Compressive Strength, Pore Size Distribution and Chloride-ion Penetration of Recycled Aggregate Concrete Incorporating Class-F Fly Ash*

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Abstract: *The effects of fly ash on the compressive strength, pore size distribution and chloride-ion penetration of recycled aggregate concrete were investigated. Two series of concrete mixtures were prepared. The concrete mixtures in series I had a water-to-binder ratio and a cement content of* 0.55 *and* 410 *kg/m*^{3}, *respectively. The concrete mixtures in series II had a water-to-binder ratio and a cement content of* 0.45 *and* 400 *kg/m*^{3} *respectively. Recycled aggregate was used as 20%, 50%, and 100% replacements of natural coarse aggregate in the concrete mixtures in both series. In addition, fly ash was used as 0%, 25% and 35% by weight replacements of cement. The results show that the compressive strengths of the concrete decreased as the recycled aggregate and the fly ash contents increased. The total porosity and average porosity diameter of the concrete increased as the recycled aggregate content increased. Furthermore, an increase in the recycled aggregate content decreased the resistance to chloride ion penetration. Nevertheless, the replacement of cement by 25% fly ash improved the resistance to chloride ion penetration and pore diameters and reduced the total porosity of the recycled aggregate concrete.*

Key words: *durability properties; recycled aggregate concrete; fly ash*

1 Introduction

Recycled aggregates are produced from the re-processing of mineral waste materials, with the largest source being construction and demolition (C&D) waste. They have been used as a replacement of the natural aggregate for a number of years. The potential benefits and drawbacks of using recycled aggregates in concrete are well understood and extensively documented[1-3]. As recycled aggregate concrete can be regarded as porous concretes, having permeability values that are twice as large as those of ordinary concretes, the use of recycled aggregate generally decreases the concrete mechanical and physical properties as the percentage of replacement of natural aggregates by recycled concrete aggregates increases[4-6]. Dhir *et al*[7] showed that the compressive strength of concrete with 100% coarse and 50% fine recycled aggregates was between 20%-30% lower than that of the corresponding natural concrete.

Only a limited amount of research results on the pore size distribution of recycled aggregate concrete are available. Uchikawa *et al*[8] reported that tests of mercury intrusion porosimetry (MIP) of recycled aggregate concrete showed an increase in the total volume of pores, especially in larger pores (> 100 nm). Gomez-Soberon[9] presented the pore size distribution, theoretical pore diameters, critical pore ratio and the surface area of recycled aggregate concrete with varying replacement levels of natural aggregate by recycled coarse and fine aggregates (55% coarse recycled gravel + 45% recycled fine gravel). He indicate that the porosity increased considerably when natural aggregate was replaced by recycled aggregate. Additionally, a reduction in the mechanical properties of the recycled aggregate concrete was seen.

It is also widely accepted that there is an inverse correlation between the volume of pores and the strength and durability of the concrete, and this relationship should also take into account the distribution of the pore size and the interconnection among them[10-12], But there is a need to gain more information on the strength and durability of fly ash recycled aggregate concrete and fly ash can be used to improve the pore size and pore shapes of the concrete.

2 Experimental

2.1 Materials

ASTM Type I portland cement and a low-calcium fly ash equivalent to ASTM Class F were used and the corresponding properties are shown in Tables 1 and 2.

Natural and recycled aggregates were used as the coarse aggregate in the concrete mixtures. In this study, locally available crushed granite was used as the natural aggregate and recycled aggregate sourced from a recycling

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plant in Hong Kong was used. According to the quality control requirements of the recycling facility, the recycled aggregate contained less than 0.5% by weight of wood and particles less dense than water and less than 1% by weight of other foreign materials. Therefore, the recycled aggregate used in this study could be considered as recycled concrete aggregate. The nominal sizes of both the natural and recycled aggregates were 20 and 10 mm. Their particle size distributions conformed to the requirements of BS 882[13]. The corresponding physical and mechanical properties of the coarse aggregates are shown in Table 3 where the porosity of the aggregates was determined using mercury intrusion porosimetry (MIP). Moreover, river sand with a fineness modulus of 2.11 was used as the fine aggregate in the concrete mixtures.

