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Long-term mechanical and durability properties of recycled aggregate concrete prepared with the incorporation of fly ash

Shi-Cong Kou [a,b], Chi-Sun Poon [a,*]

[a] Department of Civil and Environmental Engineering, The Hong Kong Polytechnic University, China
[b] Guangdong Provincial Key Laboratory of Durability for Marine Civil Engineering, College of Civil Engineering, Shenzhen University, China

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ABSTRACT

This paper presents the findings of a long-term study on the mechanical and durability properties of concrete prepared with 0%, 50% and 100% recycled concrete aggregate that were cured in water or outdoor exposure conditions for 10 years. The recycled aggregate concrete (RAC) was prepared by using 25%, 35% and 55% class-F fly ash, as cement replacements. It was found that, after 10 years, the compressive strength and modulus of elasticity of the concrete prepared with 100% recycled concrete aggregate was still lower than that of the control concrete. Over this period, the highest gain in compressive strength and modulus of elasticity was recorded for the concrete mixture prepared with 55% fly ash. Fly ash improved the resistance to chloride ion penetration but it also increased the carbonation depth of the concrete.

1. Introduction

The use of recycled aggregates (RAs) in structural concrete production is still limited probably because of the limited knowledge of the long-term and durability performance of recycled aggregate concrete (RAC). Much data are available on the short to medium-term (up to 90 days) mechanical properties of RAC [1–12]. The use of recycled aggregate generally increases the drying shrinkage, creep and water sorptivity and decreases the compressive strength and modulus of elasticity of recycled aggregate concrete compared to those of natural aggregate concrete [9–12]. It is known that when using the same water to cement ratio, as RA percentages increase, the mechanical properties of the RAC deteriorate. However, reducing the effective water–cement ratio in concrete production or adding fly ash (FA) as a supplementary binder material can improve the mechanical and durability properties such as compressive and tensile splitting strength, modulus of elasticity, drying shrinkage and resistance to chloride ion penetration of RAC prepared with recycled concrete aggregate [13–15].

There is a need to obtain more information on the long-term properties of RAC, including RAC incorporating fly ash. This paper presents the long-term experimental results of the use of fly ash as a cement replacement in proportion to the RAC. The effects of fly ash on the long-term mechanical and durability properties, such as compressive strength, tensile splitting strength, static modulus of elasticity, carbonation depth and resistance to chloride ion penetration, of RAC that were cured in water or outdoor exposure conditions for 10 years were investigated.

2. Experimental details

2.1. Materials

2.1.1. Binders

The cementitious materials used in this study were Portland cement (PC) equivalent to ASTM Type I, ASTM Class-F fly ash (FA) obtained from a local coal-fired power plant. The chemical composition and physical properties of the cement and FA are listed in Table 1.

2.1.2. 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. The recycled aggregate contained almost entirely of crushed concrete rubbles obtained mainly from building demolition projects. To ascertain that the recycled aggregate contained only crushed concrete, a hand picking step was also made to select crushed concrete lumps (>100 mm 100% old concrete) from the recycled aggregate obtained from the recycling plant and they were further crushed in the laboratory using manual and mechanical means. The nominal sizes of the natural and recycled coarse aggregates were 20 and 10 mm and their particle size distributions conformed to the requirements of BS 882 (1985). The physical and mechanical properties of the coarse

* Corresponding author. Tel.: +86 852 2766 6024; fax: +86 852 2334 6389.
E-mail address: cecspoon@polyu.edu.hk (C.-S. Poon).

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Table 1
Chemical compositions of cement and fly ash.

Contents	Cement	Fly ash
SiO_2	21.0	56.79
Al_2O_3	5.9	28.21
Fe_2O_3	3.4	5.31
CaO	64.7	<3
MgO	0.9	5.21
SO_3	2.6	0.68
Loss on ignition (%)	1.2	3.90
Specific gravity (g/cm^3)	3.15	2.31
Specific surface area (cm^2/g)	3520	3960

aggregate are shown in Table 2. The porosity of the aggregates was determined by using mercury intrusion porosimetry (MIP). River sand was used as the fine aggregate in the concrete mixtures.

2.2. Concrete mixtures

Concrete mixtures with a target initial slump of 120 mm were prepared in the laboratory. The concrete mixtures were prepared with a W/B ratio and cement content of 0.55 and 410 kg/m^3 (control concrete) respectively. Fly ash was used as 0%, 25%, 35% and 55% by weight replacements of cement and recycled aggregate was used as 0%, 50% and 100% by weight replacements of the natural coarse aggregate. The absolute volume method was adopted to design the mix proportions of the concrete mixtures as shown in Table 3. In the concrete mixtures, the 10 and 20 mm coarse aggregates were used in a ratio of 1:2.

