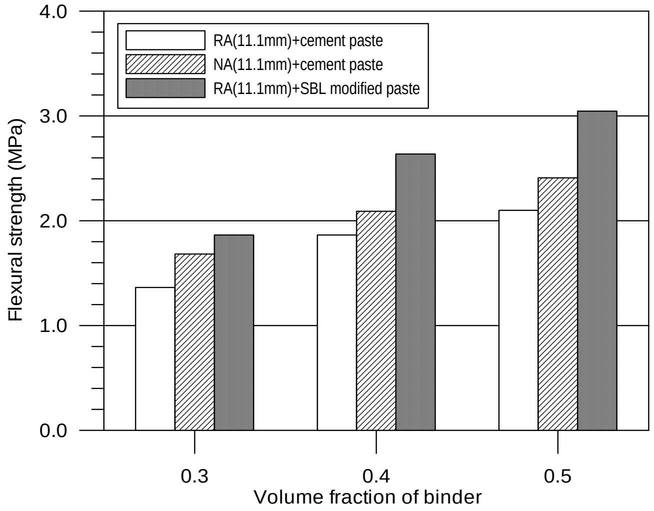


Fig. 7. Effect of SBL and NA on Flexural Strength.

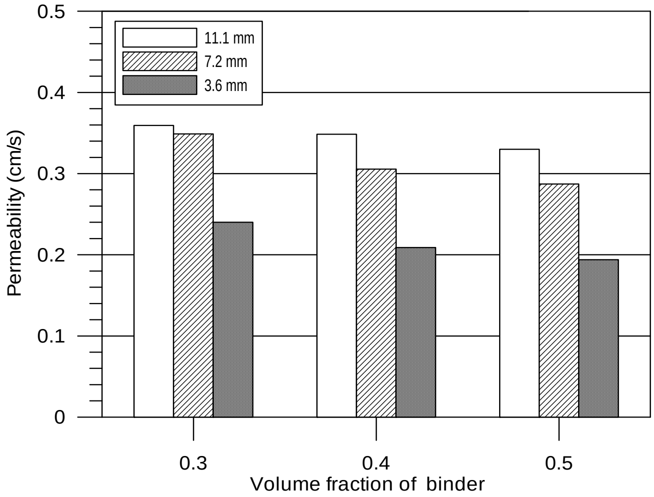


Fig. 8. Effect of Volume Fraction of the Binder on Permeability.

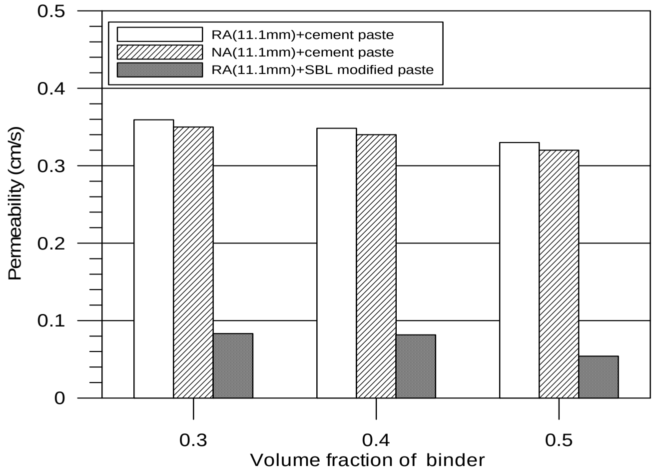
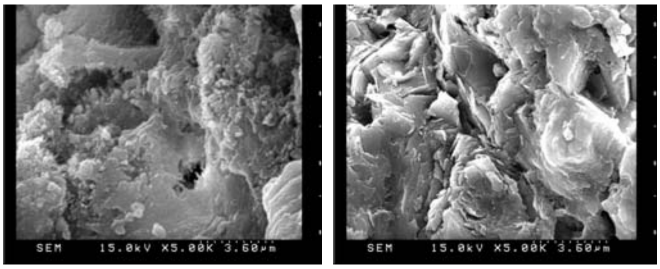


Fig. 9. Effect of SBL and NA on Permeability.

hydration products [11]. The latex composites have a high tensile strength, which will raise the flexural strength of pervious concrete. For NA concrete flexural strengths, the value of flexural strengths increased as V_f increased from 0.3 to 0.5, higher than the RA mixture. This is attributed to the rough and angular shape of NA particle, which increased the interlock force between the cement paste and the aggregate and also increased the flexural strength of pervious concrete.