Table 1 Chemical compositions of cement and fly ash

Material	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
Fly ash	3.90	56.79	5.31	28.21	< 3	5.21	0.68

Table 2 Physical properties of cement and fly ash

Property	Material	
	Cement	Fly ash
Density/(g/cm^3)	3.16	2.31
Specific surface area/(cm^2/g)	3519.5	3960

For the series II concrete mixtures, a sulfonated naphthalene formaldehyde condensate (Darex Super 20) obtained from Hong Kong Grace Construction Products was used. This superplasticizer was available as a dark-brown 40%-42% solids aqueous solution with a density of 1310 kg/m^3.

Table 3 Properties of the aggregates

Property	Size of BS test sieve/mm	Percentage passing/%				
		20 mm granite	10 mm granite	20 mm recycled aggregate	10 mm recycled aggregate	Sand
Sieve analysis	37.5	100	-	100	-	-
	20	95	-	96	-	-
	14	18	100	19	100	-
	10	4	94	4	96	100
	5	-	21	-	20	99
	2.36	-	4	-	4	96
	1.18	-	-	-	-	87
	0.6	-	-	-	-	70
	0.3	-	-	-	-	26
	0.15	-	-	-	-	2
Density/(g/cm^3)		2.62	2.62	2.58	2.49	2.63
Strength (10% fines kN)		159		126		-
Porosity (measured by MIP)		1.62		8.69		-
Water absorption/%		1.11	1.12	3.52	4.26	0.87

Table 4 Proportions of the concrete mixtures series I

Notation	Fly ash/%	Recycled aggregate/%	Constituent/(kg/m^3)				
			Water	Total cementitious material	Sand	Granite	Recycled aggregate
R0	0	0	225	410	642	1048	0
R20	0	20	225	410	642	840	204
R50	0	50	225	410	642	524	506
R100	0	100	225	410	642	0	1017
r-R0 F25	25	0	225	410	611	1048	0
r-R20F25	25	20	225	410	611	840	204
r-R50F25	25	50	225	410	611	524	506
r-R100F25	25	100	225	410	611	0	1017
r-R0F35	35	0	225	410	598	1048	0
r-R20F35	35	20	225	410	598	840	204
r-R50F35	35	50	225	410	598	524	506
r-R100F35	35	100	225	410	598	0	1017

2.2 Concrete mixtures

Two series of concrete mixtures were prepared in the laboratory. Series I mixes were prepared with a water-to-binder ratio (w/b) and a cement content of 0.55, 410 kg/m^3, respmectively. Series II mixes were prepared with w/b and a cement content of 0.45 and 400 kg/m^3, respectively. The recycled aggregates were used as 0%, 20%, 50%, and 100% by volume replacements of the natural aggregate. The level of fly ash replacement was from 25% to 35% by cement weight. Concrete made with 25% of fly ash are named r-R0F25, r-R20F25, r-R50F25 and r-R100F25, and concrete made with 35% fly ash are named r-R0F35, r-R20F35, r-R50F35 and r-R100F35, respectively. The absolute volume method was adopted to design the mix proportions of the concrete mixtures in series I and II as shown in Table 4 and Table 5, respectively.

In each concrete mixture, the 10 and 20 mm coarse aggregates were used in a ratio of 1:2.

2.3 Specimens casting and curing

For each concrete mix, 100 mm × 100 mm × 100 mm cubes, 200 mm × ϕ100 mm cylinder specimens were cast. The cubes were used to test the compressive strength. The cylinders were used to evaluate the pore size distribution and determination of chloride diffusions of concrete. All specimens were cast in steel moulds and compacted using a vibrating table. The specimens were covered with a plastic sheet and were cured in air for a period of 24 hours before they were demolded. After demolding, three cubes and three cylinders were immediately tested for the 1-day compressive strength, and the rest of the specimens were cured in a water tank at 27 ± 1℃ until other test ages were reached.

