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Influence of silane-based water repellent on the durability properties of recycled aggregate concrete

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ABSTRACT

This paper aims to investigate the durability properties of recycled aggregate concrete treated with silane-based water repellent agents, since the high water absorption of recycled aggregate concrete is a major factor jeopardizing its durability. Different dosages of silane-based water repellent agents were either coated on the surface of the concrete (hereafter "surface silane treatment") or integrally added into the concrete mixture (hereafter "integral silane treatment"). The mechanical and durability properties of the treated concrete were evaluated. It was found that integral silane treatment can improve the durability of recycled aggregate concrete, but may lead to reductions in compressive strength; surface silane treatment is more effective in improving the resistance of recycled aggregate concrete to capillary water absorption, carbonation and chloride penetration than integral silane treatment.

1. Introduction

Continuous urbanization and redevelopment of cities causes serious problems in construction and demolition waste disposal [1]. For instance, in Hong Kong, about 12 million tonnes of construction and demolition (C&D) waste was generated in 2009. About 90% (by weight) of the above C&D wastes were inert materials such as rock, concrete and soil which are usually disposed of in reclamation/earth filling projects. The reuse of these C&D wastes not only conserves the finite raw materials, but also alleviates the demand on the public landfill capacity. One of the ways to reuse C&D wastes is to recycle them as aggregates in concrete [2]. The economic and environmental benefits of using recycled aggregates have been widely recognized. In 2002, the Hong Kong government set up a temporary recycling facility in Tuen Mun which actively promoted the use of recycled aggregates [3]. From 2003 to 2007, more than 10 local projects involving reinforced pile caps, ground slabs, beams and perimeter walls, external building and retaining walls, and mass concrete have consumed over 22,700 m^3 of concrete made using recycled aggregates [4].

Numerous studies have been conducted to evaluate the mechanical properties of recycled aggregate concrete, leading to the conclusion that the mechanical strength of recycled aggregate concrete is generally lower than that of natural aggregate concrete [5–13]. Compressive and tensile splitting strengths of concrete made of recycled aggregates have been found to suffer up to a 40% loss compared with natural aggregate concrete [5]. The mechanical strength of recycled aggregate concrete depends on two factors. One is the properties of the recycled aggregates and the other is the percentage of the replacement of natural aggregate in the concrete mix proportion [6]. Poon et al. [7] found that concrete made using air-dried recycled coarse aggregates show higher compressive strength. Olorusongo [9] and Kou and Poon [13] demonstrated that the compressive strength of concrete was reduced with an increase of the replacement proportion of recycled aggregate.

Many studies have also shown that using recycled aggregates in concrete causes durability problems [14–20]. Hansen and Boegh [14] reported that, compared with the reference concrete, the shrinkage of recycled aggregate concrete was increased by up to 60%. Domingo-Cabo et al. [15] observed that the shrinkage of recycled concretes using 100% recycled aggregates was about 70% higher than that of the control concrete after a period of 180 days. Olorunsogo and Padayachee [16] reported that, at the curing ages of 3, 7, 28 and 56 days, compared with natural aggregate concrete, the water absorptivity of recycled aggregate concrete was increased by 47.3%, 43.6%, 38.5% and 28.8%, respectively, although the processes of water absorption in both types of concrete were similar and obeyed the same law [16]. Cui et al. [17] reported that the carbonation level of recycled aggregate concrete was three times that of natural aggregate concrete. The results of Crentsil et al. [18] and Salomon and Helene et al. [19] showed that, after 6 months of curing, the carbonation depth of the recycled aggre-

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gate concrete was 1.3–2.5 times that of the reference concrete. Otsuki et al. [20] reported that the resistance of recycled aggregate concrete to chloride ion penetration and carbonation were slightly inferior to those of natural aggregate concrete given that the same water–binder ratio was used. In a study carried out by Olorunsogo and Padayachee [15], it was found that the concrete mix containing 100% recycled aggregates showed a 73.2% increase in chloride conductivity at a curing age of 28 days.