2.3. Specimens casting and curing

For each concrete mixture, 100 mm cubes and 100∅ × 200 mm cylinders were cast. The cubes were used to determine the compressive strength and carbonation depth. The cylinders were used to evaluate the tensile splitting strength, the static modulus of elasticity and resistance to chloride ion penetration.

All the specimens were cast in steel moulds and compacted using a vibrating table. After demoulding, half of the specimens were cured in a water-curing tank at 27 ± 1 °C, and the other half were placed under outdoor exposure conditions near the laboratory until the ages of testing. The annual meteorological conditions in Hong Kong from 1999 to 2008 are listed in Table 4.

2.4. Tests

2.4.1. Compressive and tensile splitting strengths

The compressive and splitting tensile strengths of concrete were determined using a Denison compression machine with a loading capacity of 3000 kN. The loading rates applied in the compressive and splitting tensile tests were 200 kN/min and 57 kN/min, respectively. The compressive and splitting tensile strengths were measured at the ages of 28 days, 1 year, 3 years 5 years and 10 years.

2.4.2. Static modulus of elasticity

The static modulus of elasticity of the concrete was determined in accordance with ASTM C 469 (2002). This test was carried out on the concrete specimens at the ages of 28 days, 1 year, 3 years, 5 years and 10 years.

2.4.3. Resistance to rapid chloride ion penetration

This test was carried out on the outdoor exposed concrete specimens at the ages of 28 days, 1 year and 10 years. The ASTM 1202 rapid test method was employed to rank the chloride penetration resistance of the concrete by applying a potential difference of 60 V DC to measure the charge that had passed through the specimen. The tested concrete discs were slices of 51 mm thick, cut from the middle portion of the initially prepared 100∅ × 200 mm specimens.

2.4.4. Carbonation depth

At the ages of 28 days, 1 year, 3 years, 5 years and 10 years, the depth of carbonation of the outdoor exposed concrete specimens was determined by spraying the surface of a freshly broken concrete cube specimen with a solution of phenolphthalein [16–19]. In the non-carbonated part of the specimen where the concrete was still highly alkaline, a purple–red colouration was observed,

Table 2
Properties of natural and recycled aggregates.

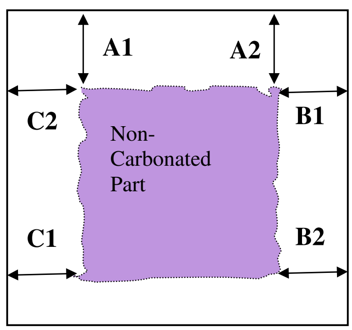
Type	Nominal size (mm)	Density (Mg/m^3)	Water absorption (%)	Strength – 10% fines value (kN)	MIP porosity (%)
Crushed granite	10	2.62	1.12	159	1.62
	20	2.62	1.11		
Recycled aggregate	10	2.35	7.19	110	8.46
	20	2.45	5.34		

Table 3
Proportioning of the concrete mixtures.

Notation	Fly ash (%)	RA (%)	Constituents (kg/m^3)						Actual slump (mm)
			Water	Cement	Fly ash	Sand	Granite	RA	
R0	0	0	225	410	0	642	1048	0	150
R50	0	50	225	410	0	642	524	506	170
R100	0	100	225	410	0	642	0	1017	195
R0 F25	25	0	225	307.5	102.5	611	1048	0	165
R50F25	25	50	225	307.5	102.5	611	524	506	190
R100F25	25	100	225	307.5	102.5	611	0	1017	210
R0F35	35	0	225	266.5	143.5	598	1048	0	185
R50F35	35	50	225	266.5	143.5	598	524	506	225
R100F35	35	100	225	266.5	143.5	598	0	1017	250
R0F55	55	0	225	184.5	225.5	530	1048	0	190
R50F55	55	50	225	184.5	225.5	530	524	506	230
R100F55	55	100	225	184.5	225.5	530	0	1017	255

Table 4
Annual values of meteorological elements of Hong Kong from 1999 to 2008. *Source*: Hong Kong observation

Year	Air temperature			Wet-bulb temperature	Dew point	Relative humidity	Pressure	Rainfall	Cloud amount
	Mean maximum (°C)	Mean (°C)	Mean minimum (°C)	Mean (°C)	Mean (°C)	Mean (%)	Mean (HPa)	Total (mm)	Mean (%)
1999	26.2	23.8	21.8	20.8	18.9	75	1011.9	2129.1	67
2000	25.5	23.3	21.5	20.7	19.1	78	1011.9	2752.3	69
2001	25.8	23.6	21.8	21.0	19.3	78	1012.2	3091.8	69
2002	26.0	23.9	22.1	21.4	19.9	79	1012.9	2490.0	70
2003	25.8	23.6	21.9	20.9	19.3	77	1013.2	1941.9	62
2004	25.6	23.4	21.7	20.6	19.0	77	1013.1	1738.6	62
2005	25.4	23.3	21.4	20.8	19.3	79	1013.0	3214.5	71
2006	25.8	23.5	21.7	21.2	19.8	80	1012.7	2627.8	70
2007	26.4	23.7	21.7	20.8	19.1	77	1012.8	1706.9	68
2008	25.8	23.1	21.1	20.3	18.5	77	1012.8	3066.2	67



$$D = \frac{A1 + A2 + B1 + B2 + C1 + C2}{6}$$

Fig. 1. Cross section of a concrete cube specimen after carbonation.