Table 5 Proportions of the concrete mixtures in series II

Notation	Fly ash/%	Recycled aggregate/%	Constituent/(kg/m^3)				
			Water	Total cementitious material	Sand	Granite	Recycled aggregate
R0	0	0	180	400	708	1108	0
R20	0	20	180	400	708	886	215
R50	0	50	180	400	708	554	538
R100	0	100	180	400	708	0	1075
r-R0 F25	25	0	180	400	688	1108	0
r-R20F25	25	20	180	400	688	886	215
r-R50F25	25	50	180	400	688	554	538
r-R100F25	25	100	180	400	688	0	1075
r-R0F35	35	0	180	400	668	1108	0
r-R20F35	35	20	180	400	668	886	215
r-R50F35	35	50	180	400	668	554	538
r-R100F35	35	100	180	400	668	0	1075

Table 6 Compressive strengths of the concrete mixtures in series I

Notation	Fly ash/%	Recycled aggregate/%	Compressive strength/MPa				
			1-day	4-day	7-day	28-day	90-day
R0	0	0	12.8	23.3	30.2	48.6	52.7
R20	0	20	11.9	22.4	29.1	45.3	50.8
R50	0	50	11.6	21.8	27.6	42.5	49.5
R100	0	100	10.2	18.6	24.4	38.1	45.5
r-R0 F25	25	0	12.1	22.8	28.6	43.6	57.9
r-R20 F25	25	20	11.5	24.3	32.8	42.8	57.3
r-R50 F25	25	50	11.1	22.9	30.4	41.7	53.4
r-R100F25	25	100	9.4	19.1	25.1	36.8	50.1
r-R0 F35	35	0	7.7	16.6	22.5	40.7	47.8
r-R20 F35	35	20	6.6	16.4	20.9	41.0	46.6
r-R50 F35	35	50	5.9	15.2	20.4	37.1	43.2
r-R100F35	35	100	4.8	14.6	19.4	25.2	37.4

Table 7 Compressive strengths of the concrete mixtures in series II

Notation	Fly ash/%	Recycled aggregate/%	Compressive strength/MPa				
			1-day	4-day	7-day	28-day	90-day
R0	0	0	25.8	45.8	53.8	66.8	72.3
R20	0	20	23.6	43.2	51.2	62.4	68.0
R50	0	50	21.1	40.3	4.8	55.8	61.5
R100	0	100	15.5	26.8	36.2	42.0	50.2
r-R0 F25	25	0	17.6	32.6	39.9	54.4	69.0
r-R20 F25	25	20	13.2	28.9	34.1	49.7	68.7
r-R50 F25	25	50	11.6	25.7	31.3	44.3	65.2
r-R100F25	25	100	11.1	21.4	28.6	39.5	52.3
r-R0 F35	35	0	12.8	25.6	30.6	45.9	56.6
r-R20 F35	35	20	11.6	23.6	28.5	43.6	55.8
r-R50 F35	35	50	10.9	21.2	26.3	40.4	52.3
r-R100F35	35	100	9.9	20.5	25.3	38.3	50.9

2.4 Tests

The compressive strength of concrete was determined using a Denison compression machine with a loading capacity of 3000 kN. The loading rate for the compressive tests was 200 kN/min in accordance with BS 1881 Part 116[14]. The compressive strength tests were carried out at the ages of 1, 4, 7, 28 and 90 days. The porosity and pore size distribution of the concrete samples were measured using a "pore size 9320" mercury intrusion porosimeter (MIP) with a maximum mercury intrusion pressure of 210 MPa. The concrete samples were obtained from the concrete cylinders prepared. Small cylindrical cores of 21 mm in diameter and 20 mm in height were drilled from tie concrete cylinder specimens at mid height using a diamond drilling machine. The concrete cores were immersed in acetone to stop the hydration. After the hydration was stopped, the concrete samples were dried at 60 °C for 72 hours. A cylindrical pore geometry and contact angle θ of

140 ° were assumed[15]. The mercury intruded pore diameter dp at an intrusion pressure of P_{In} was calculated by $dp = -4\gamma\cos\theta / P_{In}$, where $\gamma = 0.483 \ \mathrm{Mm^{-1}}$, the surface tension of mercury.