Therefore, improving the durability performance of recycled aggregate concrete is the key issue for its more extensive applications. There are some researchers who are concerned with the improvement of durability of recycled aggregate concrete. Li et al. [21,22] proposed a new particle shaping method to strengthen recycled aggregates and concluded that this method can improve the durability of recycled aggregate concrete. Kou and Poon [23] reported that, by using recycled concrete aggregates which had been first impregnated with a polymer (polyvinyl alcohol), the concrete shrinkage decreased and the resistance to chloride ion penetration increased. Otsuki et al. [20] and Ryu [24] found that the resistance to chloride penetration and carbonation of recycled aggregate concrete could be improved by using a double mixing method in concrete prepared with a high water–binder ratio.

About 50 years ago, silane was introduced as a protective agent for porous cement-based materials [25]. Silane can be added into fresh concrete during its fabrication process, as an integral water repellent material. The agent is dispersed homogeneously in the mix; hence the capillary suction of water and dissolved harmful substances such as chlorides are remarkably reduced within the whole material [26]. On the other hand, silane can also be used to coat the exposed surface of concrete in order to protect it from attack by foreign agents. In this case, a surface water repellent treatment of concrete can be used. This surface silane treatment can suppress significantly capillary water absorption and therefore improve the durability of concrete and protect the interior steel reinforcement [27–29]. Although the above research has shown that silane-based surface and integral treatments seem to be promising for natural aggregate concrete, very few studies have been conducted on the use of silane-based water repellent agents for the improvement of the durability of recycled aggregate concrete.

The objectives of this study are to investigate the influence of silane-based water repellent on the durability of concrete made with recycled aggregates and to provide an alternative method to enhance the durability of recycled aggregate concrete. Two silane addition methods, namely integral silane treatment and surface silane treatment, were adopted. Their influences on the durability properties of recycled aggregate concrete were investigated.

2. Experimental details

2.1. Materials

2.1.1. Cement

The cement used was ASTM Type I Portland cement supplied by Green Island Cement Company Limited, and is commercially available in Hong Kong. The density and specific surface area of the cement were 3.15 g/cm^3 and 3960 cm^2/g, respectively. The chemical compositions of the cement are indicated in Table 1.

Table 1
Chemical compositions 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

Table 2
Constitutes of recycled aggregates.

Constitute	Constitute of recycled aggregates (wt.%)	
	Particle size 10–20 mm	Particle size 5–10 mm
Concrete	96.67	97.46
Brick	2.18	1.63
Asphalt concrete	0.93	0.78
Grass ceramics and plastics	0.10	0.07
Wood and paper	0.08	0.05
Metal	0.04	0.01

Table 3
Properties of coarse aggregates.

Property	Particle size (mm)	Recycled aggregate	Natural aggregate
Saturated surface-dried density (kg/m^3)	20	2378	2662
	10	2321	2583
Water absorption (%)	20	6.4	0.7
	10	7.6	0.9
10% Fine value (KN)	14	140	250

2.1.2. Aggregates

In this study, both natural and recycled aggregates were used as the coarse aggregate in the concrete mixtures. The natural coarse aggregates were crushed granite with nominal particle sizes of 10 and 20 mm. The recycled aggregates derived from construction and demolition wastes were provided by a local construction waste recycling facility. The constituents of the recycled aggregate are shown in Table 2, and the properties of the coarse natural aggregates and recycled aggregates are shown in Table 3. The impurities in the recycled aggregate were about 3% by weight. Moreover, natural river sand with a fineness modulus of 2.11 was used as the fine aggregate in the concrete mixtures.

Because the aggregates used in this experiment were in a saturated surface-dried (SSD) condition, the actual mix proportions were adjusted according to the moisture content and the water absorption values of the aggregates before mixing.

2.1.3. Silane

Two types of commercially available water repellent agents were used as the integral water repellent and the surface treatment repellent, respectively in this study. The first was an emulsion designed for use as an integral water repellent. The second was designed for use as a surface treatment agent of concrete surfaces. The main component of these two types of water repellent agents is octyltriethoxysilane. The properties of the above two kinds of water repellent agents are indicated in Table 4.