while in the carbonated part, the original grey concrete colour was observed. Each result reported is the average depth of carbonation '*D*' measured. The mean value of the depth of carbonation '*D*' is shown schematically in Fig. 1.

3. Results and discussion

3.1. Compressive strength

The results of the compressive strength of the concrete under both curing conditions at the ages of up to 10 years are shown in Table 5. Each presented value is the average of three measurements. It can be seen that at all the test ages the compressive strength of the water cured RAC was lower than that of the NAC. The compressive strength decreased with increase in recycled aggregate content. At 28 days, The strength of the concretes was reduced by 12.6% and 21.6%, respectively, in comparison to the strength of the control concrete. This is due to the recycled aggregates being more porous and weaker than the natural aggregate. However, the reduction decreased with increasing curing age. After 10 years, the control concrete had a compressive strength of 67.5 MPa, whereas R50 and R100 had compressive strengths of 65.3 and 62.7 MPa, respectively with a reduction of 4.3% and 8.1%, respectively. Moreover, at all the tested ages, the compressive strength of the concrete exposed outdoors was lower than that of the water cured concrete.

In general, the concrete incorporating fly ash underwent a reduction in early age compressive strength (for both NAC and RAC). The compressive strength decreased with increase in fly ash content. At 28 days, the strength of the concrete mixture R0 with 25%, 35% and 55% of fly ash was reduced by 10.3%, 16.3% and 25.5%, respectively, in comparison to the strength of the control concrete without fly ash. Moreover, the compressive strength of concrete mixture R100 with 25%, 35% and 55% of fly ash was reduced by 3.4%, 15.5% and 30.2%, respectively, in comparison to the strength of the concrete without fly ash. The compressive strength of both the natural and recycled aggregate concrete incorporating fly ash with standard water curing significantly increased with curing age.

After 1 year, the strength of the control concrete (R0), R50 and R100 increased by 6.7%, 7.8% and 9.9%, in comparison to the

Table 5
Compressive strength of the concrete mixtures.

Notation	Fly ash (%)	R A (%)	Compressive strength (MPa)									
			28-day		1-year		3-year		5-year		10-year	
			Water cured	Air cured	Water cured	Air cured	Water cured	Air cured	Water cured	Air cured	Water cured	Air cured
R0	0	0	48.6	46.7	56.5	53.3	60.8	55.9	64.2	58.4	67.5	61.3
R50	0	50	42.5	41.3	51.2	47.1	55.6	50.6	61.4	55.1	65.3	57.5
R100	0	100	38.1	36.5	46.6	43.1	51.1	46.2	56.3	50.8	62.7	52.2
R0 F25	25	0	43.6	42.3	60.3	57.5	64.5	61.2	68.4	63.4	71.1	65.9
R50 F25	25	50	41.7	39.8	55.2	52.4	59.2	56.8	65.8	59.4	70.2	63.1
R100F25	25	100	36.8	35.2	51.2	47.6	55.3	52.6	60.3	55.5	68.5	59.1
R0 F35	35	0	40.7	38.9	50.3	46.6	61.2	55.9	66.5	59.8	69.2	63.4
R50 F35	35	50	37.1	35.9	47.6	42.3	57.2	51.1	62.3	56.7	67.5	58.8
R100F35	35	100	32.2	29.7	42.4	37.5	53.1	48.3	59.3	52.3	65.9	56.3
R0F55	55	0	36.2	34.9	48.6	41.2	57.6	52.2	62.3	55.1	67.1	60.4
R50F55	55	50	31.4	29.9	43.9	38.6	52.1	46.4	57.6	50.3	62.9	54.8
R100F55	55	100	26.6	25.6	35.1	32.5	43.9	41.1	50.8	45.8	55.6	49.4

strength of the corresponding concrete mixtures without fly ash. The compressive strengths of the concrete mixtures with 35% and 55% of fly ash were still lower than the corresponding concrete without fly ash.

After 3 years, the strength of the control concrete (R0), R50 and R100 increased by 0.9%, 2.9% and 3.9%, in comparison to the strength of the corresponding concrete mixtures without fly ash. The compressive strengths of the concrete mixtures with 55% of fly ash were still lower than the corresponding concrete without fly ash.