To perform a MIP test, the cylinder sample was cut into a tube-like penetrometer. The penetrometer was evacuated in the instrument to a pressure below 50 μm Hg. Mercury was filled and then intrusion pressure was applied by compressed air to a pressure of 0.021 MPa. Thereafter, the penetrometer was transferred to the hydraulic chamber of the instrument and hydraulic pressure was applied to a maximum pressure of 210 MPa. The intruded volume of mercury at each different pressure level was recorded and a corresponding pore size distribution curve was obtained. The chloride penetrability of concrete was determined in accordance with ASTM C1202 (1997) using a 50 mm × 100 mm concrete disc cut from the 100 mm × 200 mm concrete cylinder. The resistance of concrete to chloride ion penetration is represented by the total charge passed in coulombs during a test period of 6 hours. In this study, the chloride ion penetrability test was carried out on the concrete specimens at the ages of 28 and 90 days.

3 Results and Disscusion

3.1 Compressive strength development

The compressive strength results are presented in Table 6 and Table 7 for the concrete mixtures in series I and II, respectively. Each presented value is the average of three measurements. It is shown that the 28-day compressive strength of the concrete mixtures decreased with an increase in the recycled aggregate content. Furthermore, the use of fly ash as a partial replacement of cement also caused a reduction in the compressive strength. A closer observation for the strength development between the 28 and 90 days shows that the concrete mixtures prepared with fly ash had a greater gain in strength between 28 and 90 days. In Series I, the concrete mixtures prepared with 0%, 25% and 35% fly ash had an average of 8.2%, 26.8% and 23.3% increase in the compressive strength from 28 to 90 days, respectively. On the other hand, the concrete mixtures prepared with 0%, 25% and 35% fly ash in Series II had an average of 14.1%, 32.7% and 24.0% increase in the compressive strength from 28 to 90 days, respectively. The higher increase in strength for the concrete mixtures prepared with fly ash was attributed to the pozzolanic effects of fly ash at late ages. Furthermore, the compressive strength increased with a decrease in the w/b ratio.

3.2 Pore size distribution

In Tables 8 and 9, it can be seen that in both of the series I and II concrete mixtures, the total porosity and average pore diameter increased as the recycled aggregate content increased. At 28 days, concrete mixture R0 with 100% natural aggregate in Series I and II had a total porosity of 9.98% and 8.89%, respectively, whereas concrete mixture R100 with 100% recycled aggregate had a total porosity of 12.89% and 11.25%, respectively, an increase of 22.6% and 21.0%, respectively. The concrete mixture R0 in series I and II had an average pore diameter of 0.0299 μm and 0.0278 μm, respectively, whereas concrete mixture R100 in series I and series II had an average pore diameter of 0.0345 μm and 0.0329 μm, respectively; an increase of 13.3% and 15.5%, respectively. This is attributed to the recycled aggregates had some adhered mortar which was more porous than the original aggregates. The results at 90 days indicate that there was continuous and significant decrease in total porosity and average pore diameter beyond the age of 28 days. The decrease in total porosity and average pore diameter of concrete mixture R100 with 100% recycled aggregate in series I from 28 to 90 days was 10.4% and 7.5%, respectively. This is consistent with the results of Gomez-Soberon[9].