2.2. Mixture proportions

The concrete mixes were prepared with a constant water-to-cement ratio and cement content of 0.5 and 380 kg/m^3, respectively. Two types of coarse aggregate, natural aggregate (NA) and recycled aggregate (RA), were used in the concrete mixes. The control concrete made with natural aggregate was denoted as NAC0 and the concrete prepared with 100% recycled coarse aggregate was denoted as RAC0.

Each type of concrete was prepared in the laboratory using the two water repellent treatment methods, (i) the integral water repellent method (I) and (ii) the surface water repellent treatment method (S).

Table 4
Properties of water repellent agents.

Product	Appearance	Active ingredient	Active ingredient content (%)	Specific gravity (g/cm^3)
HE 328	Emulsion white	Octyltriethoxysilane/siloxane	50 ± 2	1.0
HP 800	Paste white	Octyltriethoxysilane/siloxane	80	0.9

The integral water repellent concrete was produced by adding the silane emulsion into the concrete mixes. For recycled aggregate concrete, two different dosages of silane emulsion, 0.5% and 1% by cement weight, were used and the corresponding specimens were denoted as RACI-0.5 and RACI-1 respectively. The natural aggregate concrete with an addition of 0.5% silane emulsion by cement weight was denoted as NACI-0.5. When mixing the concrete, the water portion of integral silane agent (HE) was counted as part of the mixing water.

The surface silane treatment concrete was produced by applying 100 g/m^2 and 200 g/m^2 of silane paste separately onto the recycled aggregate and natural aggregate concrete surfaces. The corresponding specimens were denoted as RACS-100, RACS-200, NACS-100 and NACS-200, respectively. The details of the mix proportions are summarized in Table 5.

2.3. Specimen preparation

All concrete mixtures were mixed in the laboratory using a pan mixer. In order to produce the integral water repellent concrete, 0.5% and 1% of the silane emulsion were added to the fresh mix. For each concrete mixture, 100 × 100 × 100 mm cubes were cast for compressive strength, water absorption and carbonation tests, 100 × 200 mm cylinders were cast for the test of resistance to chloride ion penetration, and 75 × 75 × 285 mm prisms were cast for the drying shrinkage measurement.

After casting, the specimens were removed from the molds after 1 day; then the prism specimens were cured in an environmental chamber under conditions of 23 °C and 50% R.H. for drying shrinkage measurement. The cubes and cylinders were cured in a water tank at 27 ± 1 °C until the ages of 4, 7, 28 and 90 days.

In preparation of the surface water repellent treatment concrete, some of the cubes and cylinders were taken out of the water tank at the age of 28 days, and stored in a controlled laboratory environment at 23 °C and a relative humidity of 50% for 14 days. Then the specimen surface was cleaned by compressed air and the silane was applied on the specimen surface by brushing. The specimens were then stored in the same laboratory conditions for another 7 days in order to allow the applied materials to dry.

2.4. Test methods

2.4.1. Slump

The standard method BS 1881 Part 102 was used to determine the slump of the fresh concrete in order to assess the influence of the addition of the silane emulsion on the workability of the concrete.

2.4.2. Compressive strength

The compressive strengths of the concrete were measured using a Denison compression machine complying with BS 1881 Part 116 at the ages of 1, 4, 7, 28 and 90 days. The results presented are average values for three identical tests.

2.4.3. Silane impregnation depth of the surface water repellent treatment

The depth of silane impregnation is a very important factor to evaluate the effectiveness of the surface water repellent treatment [30]. To achieve different surface moisture conditions before the coating of silane, one sample was oven dried at 60 °C for 24 h, while other samples were exposed in air at a controlled laboratory environment for 14 days. The samples were named "oven dried" and "air dried" respectively. The impregnation depth of silane was measured by splitting the specimen into halves and spraying a thin layer of water onto the freshly split surface. It was noted that the silane penetrated part showed a different color compared with the wet area of the split surface. The impregnation depth of the hydrophobic treatment was measured by a caliper gauge at six different positions and the average value was reported.