(a) (b)

Fig. 10. Surface Microstructure of the (a) Cement Paste (b) SBL Modified Paste.

Permeability

Fig. 8 gives permeability results for the RA concrete mix. Fig. 8 shows that the pervious concrete with RA had permeability values between 0.18 cm/s to 0.36 cm/s, which are high enough to be used as a drainage layer for pavement structures. At fixed volume fraction of the binder, RA with smaller nominal diameter has a lower permeability. Decreased permeability generally results in increased volume fraction of the binder. This may be because the smaller aggregate size may reduce void space in the concrete mix. Fig. 9 shows the effects of NA and SBL on permeability. Using the SBL modified paste apparently decreased permeability obviously compared to RA concrete without SBL added to the mixtures. The permeability of SBL modified paste pervious concrete ranges from 0.05 cm/s to 0.08 cm/s, similar to the permeability of extra fine sand [12]. SEM microscopy (Fig. 2(b) and Fig. 10) shows that SBL produce denser adhesion between RA and SBL modified paste. Besides, after adding SBL, the hydration products of SBL modified paste have a denser structure (Fig. 10). The SBL modified paste leads reduces concrete permeability; however, the phenomenon may not cause any practical problems in field utilization. A slightly lower permeability is obtained for NA concrete. Nevertheless, the differences in these values are very small and can be regarded as negligible.

Porosity

Fig. 11 gives porosity results for RA pervious concrete, showing that most of the mixtures had properties within the range from 15% to 30%, which is acceptable. The three RA with different nominal diameters appeared with different porosities, indicating that aggregate gradation had a significant effect on porosity results. Fig. 12 shows that NA resulted in a slight porosity variation; however, SBL clearly decreased the porosity. The trend fits with the permeability values. The permeability (k) is plotted as a function of porosity (p) in Fig. 13. By linear regression, the empirical relationship between permeability and porosity are statistically derived as p (%) = 229.4 × k (cm/s) - 56.0 and p (%) = 69.8 × k (cm/s) - 7.8 for cement paste and SBL modified paste, respectively.

Efficiency Analysis of RA Pervious Concrete

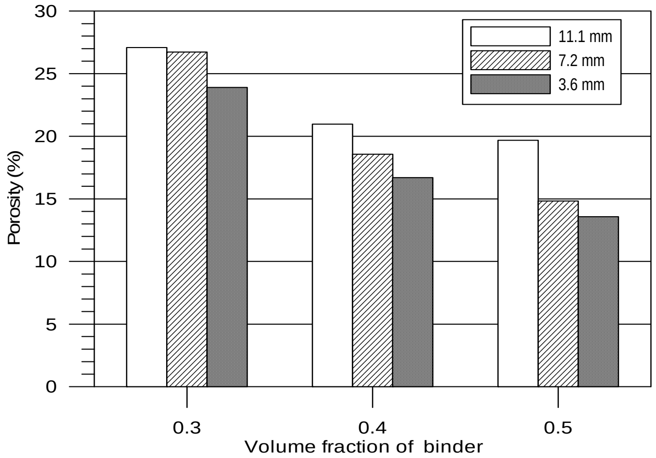


Fig. 11. Effect of Volume Fraction of the Binder on Porosity.

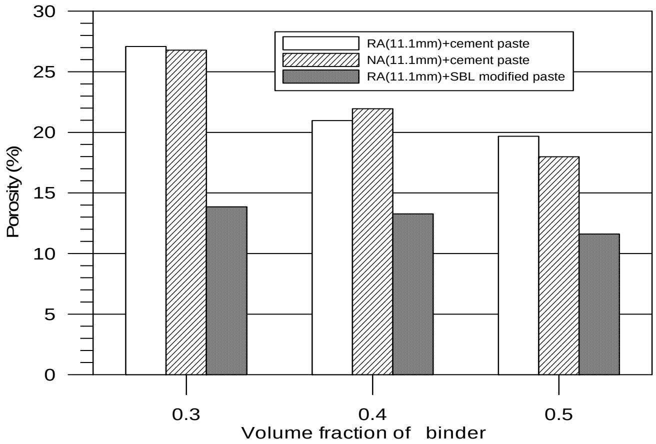


Fig. 12. Effect of SBL and NA on Porosity.