Table 8 Average pore diameters and total porosities of concrete mixtures in series I

Mix notation	Recycled aggregate/%	Fly ash/%	Average pore diameter/μm		Total porosity/%	
			28 days	90 days	28 days	90 days
R0	0	0	0.0299	0.0259	9.98	8.91
R20	20	0	0.0312	0.0277	10.74	9.39
R50	50	0	0.0322	0.0296	11.80	10.70
R100	100	0	0.0345	0.0319	12.89	11.37
r-R0F25	0	25	0.0278	0.0229	8.65	6.60
r-R20F25	20	25	0.0297	0.0243	9.62	7.90
r-R50F25	50	25	0.0302	0.0265	10.36	9.35
r-R100F25	100	25	0.0319	0.0287	11.52	9.74
r-R0F35	0	35	0.0259	0.0209	10.27	8.56
r-R20F35	20	35	0.0275	0.0221	11.35	9.68
r-R50F35	50	35	0.0293	0.0239	12.48	11.26
r-R100F35	100	35	0.0306	0.0296	13.33	11.81

Table 9 Average pore diameters and total porosities of concrete mixtures in series II

Mix notation	Recycled aggregate/%	Fly ash/%	Average pore diameter/μm		Total porosity/%	
			28 days	90 days	28 days	90 days
R0	0	0	0.0278	0.0235	8.89	6.70
R20	20	0	0.0286	0.0254	9.31	7.98
R50	50	0	0.0305	0.0269	10.49	8.95
R100	100	0	0.0329	0.0289	11.25	10.05
r-R0F25	0	25	0.0255	0.0215	7.66	5.72
r-R20F25	20	25	0.0267	0.0234	8.34	6.69
r-R50F25	50	25	0.0281	0.0251	9.29	7.81
r-R100F25	100	25	0.0299	0.0267	10.39	9.23
r-R0F35	0	35	0.0228	0.0195	9.19	7.21
r-R20F35	20	35	0.0243	0.0205	10.04	8.28
r-R50F35	50	35	0.0261	0.0228	10.68	9.26
r-R100F35	100	35	0.0278	0.0249	11.09	10.37

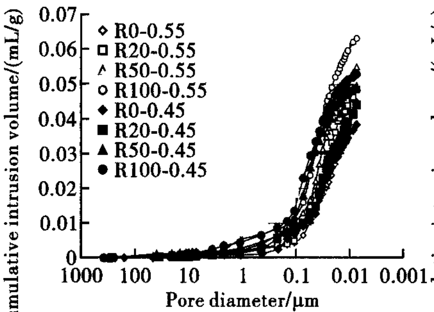

Fig.1 Pore size distribution of concrete mixtures without fly ash in series I and II at 28 days

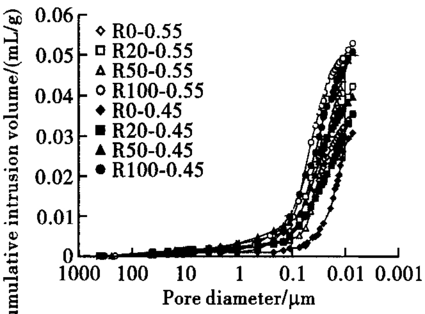

Fig.2 Pore size distribution of concrete mixtures without fly ash in series I and II at 90 days

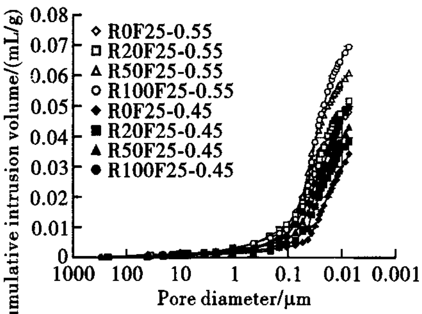

Fig.3 Pore size distribution of concrete mixtures with 25% fly ash in series I and II at 28 days