2.4.4. Capillary water absorption

The capillary water absorption of the concrete was measured following the method of ISO 15148:2002(E) [31]. In order to ensure one dimensional water transport, except the top and bottom surfaces, all the surfaces of the specimens were sealed with an epoxy resin. The specimens were dried at 105 °C for 24 h. Then one of the two exposed surfaces of the specimens was immersed in water at a depth of 5 mm for 0.25, 0.5, 1, 2, 4, 8, 24, 48, 72 and 96 h. The water absorbed by capillary suction was determined by weighing the specimens after different durations of immersion.

A simple equation can be deduced from the theory of capillarity to describe capillary absorption as a function of time [32,33]:

$$\Delta W = A \cdot \sqrt{t} \tag{1}$$

In Eq. (1), W is the amount of water absorbed by capillary suction per unit area, t is the time of immersion and A is the coefficient of capillary suction.

Table 5
Mix proportions of concrete mixtures.

Notation	W/C	Cement (kg/m^3)	Water (kg/m^3)	Sand (kg/m^3)	HE	HP	NA (kg/m^3)		RA (kg/m^3)	
					328	800	10 mm	20 mm	10 mm	20 mm
NAC0					–	–				
NACI-0.5					0.50%	–				
NACS-100					–	100 g/m^2	373	747	–	–
NACS-200	0.5	380	190	687	–	200 g/m^2				
RAC0					–	–				
RACI-0.5					0.50%	–				
RACI-1					1%	–	–	–	314	629
RACS-100						100 g/m^2				
RACS-200						200 g/m^2				

2.4.5. Drying shrinkage test

The drying shrinkage of the concrete prisms was determined in accordance with ASTM C490. When the concrete prisms were removed from their molds, the initial length of each specimen was measured. Then relevant specimens of the integral water repellent concrete and the control concrete were stored in a chamber at 23 °C and 50% RH. The length of the specimens was measured at 1, 4, 7, 28, 56, 91 and 112 days.

2.4.6. Carbonation depth

Carbonation depth was measured in an accelerated carbonation experiment. The two ends of each specimen were sealed with an epoxy resin, and stored in a carbonation chamber with 4% carbon dioxide by volume, following the recommendations of RILEM CPC-18 [34]. At the ages of 28, 56, and 112 days, specimens were taken out from the chamber. In order to measure the carbonation depth, the samples were split in half and sprayed with a phenolphthalein solution immediately. The carbonation concrete showed a different color compared with other areas, and therefore, the depth could be measured by a caliper gauge. The average values of the depths at six different positions were used for evaluation.

2.4.7. Chloride ion penetrability

The chloride ion penetrability was measured in accordance with ASTM C1202-94 [35], to measure the amount of electric current passing through the specimens during a 6 h period. At the age of 28 days, the 100 × 200 mm concrete cylinders were taken out of the water tank and were cut into 50 mm thick × 100 mm diameter concrete slices. Epoxy coating was applied onto the side surfaces of the concrete slices to make them impermeable. The slices were then placed in a desiccator under vacuum with a negative pressure of 900 mbar for 4–6 h. After that, the desiccator was filled with distilled water, which was totally enclosed under vacuum conditions for 24 h. One side of the slice was immersed in a sodium chloride solution and the other side was immersed in a sodium hydroxide solution. A potential difference of 60 V dc was maintained between the two sides. The current was recorded every 30 min during a 6-h test period.

3. Results and discussion

3.1. Slump

The results of the slumps of the concrete mixtures are shown in Fig. 1. The average values of three measurements are presented. It is seen that the slump values of both the recycled and natural aggregate concrete increased with the addition of silane. The slump values of the integral water repellent concrete mixtures NACI-0.5, RACI-0.5 and RACI-1, were significantly higher than the corresponding concrete mixtures NAC0 and RAC0 without silane. This may be attributed to silane being a hydrophobic material, which led to a higher free water content in the concrete mixture. Moreover, the slump values of the recycled aggregate concrete slightly increased with increase in silane content.