After 10 years, the strengths of the concrete mixtures with 25% fly ash increased by 5.3%, 7.5% and 9.3%, respectively. Moreover, the strengths of the corresponding concrete mixtures with 35% fly ash increased by 2.5%, 3.4% and 5.1%, respectively. However, the strengths of the concrete mixtures with 55% fly ash were still 0.6%, 1.4% and 11.30%, respectively lower than the control concrete.

Although the compressive strength of the concrete exposed outdoors was lower than that of the corresponding concrete cured in water, similar trends of strength development were observed.

Fig. 2 shows the compressive strength gain of the concrete from the 28th day to 1, 3, 5 and 10 years with standard water curing. The highest percentage gain in compressive strength was recorded for the 55% fly ash RAC followed by 35% fly ash RAC, 25% fly ash RAC, RAC and the control concrete. The compressive strengths of the control concretes, R0F25, R0F35 and R0F55 increased by 38.9%, 63.1%, 70.0% and 85.4%, respectively between 28 days and 10 years, and 16.3%, 38.3%, 23.6% and 34.3% of the increases, respectively, occurred in the first year. The concrete mixtures R100, R100F25, R100F35 and R100F55 had strength gains of 64.6%, 86.1%, 104.7% and 109%, respectively, between 28 days and 10 years, and 22.3%, 39.1%, 31.1% and 32.0% of the gains, respectively, were in the first year.

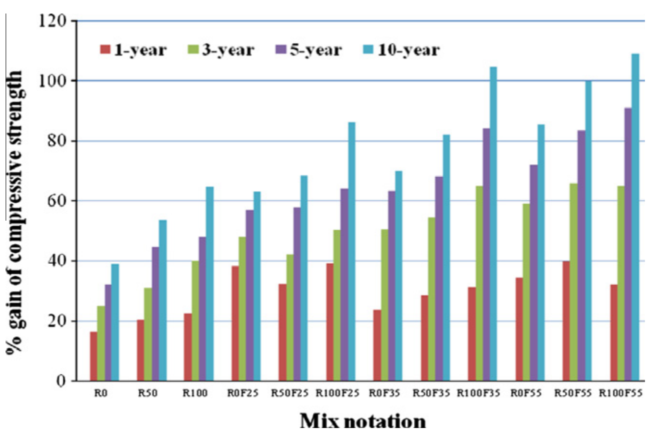


Fig. 2. % Gain of compressive strength of concrete mixture with standard water curing.

The concrete mixture R100F55 had the highest compressive strength gain and this might be attributed to incorporating fly ash into the RAC. Due to the recycled aggregates being more porous, some part of the cement and fly ash would be able to penetrate into the aggregate, which subsequently would increase the bond strength between the aggregates and the hydrated cementitious matrix. With the presence of fly ash, the cracks in the recycled aggregates were reduced due to the healing effect after a prolonged period of curing of the fly ash blended cement pastes. Therefore the concrete made with recycled concrete aggregate, and the quality of the interfacial transition zone, was better than that of the old paste and natural aggregate concrete. The bond between the new cement paste and recycled concrete aggregate was enhanced.

3.2. Splitting tensile strength

The splitting tensile strengths of the concrete cured in water and the outdoor environment at the ages up to 10 years are shown in Table 6. The results show that before 1 year the variation in splitting tensile strength with recycled aggregate content was similar to that observed for compressive strength. The splitting tensile strength decreased with increase in recycled aggregate and fly ash content. At 28 days, the splitting tensile strength of the control mixture (R0) was higher 5.0% and 7.5%, respectively, than that of the concrete mixtures R50 and R100 incorporating 50% and 100% recycled aggregate.

However, comparing the results at 1 year and 10 years shows that there was continuous and significant improvement in the splitting tensile strength of RAC beyond the age of 1 year. At 1 year, the splitting tensile strengths of the concrete mixtures with 100% recycled aggregate were higher than that of the control mixtures. Moreover, at all the test ages the splitting tensile strength of the concrete mixture exposed outdoors was lower than that of the corresponding concrete mixture with standard water curing.

Fig. 3 shows the splitting tensile strength gain of the concrete from 28 days to 1, 3, 5 and 10 years with standard water curing. It can be seen that the splitting tensile strengths of the control concretes, R0F25, R0F35 and R0F55 increased by 38.9%, 43.0%, 44.1% and 39.8%, respectively, between 28 days and 10 years, and 3.9%, 11.3%, 8.3% and 8.6% of the increase, respectively, occurred in the first year. The concrete mixtures R100, R100F25, R100F35 and

Table 6
Tensile splitting strength of the concrete mixtures.