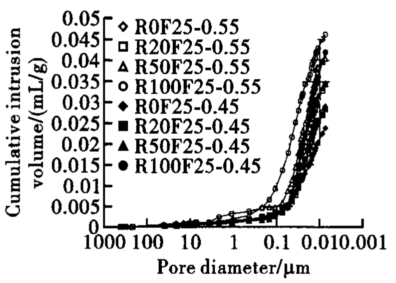

Fig.4 Pore size distribution of concrete mixtures with 25% fly ash in series I and II at 90 days

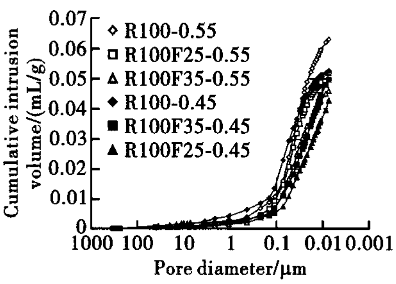

Fig.5 Pore size distribution of concrete mixtures with varing percentage of fly ash in series I and II at 28 days

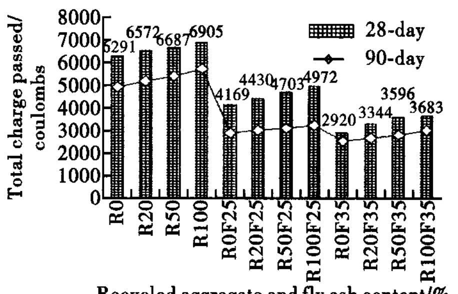

Fig.6 Total charge passed in coulombs of concrete mixtures in series I

In Fig. 1 and Fig. 2 it can be seen that the pore size distribution of the concretes made with recycled aggregates was shifted to the larger pore size range, demonstrating the pore coarsening effect of the recycled aggregates. All the recycled aggregate concrete specimens recorded higher intrusion volumes in pores of sizes larger than 0.01 μm in comparison with the natural aggregate concrete.

It can also be seen from Tables 8 and 9 that in both of the series I and II concrete mixtures, the replacement of cement by 25% fly ash resulted in lower MIP porosities of recycled and natural aggregate concrete at the ages of 28 days and 90 days. However, the replacement of cement by 35% fly ash resulted in higher MIP porosities of the concretes. At 28 days, concrete mixtures R100 with 100% recycled aggregate and no fly ash in series I and II had total porosity values of 12.89% and 11.25%, respectively, whereas concrete mixtures r-R100F25 with 100% recycled aggregate and 25% fly ash in series I and II had total porosity values of 11.52% and 10.39%, respectively, a reduction of 10.6% and 7.6%, respectively. Concrete mixtures r-R100F35 with 100% recycled aggregate and 35% fly ash in Series I and II had total porosity values of 13.33% and 11.49%, respectively, an increase of 3.3% and 2.1%, respectively, in comparison with the total porosity of the concrete mixture R100.

In both of series I and II concrete mixtures, the average pore diameter of the recycled and natural aggregate concrete was decreased with an increase in fly ash content. At 28 days. The concrete mixtures R100 in series I had an average pore diameter of 0.0345 μm, whereas the concrete mixtures r-R100F25 and r-R100F35 had average pore diameters of 0.0319 μm and 0.0306 μm, respectively; a reduction of 7.5% and 11.3%, respectively. The decrease in average pore diameter was, mostly, due to that fly ash particles are predominantly amorphous and spherical in nature, and it is smaller than that of the cement. The results at 90 days indicate that there was a continuous and significant decrease in total porosity and average pore diameter of recycled and natural aggregate concrete with fly ash beyond the age of 28 days. The decrease in total porosity and average pore diameter of concrete mixture r-R100F25 with 100% recycled aggregate and 25% fly ash in series I from 28 to 90 days was 15.5% and 10.0%, respectively. This decrease was higher than that of corresponding concrete mixture without fly ash (10.4% and 7.5%).

In Fig.3 and Fig.4 it can be seen that the pore size distribution of the recycled and natural aggregate concretes made with fly ash was shifted to the smaller pore size range, demonstrating the pore refining effect of the fly ash. All the fly ash concrete specimens recorded lower intrusion volumes in pores of sizes larger than 0.01 μm in comparison with the concrete mixtures without fly ash.