3.2. Compressive strength

Fig. 2 shows the development of the compressive strength of the concretes. It can be seen that the 28-day compressive strength of concrete mixture RAC0 prepared with 100% recycled aggregate was 18% lower than the corresponding concrete mixture NAC0 prepared with 100% natural aggregate. Moreover, the compressive strength of both the natural and recycled aggregate concrete significantly decreased with the addition of silane. The 28-day compressive strength of the concrete mixtures NACI-0.5 and RACI-0.5 were

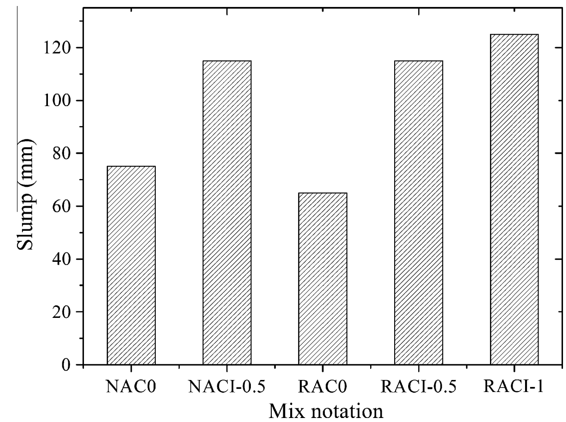

Fig. 1. Slump of concrete.

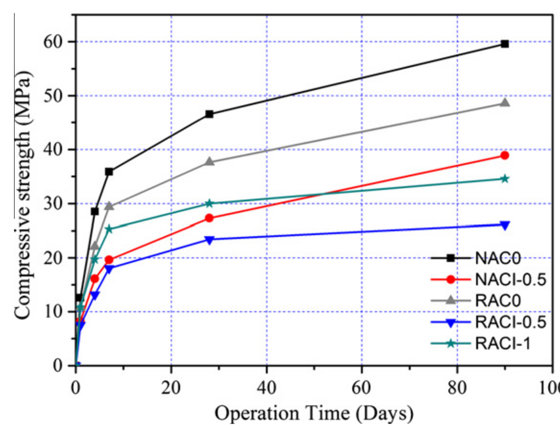

Fig. 2. Development of compressive strength of concrete.

41% and 38% lower than those of NAC0 and RAC0, respectively. This might be due to the fact that after the hydrolysis of silane, the reactive silanol groups could anchor to the cementitious materials or to the aggregate, making their surfaces hydrophobic [36]. As a consequence, the degree of hydration of cement-based materials could be retarded by the presence of the silane emulsion [37] leading to a loss of mechanical strength. However, this could be compensated by lowering the water–cement ratio [38] due to the much higher slump values as a result of silane addition. Moreover, it should be noted that the compressive strength of the concrete mixture RACI-1 with 1% silane addiction was higher than that corresponding concrete mixture RACI-0.5 with 0.5% silane addiction. This also may be attributed to the higher silane addiction lead to higher slump values in the concrete.

3.3. Capillary water absorption

The capillary water absorption of the concrete was measured during an immersion duration of 96 h. The results are shown in Fig. 3. The presented values are the average of three separate measurements. Table 6 shows the capillary water absorption coefficients of the concrete mixtures and their relative ratios with respect to the control samples.

The results indicate that the silane-based water repellent agents had a significant effect on the capillary water absorption of the concrete. The capillary water absorption coefficients of NACI-0.5, NACS-100 and NACS-200 decreased by 63%, 80% and 81%, respectively when compared with NAC0. Moreover, the capillary water

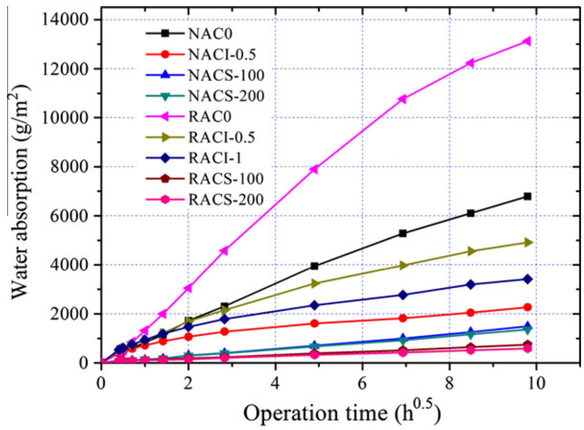

Fig. 3. Water absorption of concrete.

Table 6
Capillary water absorption coefficient and decrease rate of integral silane treated concrete.