Notation	Fly ash (%)	RA (%)	Tensile splitting strength (MPa)									
			28-day		1-year		3-year		5-year		10-year	
			Water cured	Air cured	Water cured	Air cured	Water cured	Air cured	Water cured	Air cured	Water cured	Air cured
R0	0	0	3.32	3.21	3.45	3.31	3.76	3.54	4.23	4.01	4.61	4.25
R50	0	50	3.16	3.09	3.51	3.41	3.92	3.62	4.41	4.14	4.71	4.32
R100	0	100	3.06	2.98	3.56	3.44	4.12	3.78	4.45	4.18	4.83	4.41
R0 F25	25	0	3.28	3.14	3.65	3.42	3.89	3.58	4.25	3.92	4.69	4.27
R50 F25	25	50	3.09	3.01	3.62	3.46	3.94	3.85	4.41	4.15	4.75	4.32
R100F25	25	100	2.96	2.91	3.75	3.54	4.12	3.91	4.40	4.21	4.81	4.49
R0 F35	35	0	2.90	2.81	3.14	3.02	3.36	3.18	3.68	3.42	4.18	3.77
R50 F35	35	50	2.78	2.72	3.24	3.11	3.38	3.21	3.72	3.53	4.24	3.88
R100F35	35	100	2.56	2.48	3.31	3.12	3.47	3.26	3.77	3.55	4.28	3.91
R0F55	55	0	2.66	2.58	2.89	2.73	3.04	2.91	3.22	3.01	3.72	3.30
F50F55	55	50	2.42	2.36	2.93	2.80	3.12	2.96	3.28	3.05	3.75	3.36
R100F55	55	100	2.23	2.19	3.01	2.89	3.24	3.11	3.41	3.14	3.81	3.48

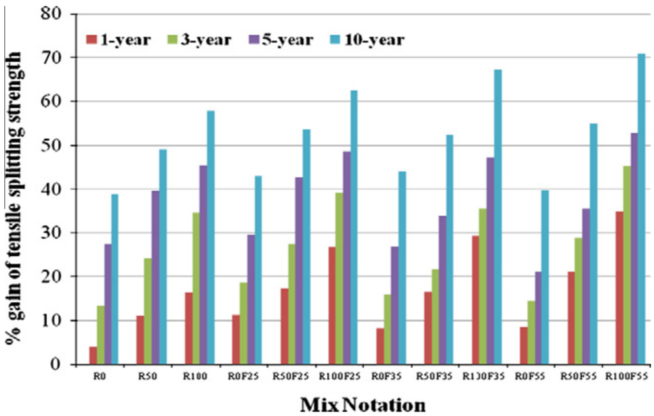


Fig. 3. % Gain of tensile splitting strength of concrete mixture with standard water curing.

R100F55 had strength gains of 57.8%, 62.5%, 67.2% and 70.9%, respectively between 28 days and 10 years, and 16.3%, 26.7%, 29.3% and 35.0% of the gains, respectively, were in the first year.

After 10 years, the concrete mixture R100F25 with 100% recycled aggregate and 25% fly ash had the highest splitting tensile strength (4.81 MPa), and the concrete mixture R100F55 with 100% recycled aggregate and 55% fly ash had the highest strength gain (70.9%). This might also be due to the recycled aggregate concrete incorporating fly ash having improved the microstructure of the Interfacial Transition Zone (ITZ) and increased the bond strength between the new binder and the aggregates. According to Maso [20] increasing the bond strength increases the concrete strength and an increase in bond strength improves the tensile strength more than the compressive strength.

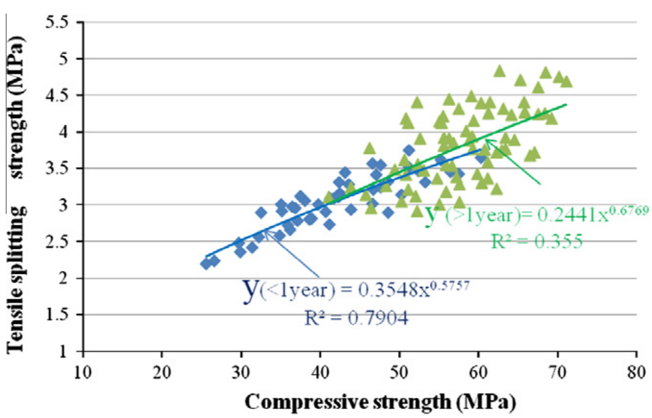


Fig. 4. Relationship between tensile splitting strength and compressive strength of concrete.

Fig. 4 shows the relationship between the splitting tensile strength and the compressive strength of the concrete before and after 1 year. The results show that there are good correlations between the compressive strength and the splitting tensile strength for the concrete mixtures before 1 year. However, after 1 year the low correlation coefficient (0.36) obtained from regression analysis indicates that the correlation between compressive strength and splitting strength was poor due to fly ash and recycled aggregate significantly improved the splitting tensile strength of the concrete. This further demonstrates the beneficial effect of using recycled aggregates together with fly ash in concrete.