Fig.5 shows that in both of the Series I and II concrete mixtures, and for the concrete mixtures R100 (0% fly ash), r-R100F25 (25% fly ash) and r-R100F35 (35% fly ash), the concrete mixture r-R100F25 had the lowest intrusion volume in pores of sizes larger than 0.01 μm.

The pore size distributions were also determined for concrete mixtures prepared with the water-to-binder (w/b) ratios of 0.55 and 0.45. The total porosity and the average pore diameter of natural and recycled aggregate concrete decreased with a decrease in water-to-binder ratio.

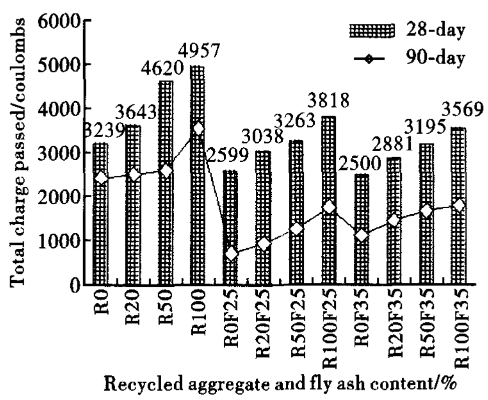

Fig.7 Total charge passed in coulombs of concrete mixtures in series II

3.3 Chloride penetrability

The resistances to chloride ion penetration of the concrete mixtures in series I and II are shown in Fig.8 and Fig.9, respectively. The results show that the resistance to chloride ion penetration decreased as the recycled aggregate content increased. However, at the same recycled aggregate replacement level, the use of fly ash as a partial replacement of cement increased the resistance to chloride ion penetration. According to Leng *et al*[16], the reasons for the enhanced resistance to chloride ion penetration were: the use of fly ash improved the distribution of pore size and pore shape of concrete; more C-S-H products were formed as fly ash hydrated, which absorbed more chloride ions and blocked the ingress path, and the presence of C_3A in fly ash could absorb more chloride ions to form Friedel's salt $C_3A \cdot CaCl_2 \cdot 10H_2O$.

Furthermore, it is shown that the reduction in the w/b ratio (a comparison between Fig.6 and Fig.7) increased the resistance to chloride ion penetration. Since the volume of pores within a concrete reduced as the w/b ratio decreased, the concrete became more impermeable and the resistance to chloride ion penetration increased accordingly. These results also agree with those reported by Leng *et al*[16]. Moreover, it was found that the resistance increased as the curing age increased from 28 to 90 days. It was due to the increase in the volumes of hydration products (Mindess *et al*[17]), thus forming impermeable regions and increasing the resistance to chloride ion penetration.

4 Conclusions

a) The compressive strength decreased as the recycled aggregate content increased. However, the reduction could be adequately compensated by the use of a lower w/b ratio. At the same recycled aggregate replacement level and w/b ratio, the use of fly ash as a partial replacement of cement decreased the compressive strength.

b) The total porosity and average pore diameter increased as the recycled aggregate content increased. The pore size distribution of the concrete made with recycled aggregates was shifted to the larger pore size range, demonstrating the pore clarifying effect of the recycled aggregates.

c) The replacement of cement by 25% fly ash resulted in lower MIP porosities of recycled and natural aggregate concrete at the ages of 28 and 90 days. However, the replacement of cement by 35% fly ash resulted in slightly higher MIP porosities of the concretes.

d) All the fly ash concretes specimens recorded lower intrusion volumes in pores of sizes larger than 0.01 μm in comparison with the concrete mixtures without fly ash.

e) The total porosity and average porosity diameter of natural and recycled aggregate concrete decreased with a decrease water-to-binder ratio.

f) The resistance to chloride ion penetration decreased as the recycled aggregate content increased. However, the resistance was improved by incorporating fly ash in the concrete mixtures. A decrease in the w/b ratio improved the resistance to chloride ion penetration. Furthermore, it was found that the resistance increased as the curing age increased from 28 to 90 days.

