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Properties of concrete prepared with PVA-impregnated recycled concrete aggregates

Shi-Cong Kou, Chi-Sun Poon *

Department of Civil and Structural Engineering, The Hong Kong Polytechnic University, Hung Hom, Kowloon, Hong Kong

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ABSTRACT

This paper reports an experimental study to improve the properties of recycled concrete aggregates (RCA) by their impregnation with polyvinyl alcohol (PVA). The effects of PVA on the development of strength and durability properties of the recycled aggregate concrete were evaluated. The experimental investigation was conducted in two parts. Firstly, the optimal concentration of PVA solution required to improve the recycled aggregates was determined. The RCA was soaked in 6%, 8%, 10%, 12% PVA solutions, and impregnation was conducted under a controlled laboratory environment. Density, crushing value (10% fines value), and water absorption of the PVA impregnated RCA (PI-RCA) were determined. Secondly, the slump, slump loss, compressive and tensile splitting strength, dimensional change (shrinkage) and chloride penetrability of the concretes prepared with the RCA that had been impregnated with the optimal (10%) PVA concentration were determined. It was found that the 10% fines value of the PI-RCA was higher, and the water absorption of the PI-RCA were lower when compared to the untreated RCA. The results show that there was not only an improvement in the mechanical properties of the concrete made with PI-RCA, but also the shrinkage of PI-RCA decreased while the resistance to chloride-ion penetration of the concrete produced increased.

1. Introduction

The quantities of construction and demolition (C&D) wastes generated in Hong Kong have significantly risen from 13.6 million tons in 1999 to over 27 million tons in 2006 [1]. In the past, the inert portions of these C&D wastes, such as rock, concrete and soil, have been beneficially reused as fill materials in forming land for the fast growing infra-structural development. However, the increasing awareness on environmental protection by the public has resulted in a substantial reduction in public filling capacity to accommodate the C&D wastes.

Research work on recycled aggregates has been well documented [2–6]. Generally, the mechanical properties, such as compressive and tensile splitting strengths of concrete made with recycled aggregates, were found to suffer up to a 40% loss compared to natural aggregate concrete [7], and the drying shrinkage increased by up to 60% [8]. Similar findings were reported in more recent studies [9–13]. Most of the adverse effects are attributed to the higher water demand and lower workability of the concrete incorporating recycled aggregates (RCA), particularly the finer fraction, which is derived from the old, porous cement mortar attached to the RCA.

The most distinctive difference between the properties of the RCA and natural aggregates is on water absorption, being high in the RCA due to the presence of the porous cement mortar. The presence of cracks and the porous nature of the old cement mortar affect the bond between the RCA and cement paste when used in new concrete [14]. The development of techniques which can minimize this adverse effect is very important. These techniques are expected to consolidate the adhering mortar layer and reduce the porosity of RCA, thereby improving the interfacial bond between RCA and new cement paste in the new concrete. Shayan and Xu [15] reported the use of lime and silica fume to improve the surface properties of RCA and the results clearly demonstrated that the improved RCA can be used to produce 50 MPa structural concrete with durability properties similar to those of natural aggregate concrete. Tsujino et al. [16] conducted experiments on using two types of surface improving agent, an oil-type and a silane-type, to improve the properties of recycled aggregates.

Otsuki et al. [17] developed a double mixing method. In this method, the coarse and fine aggregate was initially mixed for 1 min. Half of the required water was added and mixed with the aggregate for one additional minute. After that, cement was added and mixed with the aggregate for approximately one minute. Finally, the rest of the required water was added and the materials were further mixed for 90 s before casting. This mixing method was able to enhance the compressive strength of the concrete prepared with

* Corresponding author. Tel.: +852 2766 6024; fax: +852 2334 6389.
E-mail address: cecspoon@polyu.edu.hk (C.-S. Poon).

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coarse RCA by improving the interfacial transition zone between the RCA and the cement paste. Poon and Chan [18] found that the adverse effects (i.e., strength reduction) due to the use of fine recycled aggregates could be minimized by the deployment of the double mixing method, which can be easily implemented in pre-cast concrete production. Tam and Tam [19] reported that the additions of silica fume and the use of a two-stage mixing approach can fill up the weak areas in the RA and thus develop a stronger interfacial layer around aggregates, and hence a higher strength of the concrete.