3.3. Static elastic modulus

The test results of the modulus of elasticity of the concrete are shown in Table 7. The results indicate that use of large proportions of recycled aggregate reduced the modulus of the concrete compared to that of the control mixture at the ages up to 10 years. At 28 days, the modulus of elasticity values of concrete mixtures R50 and R100 incorporating 50% and 100% recycled aggregate was reduced by 12.6% and 25.2%, respectively, than that of the control mixture. However, the 1-year and 10-year results indicated that the modulus of elasticity values of the concrete mixtures with recycled aggregate increased with age. Moreover, the modulus of elasticity of the concrete decreased with increase in fly ash content. At all the test ages, the concrete mixture with 55% fly ash had the lowest modulus of elasticity.

Fig. 5 shows the percentage gains in the modulus of elasticity of the concrete from 28 days to 1, 3, 5 and 10 years with standard water curing. The trend is: 55% fly ash RAC > 35% fly ash RAC > 25% fly ash RAC > RAC and >control concrete. The concrete mixtures R100, R100F25, R100F35 and R100F55 had gains of 31.3%, 33.9%, 40.7% and 46.1%, respectively, between 28 days and 10 years, and 7.2%, 7.9%, 11.2% and 14.8% of the gain, respectively, was in the first year.

Fig. 6 shows the relationship between the modulus of elasticity and the compressive strength of the concrete. The results show that there are good correlations between the compressive strength and the modulus of elasticity for all the concrete mixtures. Furthermore, the ACI 318-08 equation for estimating the modulus of elasticity in terms of compressive strength of natural concrete is also

Table 7
Static elastic modulus of the concrete mixtures.

Notation	Fly ash (%)	RA (%)	Static elastic modulus (GPa)									
			28-day		1-year		3-year		5-year		10-year	
			Water cured	Air cured	Water cured	Air cured	Water cured	Air cured	Water cured	Air cured	Water cured	Air cured
R0	0	0	30.1	29.5	32.1	30.9	33.6	32.4	35.8	34.3	37.6	35.1
R50	0	50	26.3	25.8	28.1	27.4	30.2	29.3	31.6	31.2	33.7	32.4
R100	0	100	22.5	21.6	24.1	22.8	25.4	24.9	27.8	26.3	29.5	27.4
R0 F25	25	0	29.1	28.5	31.3	29.8	33.9	32.1	35.2	34.1	37.0	36.5
R50 F25	25	50	27.7	27.1	30.2	28.6	31.1	30.0	34.2	32.0	36.1	35.3
R100F25	25	100	23.9	23.1	25.8	24.6	27.4	26.3	29.2	28.4	33.2	31.1
R0 F35	35	0	28.5	27.4	30.9	29.2	31.8	30.2	34.6	33.1	36.5	34.2
R50 F35	35	50	24.8	23.9	27.2	25.8	28.3	27.4	30.8	29.2	32.8	30.5
R100F35	35	100	21.6	20.7	24.0	22.6	26.7	26.5	28.6	27.3	30.4	28.1
R0F55	55	0	26.4	25.4	28.9	27.0	29.5	28.3	32.6	31.1	34.4	32.4
F50F55	55	50	22.1	21.3	24.8	23.6	26.3	25.4	28.7	27.5	31.5	29.6
R100F55	55	100	20.4	19.5	23.4	22.3	24.8	24.6	27.2	26.1	29.8	27.6

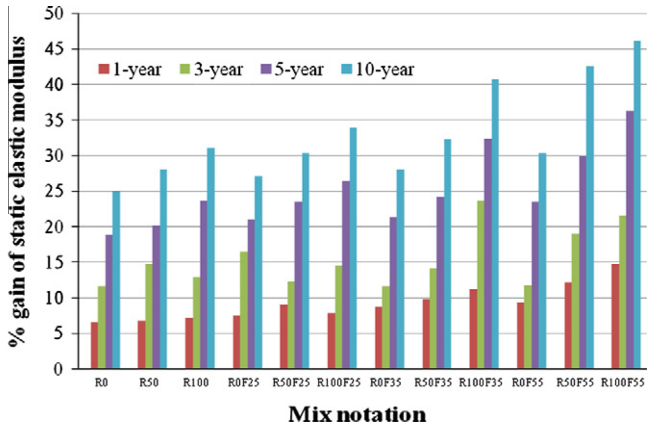


Fig. 5. % Gain of static elastic modulus of concrete mixture with standard water curing.