Table 4 gives the compressive strength, flexural strength and permeability data of RA pervious concrete. The mechanical and permeability properties of RA pervious concrete are affected by many factors. To determine the optimal mixture of RA pervious concrete, the current study conducted the efficiency coefficient method [13] by selecting the following variables: compressive strength, flexural strength and permeability. To realize the efficiency of all the variables, the total efficiency factor (*d*) is assumed as follows:

$$d = (d_1 \times d_2 \times d_3)^{1/3} \tag{5}$$

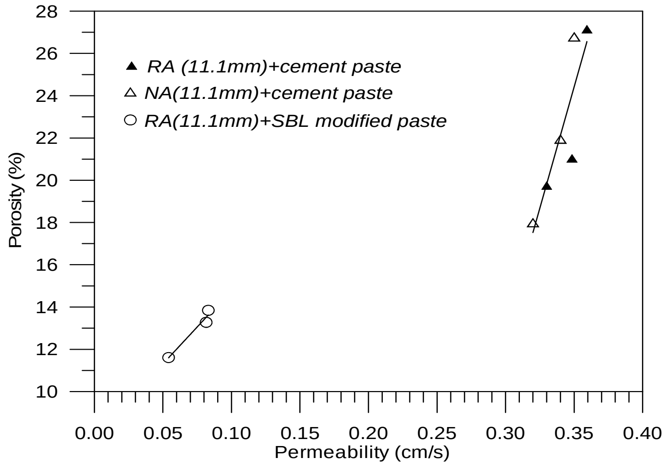


Fig. 1. Relationship between Permeability and Porosity.

where d_1, d_2, d_3 are the efficiency factors for compressive strength flexural strength and permeability, respectively. The efficiency factors d_1 can be written as $f_c/f_{c(max)}$, efficiency factors d_2 can be written as $R/R_{(max)}$ and efficiency factors d_3 can be written as $k/k_{(max)}$, respectively. Table 4 shows that at the same volume fraction of the binder, the nominal diameter of aggregate increases, resulting in a higher total efficiency factor. At the same nominal diameter of aggregate, the total efficiency factor increases as volume fraction of the binder increases. The aggregate to cement ratio is the main factor influencing the total efficiency factor. When the recycled aggregate to cement ratio is 3.9, the volume fraction of the binder is 0.5, and the nominal diameter of RA is 11.1 mm, the maximum total efficiency factor is obtained.

Conclusions

The current study conducted a laboratory test to detect the strength and permeability characteristics of recycled aggregate pervious concrete. This study illustrates the influence that the binder and aggregate types, volume fraction of the binder and different nominal diameters of particle have on recycled aggregate pervious concrete properties and behavior. The conclusions are drawn as follows:

1. The unit weight of RA concrete is less than NA concrete. This could be attributed to light adherence and the porous nature of old cement mortar to the recycled aggregate.
2. The Vebe time of RA concrete was lower than NA concrete mixture with the same particle size and volume fraction of the

Table 4. Efficiency Analysis of RA Pervious Concrete.

Mix No.	*Cc*	f_c (MPa)	*R* (MPa)	*k* (cm/sec)	D_1	d_2	d_3	*d*
A3MR	6.5	8.2	1.36	0.359***	0.651	0.649	1.000	0.750
A4MR	4.9	10.8	1.86	0.348	0.857	0.887	0.969	0.903
A5MR	3.9	12.6*	2.10**	0.330	1.000	1.000	0.919	0.972
B3MR	6.9	7.6	1.23	0.349	0.603	0.584	0.972	0.700
B4MR	5.2	10.4	1.82	0.305	0.825	0.866	0.850	0.847
B5MR	4.1	11.4	1.94	0.287	0.905	0.922	0.799	0.874
C3MR	7.2	5.1	0.95	0.240	0.405	0.455	0.669	0.497
C4MR	5.4	8.1	1.23	0.209	0.643	0.584	0.582	0.603
C5MR	4.3	11.1	1.74	0.194	0.881	0.829	0.540	0.733

Note: * $f_{c(max)}$; ** $R_{(max)}$; *** $k_{(max)}$.

binder. This increase in concrete workability is due to the spherical particles of RA.

3. The Vebe time of RA concrete was lower than NA concrete mixture with the same particle size and volume fraction of the binder. This increase in concrete workability is due to the spherical particles of RA.
4. The use of styrene-butadiene latex and natural aggregate could produce pervious concrete with higher compressive strength and lower permeability properties.
5. The aggregate to cement ratio has an important factor effect on compressive strength of RA pervious concrete.
6. When the recycled aggregate to cement ratio is 3.9, the volume fraction of the binder is 0.5, and the nominal diameter of RA is 11.1 mm simultaneously, the maximum total efficiency factor is obtained in this study.

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