References

[1] CS Poon and Salman Azhar. An Investigation on the Scope and AppliCations of Recycled Aggregates in the Hong Kong Construction Industry[J]. *One day Annual Seminar on Environmentally Friendly Structures*, 2001, (5):45-54

[2] Collins RJ. Recycled Aggregates-application and Control Issues[C]. *In: Proceeding of the International Conference on the Use of Recycled Concrete Aggregates*. Edited by RK Dhir, NA Henderson and MC Limbachiya, Thomas Telford, UK, 1998:169-175

[3] CS Poon, SC Kou and L Lam. Use of Recycled Aggregates in Moulded Concrete Bricks and Blocks[J]. *Construction and Building Materials*, 2002, 16:281-289

[4] PJ Wainweight, A Trevorrow, Y Yu Y Wang. Modifying the Performance of Concrete Made with Coarse and Fine Recycled Concrete Aggregates[M]. In: EK Lauritzen (Ed), *Guidelines for Demolition and Reuse of Concrete and Masonry*, E &FN SPON, Denmark, 1993:319-330

[5] IB Topcu, S Sengel. Properties of Concretes Produced with Waste Concrete Aggregate[J]. *Cement and Concrete Research*, 2004, 34:1307-1312

[6] JZ Xiao, JB Li, Ch Zhang. Mechanical Properties of Recycled Aggregate Concrete under Uniaxial Loading[J]. *Cement and Concrete Research*, 2005, 35:1187-1194

[7] RK Dhir, MC Limbachiya, T Leelawat. Suitability of Recycled Concrete Aggregate for Use BS 5328 Designated Mixes [J]. *Proc. Instn Civ. Engrs & Bldgs*, 1999, 134(8): 257-274

[8] H Uchikawa, S Hanehara. *Recycling of Concrete Waste*[M]. In: RK Dhr, TD Dyer (Eds), Concrete for Environment Enhancement and Protection, E&FN SPON, London, 1996: 163-172

[9] JM V Gomez-Soberon. Porosity of Recycled Concrete with Substitution of Recycled Concrete Aggregates an Experimental Study[J]. *Cement and Concrete Research*, 2002, 32: 1301-1311

[10] A Mueller, A Winkler. *Characteristics of Processed Concrete Rubble*[M]. In: K R Dhir, NA Henderson, MC Limbachiya (Eds), Uses of Recycled Concrete Aggregate. Sustainable Construction, Tomas Telford, London, 1998:1109-1119

[11] PJ Wainwright, JG Cabrera. *Use of Demolition Concrete to Produce Durable Structural Concrete*[M]. In: J J K M Goumans, H A Van Der Sloot, T G Aalbers (Eds), Environmental Aspects of Construction with Waste Materials, Elsevier, The Netherlands, 1994: 553-562

[12] B Zhang. Relationship between Pore Structure and Mechanical Properties of Ordinary Concrete Under Bending Fatigue[J]. *Cement and Concrete Research*, 1998, 28 (5): 699-711

[13] British Standard Institute, BS 812: Part 103.1. *Methods for Determination of Particle Size Distribution*[S], 1985

[14] BS 1881 Part 116. *Testing Concrete Part* 116: *Method for Determination of Compressive Strength of Concrete Cubes*[S]. British Standards Institution, 1983

[15] BS 7591 Part 1. *Method of Evaluation by Mercury Porosimetry* [S]. British Standards Institution, 1992

[16] Leng F, Feng N and Lu X. An Experimental Study on the Properties of Resistance to Diffusion of Chloride Ions of Fly Ash and Blast Furnace Slag Concrete[J]. *Cement and Concrete Research*, 2000, 30(6): 989-992

[17] Mindess S, Young JF and Darwin D. *Concrete*[M]. 2nd edition, Prentice Hall, 2003