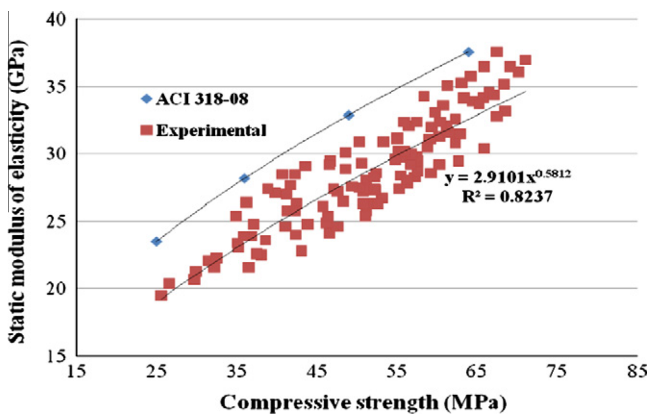


Fig. 6. Relationship between modulus of elasticity and compressive strength of concrete.

plotted in Fig. 6. It is clear that the equation overestimates the modulus of elasticity of all the test results.

3.4. Resistance to chloride ion penetration

The results (only for the outdoor exposed concrete) on the resistance to chloride ion penetration at the ages up to 10 years are given in Fig. 7. Recycled aggregate decreased the resistance to chloride ion penetration of the concrete at all test ages. The incorporation of fly ash significantly increased the resistance to the chloride ion penetration of both the natural and recycled aggregate concrete at all test ages. The effectiveness of fly ash was further demonstrated by comparing the results of R100 with that of R100F25, R100R35 and R100F55, respectively (by 28.1%, 33.0% and 43.1%, respectively). After 10 years, further reductions in total charge passed were observed. The fact that the incorporation of fly ash improves the resistance to chloride penetration of concrete has been confirmed by many research studies [21,22]. This is due to the reduction in the average pore size of the paste and the improvement of the interfacial transition zone [21].

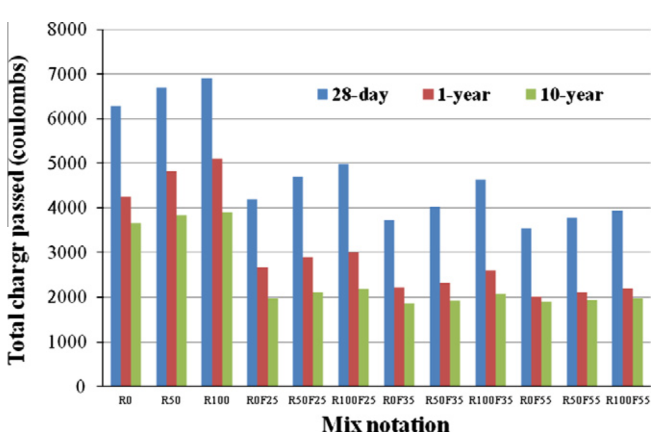


Fig. 7. Total charge passed in coulombs of outdoor exposed concrete.

Fig. 8 shows the percentage reduction of total charge passed of the outdoor exposed concrete from 28 days to 10 years. When compared with the 28th day results, at 10 years the reduction in the charge passed decreased with increase in fly ash content. The concrete incorporating 55% of fly ash had the lowest reduction in the charge passed. This might be due to the concrete mixture with 55% fly ash having the lowest amount of residual calcium hydroxide. The resistance to chloride ion penetration of concrete increases when calcium hydroxide is carbonated to calcium carbonate. This finding is consistent with the results of Chindaprasirt et al. [23] who reported that exposure to carbon dioxide significantly decreases the chloride ion penetration resistance of mortars containing pozzolans.

3.5. Carbonation depth

The results of carbonation depth of the outdoor exposed concrete at the ages of up to 10 years are listed in Table 8. Fig. 9 shows

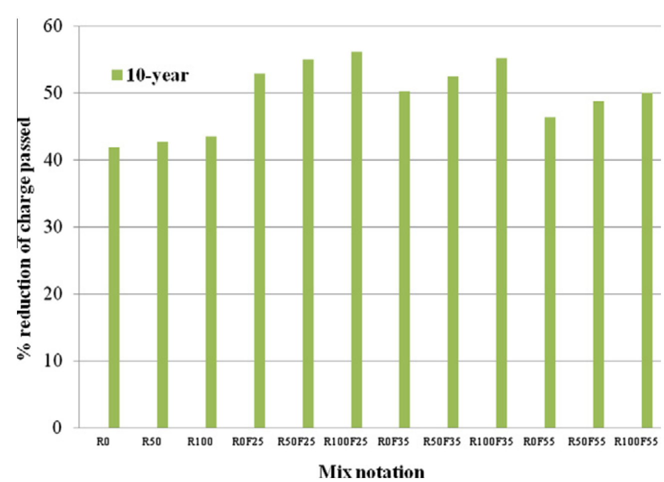


Fig. 8. % Reduction of total charge passed in coulombs of outdoor exposed concrete.

Table 8
Carbonation depth of outdoor exposed concrete.