Mix notation	RAC0	RACI-0.5	RACI-1	RACS-100	RACS-200
Coefficient of capillary suction (kg/(m^2 h$^{0.5}$))	1446.0	560.9	402.2	77.6	62.8
Decrease rate (%) compared to RAC0	100	61	72	95	96
Mix notation	NAC0	NACI-0.5	NACS-100	NACS-200	–
Coefficient of capillary suction (kg/(m^2 h$^{0.5}$))	732.8	268.0	148.1	137.3	–
Decrease rate (%) compared to NAC0	100	63	80	81	–

Table 7
Silane impregnation depth of surface treated concrete.

Mix notation	Impregnation depth (mm)	
	Oven dried	Air dried
NACS-100	6.8	2.4
NACS-200	8.5	3.0
RACS-100	7.8	3.7
RACS-200	9.1	4.1

absorption coefficient of the recycled aggregate concrete mixtures RACI-0.5, RACI-1, RACS-100 and RACS-200 decreased by 61%, 72%, 95% and 96%, respectively when compared with RAC0. The integral water repellent concrete prepared by direct mixing with silane emulsion was less efficient in repelling water when compared to the surface water repellent treatment concrete [39,40]. Furthermore, the experimental results show that the surface silane treatment was more effective for the recycled aggregate concrete than the natural aggregate concrete. The main reason is that the porosity of recycled aggregate concrete was higher so that the silane could penetrate deeper into the concrete (Table 7). The protection of concrete against intruding salts and water usually increases with the penetration depth of the impregnation agent [41].

3.4. Silane impregnation depth

The experimental results of the impregnation depth of silane surface treated concrete are shown in Table 7. It is obvious that the impregnation depth of the concrete that had been oven dried was deeper than the corresponding air dry concrete, and the impregnation depth of recycled aggregate concrete was deeper than that of natural aggregate concrete. It can also be concluded that the penetration depth of surface treated silane into concrete mainly depends on four factors: the type of hydrophobic agent applied, the porosity of the concrete, the initial moisture content and the surface treatment of the concrete substrate [38].

3.5. Drying shrinkage

Figs. 4 and 5 present the drying shrinkage results and the weight loss of the integral water repellent concrete, respectively. It can be seen that for the natural aggregate concrete, addition of silane emulsion did not have a significant influence on the shrinkage and weight loss. This is in agreement with the observation of Wittmann [37], who reported that shrinkage of plain and integral water repellent concrete was almost the same. Moreover, the drying shrinkage and weight loss of the integral water repellent recycled aggregate concrete was increased with an increase in silane content. The drying shrinkage and weight loss of RACI-1 was higher than those for the other types of concrete.

3.6. Carbonation depth

Fig. 6 presents the results of the carbonation depth of concrete at ages of up to 112 days. It is seen that at all test ages, the carbonation depth of the untreated recycled aggregate concrete was about two times higher than that of the natural aggregate concrete. The carbonation depth of the recycled aggregate concrete decreased significantly with the increase of the dosage of silane. Moreover, the carbonation depth of the silane surface treated recycled aggregate concrete was lower than the corresponding concrete prepared with integral silane treatment. This is consistent with the results of Basheer et al. [42] who found that the carbonation rate of concrete correlated well with its short-term water absorption values.

3.7. Chloride penetrability

The test results of the resistance to chloride ion penetration of concrete are shown in Fig. 7. The total charge passed for NACI-0.5, NACS-100 and NACS-200 was reduced by 0.4%, 7.0% and 30.4% respectively compared with NAC0. Moreover, the total charge passed for RACI-0.5 and RACI-1 was 1.3% and 36.3% respectively lower than that of RAC0, while the total charge passed of RACS-100 and RACS-200 was 41.4% and 68.4%, respectively, lower than that of RAC0. It can be seen that the silane treatment was very effective, especially for recycled aggregate concrete subjected to