Polyvinyl alcohol (PVA) is a water soluble polymer used as a cement modifier [20]. The PVA polymer is usually added in small amounts (up to 3 wt.% based on cement mass) [20–24] to improve workability and water retention abilities [20,21,23]. Some researchers have noted that when PVA was added, there was a decrease of compressive strength of concrete due to the increase in air voids content [24]. Others, however, have found improvements of compressive strength and reduction of porosity when PVA was used with fly ash blended cement [22]. An important modification observed with the use of PVA in concrete was the significant increase in the bond strength between the cement paste and the aggregates [23].

The aim of this study was evaluate the feasibility to improve the properties of RCA by using PVA. The paper reports the influence of the PVA impregnation (PI-RCA) on the strength development and durability properties of the concrete. In this study, an experimental investigation was conducted to determine the optimal concentration of PVA solution for RCA treatment and, evaluate the fresh and hardened properties of the concrete prepared with the PI-RCA.

2. Materials

2.1. Cement

The cement used in this study was ASTM Type I Portland cement with a density of 3.15 g/cm^3 and specific surface area of 3960 cm^2/g, which was supplied by Green Island Cement Company Limited in Hong Kong. The chemical compositions of the cement are given in Table 1.

2.2. Aggregates

Natural and recycled aggregates were used as the coarse aggregate in the concrete mixtures. In this study, crushed granite was used as the natural aggregate, and the recycled aggregates were crushed old concrete rubbles obtained from the demolishing of reinforced concrete buildings at the old Kai Tak Airport in Hong Kong. Moreover, natural river sand with a fineness modulus of 2.11 was used as the fine aggregate in the concrete mixtures.

2.3. PVA

Polyvinyl alcohol (PVA), which was 88% hydrolyzed and with a molecular weight of 22,000, was used. The PVA was supplied by Advanced Technology and Industrial Company Limited.

Table 1
Chemical composition of cement.

Materials	Composition (%)						
	LOI	SiO_2	Fe_2O_3	Al_2O_3	CaO	MgO	SO_3
Cement	2.97	19.61	3.32	7.33	63.15	2.54	2.13

3. Experimental details

3.1. Treatments of RCA, polymer impregnation

The procedure of treatment (impregnation with PVA) of RCA is described below: (1) the 20 mm and 10 mm RCA were put in desiccators with a vacuum pumps operating at a pressure of 920 mbar for 6 h; (2) 120 g, 160 g, 200 g and 240 g of PVA powder was added into 2 l boiled water separately to prepare the polymer solutions, hence the concentrations of PVA solution were 6%, 8%, 10% and 12% respectively. After the PVA powder was dissolved, the polymer solution was allowed to cool down to room temperature; (3) after that, the polymer solution was added into the desiccators prepared in (1 above) slowly through a funnel. The aggregates were soaked in the polymer solutions for 24 h with the vacuum pump turned on; (4) after the specified period of soaking, the aggregates were removed from the desiccators and used for testing of aggregates properties; (5) the procedures described in (1–4) were repeated until sufficient quantities of PI-RCA were obtained; (6) for the concrete mixtures, the 10% PVA treated recycled aggregates were used at oven-dried and air-dried conditions. For the oven-dried PI-RCA, the PI-RCA were dried at a temperature of 60 °C for 24 h, while for the concrete mixtures prepared with air-dried PI-RCA, the PI-RCA were allowed to dry in a laboratory controlled environment (T = 23 ± 1 °C, RH = 65 ± 2%) for 2 days before use.

3.2. Concrete specimens casting and curing

The concrete mixes were prepared with a water-to-cement ratio of 0.50 and the cement content was kept constant at 380 kg/m^3. The PI-RCA was used in oven-dry and air-dry conditions, respectively. The proportions of the concrete mixes were designed using the absolute volume method. The mix proportions of the concrete mixtures with the aggregates at the saturated surface-dried (SSD) condition are shown in Table 2. The actual proportions at mixing were adjusted according to the moisture contents and water absorption values of the aggregates.

For each concrete mix, 100 mm cubes, 75 × 75 × 285 mm prisms and 200 × 100 mm diameter cylinders were cast. The cubes and the prisms were used to determine the compressive strength and the drying shrinkage of the concrete, respectively. The cylinders were used to evaluate the tensile splitting strength and the resistance to chloride-ion penetration of the concrete. All specimens were cast in steel moulds and compacted using a vibrating table. The specimens were demolded after curing for 24 h at a controlled laboratory environment. The specimens were cured in a water curing tank at 27 ± 1 °C until the ages of 3, 7, 28 and 90 days were reached.