Notation	Fly ash (%)	RA (%)	Carbonation depth (mm)				
			28-day	1-year	3-year	5-year	10-year
R0	0	0	3.22	5.03	6.13	8.21	12.09
R50	0	50	3.35	5.25	6.98	8.78	12.79
R100	0	100	3.48	5.58	7.68	9.46	13.36
R0 F25	25	0	3.42	5.32	7.18	9.33	13.61
R50 F25	25	50	3.53	5.64	7.86	9.82	14.43
R100F25	25	100	3.76	6.13	8.94	10.57	15.54
R0 F35	35	0	3.68	5.95	8.32	10.65	15.68
R50 F35	35	50	3.95	6.62	9.13	11.72	17.22
R100F35	35	100	4.15	7.12	10.68	13.75	18.37
R0F55	55	0	4.49	7.62	10.47	13.71	20.25
F50F55	55	50	4.74	8.23	11.36	15.35	22.64
R100F55	55	100	5.15	9.05	13.09	18.54	25.25

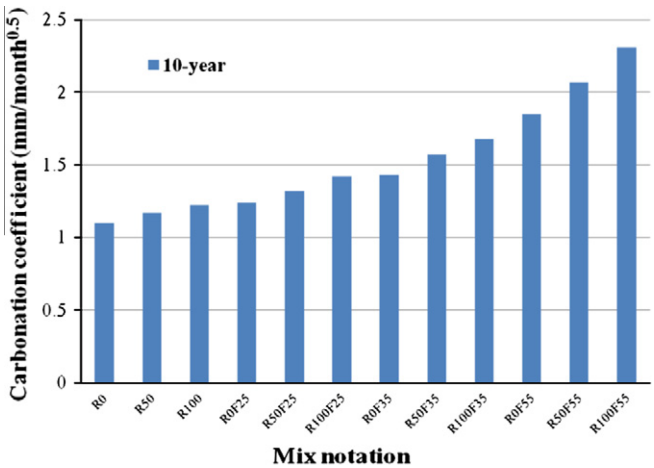


Fig. 9. Carbonation coefficient of concrete after 10 years outdoor exposure.

the carbonation coefficients calculated by using the formula: $K = D/t^{0.5}$ (mm/month$^{0.5}$) after 10 years of exposure. It can be observed that the use of recycled aggregate in concrete decreased the resistance of concrete to carbonation at all test ages. This may be attributed to the recycled aggregate being more porous. This is consistent with the results of Evangelista and de Brito [24] who reported that the carbonation depth of concrete increased with increase in recycled fine aggregate replacement ratio.

The results also show that incorporating fly ash increased the carbonation depth and the carbonation depth increased with increase in fly ash content. This is largely attributed to the lower calcium hydroxide content in the fly ash concrete. This is consistent with the findings of other researchers [25–28]. After 10 years of outdoor exposure, when compared with the concrete prepared without fly ash, at the fly ash content of 55%, the carbonation coefficient was approximately 1.68 times for the natural aggregate concrete and 1.89 times for the recycled aggregate concrete. These findings are in agreement with the results of Khunthongkeaw et al. [29] who reported that at a fly ash content of 50%, the carbonation coefficient was approximately 2–3 times as large as that of the OPC only concrete mixture.

4. Conclusion

In this paper, the effect of fly ash on the properties of 10-year-old concrete made with recycled aggregate was investigated. Based on the results and discussion, the following conclusions can be drawn:

1. Due to pozzolanic reaction between fly ash and $Ca(OH)_2$ in the RAC, the long-term mechanical and durability properties of the concrete were significantly improved.
2. After 10 years, the compressive strength of recycled aggregate concrete was still lower than that of corresponding natural aggregate concrete. However, the reduction in the strength decreased with increase in curing age. The concrete mixture with 100% recycled concrete aggregate had the highest strength gain of more than 60% between 28 days and 5 years.
3. At 1 year, the splitting tensile strengths of the concrete mixtures prepared with 100% recycled aggregate were higher than that of the corresponding natural aggregate concrete. After 5 years, the concrete mixture with 100% recycled concrete aggregate had the highest splitting tensile strength and strength gain (from 16.3% to 45.4%).
4. Compared to that of the control mixture, the use of large proportions of recycled aggregate in concrete reduced the modulus after 10 years of curing.
5. After 10 years of outdoor exposure, the resistance to chloride ion penetration of recycled aggregate concrete was still lower than that of the normal aggregate concrete. The concrete mixture incorporating fly ash significantly improved the resistance to chloride ion penetration.
6. The carbonation coefficient of concrete increased with recycled aggregate content and fly ash content.
7. The study results suggest that the optimal mix proportions for RAC mixtures are: 50% RA as a replacement of natural aggregates and 25% FA as a replacement of OPC.

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