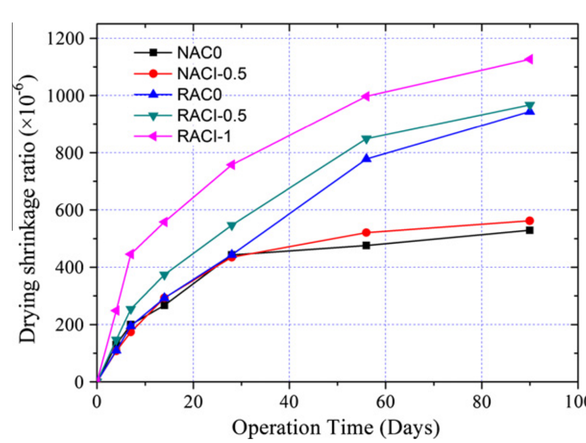

Fig. 4. Development of drying shrinkage of concrete.

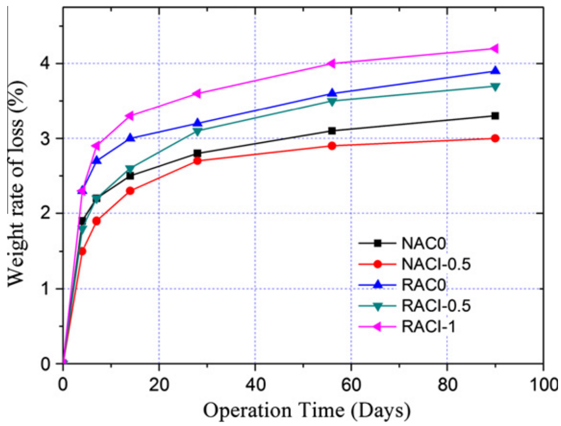

Fig. 5. Rate of weight loss of concrete.

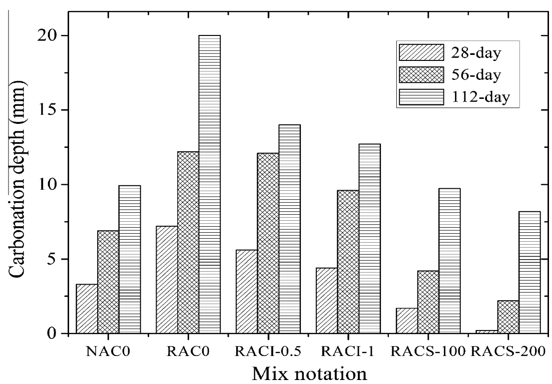

Fig. 6. Carbonation depth of concrete.

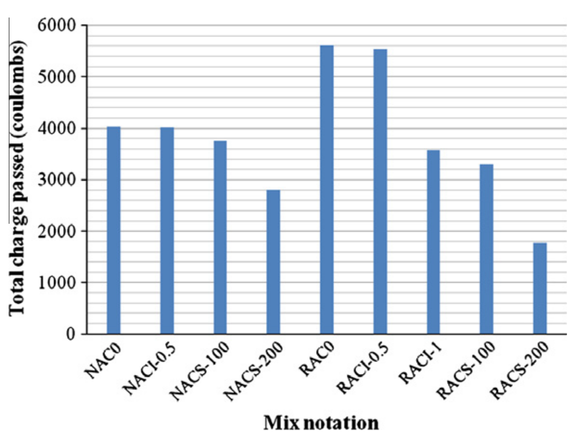

Fig. 7. Total charge passed through concrete.

surface water repellent treatment, in improving the concrete's resistance to chloride ion penetration.

4. Conclusion

Based on the above comprehensive experimental test results and discussion, the following conclusions can be drawn:

- The mechanical properties and durability of recycled aggregate concrete are lower than natural aggregate concrete when the same mix proportion is used.
- Both the integral water repellent method and the surface water repellent treatment method based on silane can improve the durability of recycled aggregate concrete.
- Compared with integral water repellent concrete, the surface water repellent treatment is more effective in reducing capillary water absorption and improving resistance to carbonation and chloride penetration.
- The surface water repellent treatment can achieve a larger impregnation depth of silane in recycled aggregate concrete than in natural aggregate concrete due to the higher porosity of the former. Hence the durability enhancement of recycled aggregate concrete subjected to surface water repellent treatment is more significant than that of natural aggregate concrete.
- The use of the integral water repellent treatment by using silane may significantly reduce the compressive strength of concrete.

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