Table 2
Physical properties of PVA-impregnated recycled concrete aggregate.

Particle size (mm)		Density (kg/m^3)		Water absorption (%)		10% fine value (KN)
PVA concentration (%)		20	10	20	10	14
6	Oven-dried	2431	2353	5.89	6.12	126
	Air-dried	2434	2356	4.25	5.84	132
8	Oven-dried	2442	2361	4.63	4.83	130
	Air-dried	2453	2367	2.98	3.17	137
10	Oven-dried	2461	2372	2.39	4.32	154
	Air-dried	2473	2385	1.62	2.38	158
12	Oven-dried	2468	2378	2.35	4.12	155
	Air-dried	2482	2389	1.57	2.27	160

3.3. Testing

3.3.1. Determination of properties of aggregates

The water absorption, density, and crushing strength (10% fines value (TFV)) of the natural aggregate, recycled concrete aggregate and PVA-improved recycled concrete aggregate (PI-RCA) were conducted according to BS 812: Part 2, Part 109, Part 111 and Part 112, respectively. The TFV test is a variation of the traditional crushing value test in which the load (in kN) required to produce 10% fines from the 10–14 mm aggregate particles is determined.

3.3.2. Slump

The slump of the fresh concrete prepared was measured using the standard slump test apparatus. A portion of about 20 l (three times the quantity required for the slump test) of fresh concrete were taken for the slump test. Slump values were regularly measured at the intervals of 15 min, with the first value measured immediately after mixing and the last value measured at the 180th minute. Plastic films were used to cover the concrete mixtures during the intervals between tests.

3.3.3. Compressive and tensile splitting strength

The compressive and tensile splitting strengths of concrete were determined using a Denison compression machine with a loading capacity of 3000 kN. The loading rates for the compressive and splitting tensile tests were 200 kN/min and 57 kN/min in accordance with BS 1881 Part 116 and BS 1881 Part 117, respectively. The compressive and tensile splitting strength tests were carried out at the ages of 3, 7, 28 and 90 days.

3.3.4. Dimensional change (shrinkage) test

A modified British Method (BS 1881, Part 5) was used for the test. After removing the concrete prisms from the curing tank, the initial length of each specimen was measured. The specimens were then stored in an environmental chamber with a temperature of 55 °C and a relative humidity of 95% until the next measurements at 1, 4, 7, 28, 56, 90 and 112 days. Before each measurement was taken on the scheduled day, the specimens were first removed from the environmental chamber and conveyed to a second cooling chamber for about 4 h at a controlled temperature of 25 °C and a relative humidity of 75%. The length of each specimen was then measured within 15 min using a digital meter before delivering the specimens back to the environmental chamber for the subsequence drying process. The procedure of drying, cooling and measuring continued until the final length measurement at 112 days was recorded.

3.3.5. Determination of chloride-ion penetrability

The chloride-ion penetrability of the concrete mixtures was determined in accordance with ASTM C1202 using a 50 mm thick × 100 diameter concrete disc that was mechanically cut from the 100 × 200 mm concrete cylinders. The resistance of concrete against chloride-ion penetration is represented by the total charge passed in coulombs during a test period of 6 h. In this study, the chloride penetrability test was carried out on the concrete specimens at the ages of 28 and 90 days.

4. Results and discussion

4.1. Properties of PI-RCA

The test results of the properties of PI-RCA such as density, water absorption and 10% fine value of PVA-improved recycled concrete aggregates are shown in Tables 3 and 4 together with those for natural granite and RCA. The values are the averages of three measurements. It was found that the properties of RCA improved with PVA impregnation. The density and 10% fine value of RCA increased with an increase in concentration of PVA solution. Moreover, the water absorption of RCA was significantly decreased. Table 4 shows that the properties of 12% PVA treated RCA was only marginally better than that of the 10% PVA treated RCA; and hence, it was considered that 10% PVA solution treatment was optimum.

4.2. Initial slump and slump loss of concrete

Fig. 1 depicts the changes of concrete slump with time for the concrete mixtures. The slump values are also the averages of three measurements. It can be seen that, compared with the control, the initial slump of the concretes prepared with both RCA and PI-RCA increased. The mix prepared with RCA had the highest slump value of 215 mm. This was due to the higher initial free water content in the concrete mixture. This was in turn due to the higher water absorption value of the RCA (see Tables 3 and 4) which was used at the air-dried condition with a moisture content at mixing much lower than the water absorption value. Additional amounts of water were added to maintain the mix proportions as listed in

Table 3
Physical properties of natural, recycled concrete, and 10% PVA-impregnated recycled concrete aggregate.

Property	Particle size (mm)	Aggregate type			
		Natural granite	Recycled concrete	PVA-modified (oven-dried)	PVA-modified (air-dried)
Density (kg/m^3)	20	2662	2423	2466	2472
	10	2583	2356	2378	2385
Water absorption (%)	20	0.68	6.23	2.39	1.62
	10	0.87	7.76	4.32	2.38
10% fine value (KN)	14	168	120	154	158

Table 4
Proportions of concrete mixtures.

Notation	Proportion (kg/m^3)							
	Cement	Water	W/C	Sand	10 mm granite	20 mm granite	10 mm RCA	20 mm RCA
Control	380	190	0.50	687	373	747	–	–
R-100	380	190	0.50	687	–	–	335	690
RP(O)-100	380	190	0.50	687	–	–	338	701
RP(A)-100	380	190	0.50	687	–	–	339	704

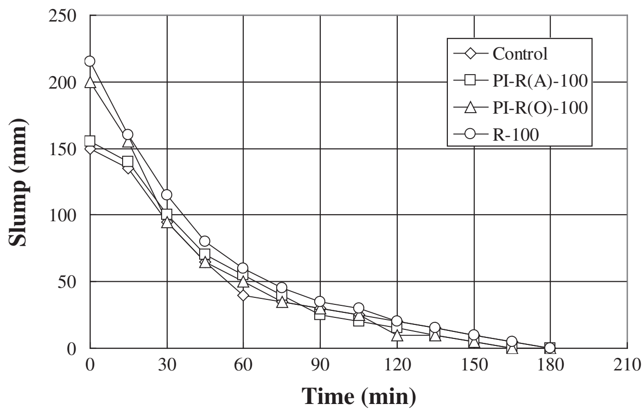

Fig. 1. Slump change of concrete mixtures.

Table 2. It is also shown in Fig. 1 that the rate of slump loss was quicker for the RCA concretes within the first hour after mixing, but turned slower afterwards. To reach zero-slump, the concrete mixture without recycled aggregate took about 150 min, while the mixture with RCA and PI-RCA took over 3 h. The reasons why the mixtures with RCA and PI-RCA took longer than other mixtures to achieve zero-slump may be due to the larger amount of initial free water present at the time of mixing.

4.3. Compressive and tensile splitting strength

The developments of the compressive strength of the concrete mixtures up to 90 days are presented in Fig. 2. Table 5 gives the relative compressive strength (expressed as percentages of that of the control mixtures (100% natural aggregate)) of the concrete mixtures. It is seen that although both the air-dried and oven-dried PI-RCA improved the compressive strength of the concrete mixtures, the compressive strength of the concrete mixtures was still lower than that of the control at the all tested ages. At 28 days the compressive strength of concrete prepared with RCA, oven-dried and air-dried PI-RCA was 11%, 10% and 6% lower than that of the control concrete. The concrete mixtures prepared with air-dried PI-RCA had higher compressive strength than that of the mixtures with oven-dried PI-RCA.

The concrete mixtures with PI-RCA had higher compressive strength than that of RCA without PVA. This may be attributed to the following: (i) PVA improved the physical and mechanical properties of the recycled concrete aggregate due to PVA was able to fill up the pores of the old porous cement mortar that had been attached on the recycled aggregate; (ii) PVA attached on the RAC surface was dissolved during concrete mixing and it altered the state of flocculation/coagulation of the cement [20]; (iii) bleeding in the new mortars was reduced; (iv) reduced water/cement ratio at the interfaces and (*v*) adding of PVA improved the adherence between the paste and the aggregates [20,22,23,25,26]. This is consistent with the results of Mansur et al. [27] who reported that PVA addition reduced the thickness of the porous transition zone between porcelain tiles and the bulk cement paste.

In general, the results at 90 days show that the compressive strength of concrete made with air-dried PI-RCA was only 1% lower than that of the control concrete. This can be attributed to the infilling ability of the new cement hydrates into the porous old cement mortars which would improve the cement/aggregate bonding and healing of cracks at the interfacial region after the longer period of hydration.

Moreover, the concrete mixtures with oven-dried PI-RCA had lower compressive strength than that of air-dried PI-RCA mixtures; which may be due to the fact that attached PVA chains on RCA surface was aged by the higher temperature.

Table 6 provides the relative tensile splitting strength (expressed as percentages of that of the control) of the concrete mixtures and Fig. 3 shows the development of the tensile splitting strength with age. It can be seen that before 28 days the tensile splitting strength of the concrete mixtures with RCA and PI-RCA was lower than that of the control concrete, but the air-dried PI-RCA mixture attained a higher tensile splitting strength value than RCA. However, at 90 days, the tensile splitting strength of the

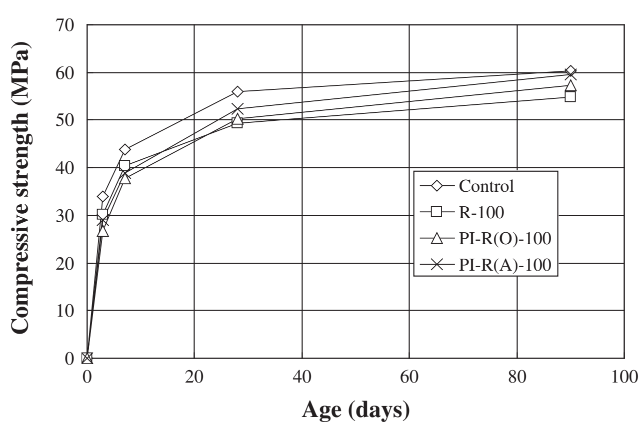

Fig. 2. Development of compressive strength of the concrete mixtures.

Table 5
Compressive strength relative to the control.

W/C	Age (days)	Control	R-100	PR(O)-100	PR(A)-100
0.50	3	1	0.86	0.79	0.85
	7	1	0.92	0.86	0.88
	28	1	0.89	0.90	0.94
	90	1	0.91	0.95	0.99

Table 6
Tensile splitting strength relative to the control.

W/C	Age (days)	Control	R-100	PR(O)-100	PR(A)-100
0.50	3	1	0.94	0.85	0.93
	7	1	0.93	0.87	0.97
	28	1	0.93	0.87	0.94
	90	1	1.01	0.92	1.03

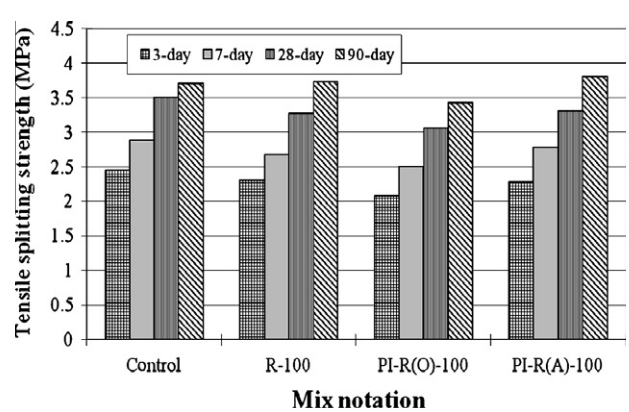

Fig. 3. Tensile splitting strength of concrete mixtures.

concrete mixtures prepared with both the RCA and air-dried PI-RCA were slightly higher than that of the control concrete indicating again the better bonding between the RCA and the new cement mortar.

The relationship between the compressive strength and tensile splitting strength of the concrete mixtures prepared with PI-RCA are plotted in Fig. 4 and it shows that there was a very good linear correlation between compressive strength and tensile splitting strength.

4.4. Shrinkage

The shrinkage values (tested at 112 days) of the concrete mixtures are in Fig. 5. Each presented value is the average of three measurements. It can be seen that the shrinkage of the concrete mixtures prepared with RCA and PI-RCA was higher than that of the control. However, the shrinkage of the concrete mixtures made with PI-RCA was approximately 15% lower than that of the concrete with RCA. This may be explained by the fact that PI-RCA had a lower water absorption capacity than that of RCA (see Table 3).

4.5. Chloride penetrability

Fig. 6 shows the test results of resistance in the concrete specimens to chloride-ion penetration at 28 and 90 days. The results show that when compared with the RCA concrete mixture, the resistance to chloride-ion penetration was significantly increased with the incorporation of the PI-RCA in the concrete mixes. At 28 days, the concretes made with air-dried and oven-dried PI-RCA showed approximately 35% and 32% higher resistance to chloride penetration than that of the concrete made with RCA. The enhanced performance was similar to that of the control concrete.

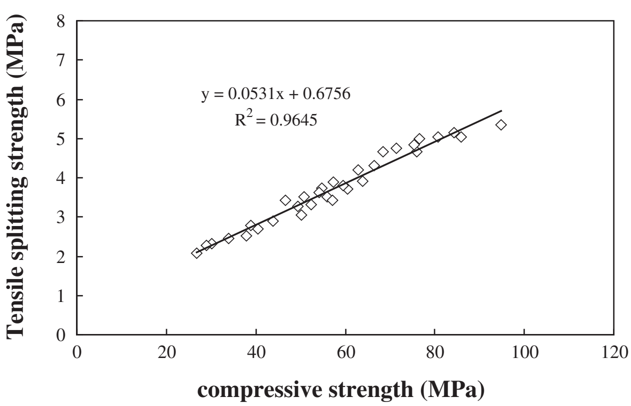

Fig. 4. Relationship between compressive strength and tensile splitting strength.

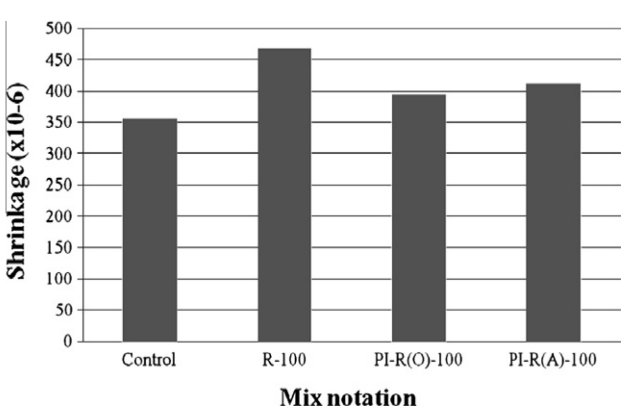

Fig. 5. Shrinkage of concrete mixture at 112 days.

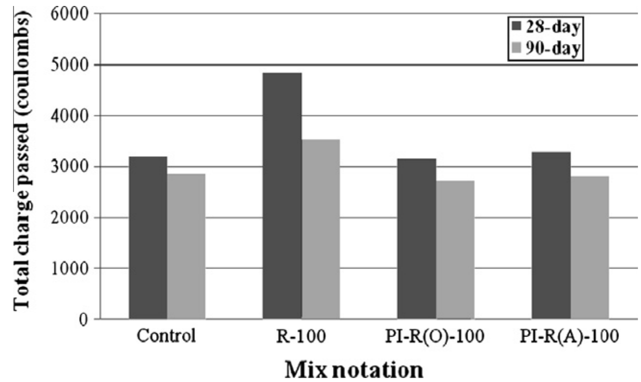

Fig. 6. Total charge passed of the concrete mixtures.

5. Conclusion

The work delineated in this paper has shown that RCA is a useful resource and, together with PVA modifications, it can be used for the production of structural concrete. The concrete mixtures were subjected to durability tests including shrinkage and rapid chloride permeability. Not only did the mixtures demonstrate satisfactory levels of performance, but the performance levels were comparable to those of concrete containing natural aggregate only. Based on the test results and discussion above, the following conclusions can be drawn:

- PVA solutions can be used to improve the properties of RCA. In this study, a 10% solution was found to be optimal.
- The compressive strength of concrete made with RCA and PI-RCA at oven-dry and air-dry conditions was still lower than that of the control concrete at 28 days. However, at 90 days, the compressive strength of the concrete made with air-dried PI-RCA was similar to the control concrete.
- Before 28 days, the tensile splitting strength of concrete mixtures with RCA and PI-RCA was lower than that of the control concrete. However, at 90 days, the tensile splitting strength of the concrete mixtures prepared with RCA and air-dried PI-RCA were slightly higher than that of the control concrete.
- The drying shrinkage of the concrete mixtures made with PI-RCA was approximately 15% lower than that of the concrete with RCA.
- At 28 days, the concretes made with air-dried and oven-dried PI-RCA showed approximately 35% and 32% higher resistance to chloride penetration than that of the concrete made with RCA.
- The results are encouraging and show that the PVA improved RCA can be used to produce structural concrete with durability properties that are similar to those of natural aggregate concrete.

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