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Comparisons of natural and recycled aggregate concretes prepared with the addition of different mineral admixtures

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ABSTRACT

This paper presents the results of a laboratory study on the performance of natural and recycled aggregate concrete prepared with the incorporation of different mineral admixtures including silica fumes (SF), metakaolin (MK), fly ash (FA) and Ground granulated blast slag (GGBS). The compressive and splitting tensile strength, drying shrinkage, chloride ion penetration and ultrasonic pulse velocity (UPV) of the concrete mixtures were determined. The test results, in general, showed that the incorporation of mineral admixtures improved the properties of the recycled aggregate concretes. SF and MK contributed to both the short and long-term properties of the concrete, whereas FA and GGBS showed their beneficial effect only after a relatively long curing time. As far as the compressive strength is concerned, the replacement of cement by 10% of SF or 15% of MK improved both mechanical and durability performance, while the replacement of cement by 35% FA or 55% GGBS decreased the compressive strength, but improved the durability properties of the recycled aggregate concretes. Moreover, the results show that the contributions of the mineral admixtures to performance improvement of the recycled aggregate concrete are higher than that to the natural aggregate concrete.

1. Introduction

The possible use of recycled aggregates (RA) derived from construction and demolition (C&D) wastes have received increasing interest, due to its potential to be used in environmentally friendly concrete structures. Moreover, the shortage of supply of natural aggregates in some parts of the world leads to the need to develop recycled aggregate as an alternative source of aggregate. The issue of recycling rubbles from building demolition in the concrete industry has been widely discussed by many researchers [1–3]. A number of previous publications [4–7] studied the mechanical behavior of concretes containing RA. The results showed how the strength loss caused by recycled concrete aggregate at equal water to cement ratio (W/C) could be reduced if better concrete was used as coarse recycled aggregate and if a lower proportion of fine recycled aggregate was added.

Although it is environmentally beneficial to use RA, the current specifications and experience in many parts of the world are not able to support and encourage the recycling of C&D waste [8]. Also, some technical problems, including the lack of information on the interfacial transition zone between cement paste and RA, increase in porosity and presence of traverse cracks within RA, high levels of sulphate and chloride contents, the presence of impurities and attached cement mortar on the RA, poorer grading, and high variations in quality, render the use of RA, especially in structural concrete difficult [9–20].

Mineral admixtures such as fly ash (FA), silica fume (SF), metakaolin (MK) and Ground granulated blast slag (GGBS) have been utilized for many years either as supplementary cementitious materials in Portland cement concretes or as a component in blended cement [21–25]. Generally, due to their high pozzolanic activity, the inclusion of MK and SF improves the mechanical and durability properties of the concrete [26–33]. The use of GGBFS as a partial replacement of ordinary Portland cement improves strength and durability of the concrete by creating a denser matrix and thereby would increase the service life of the concrete structures. It is well known that the incorporation of FA and GGBS with normal fineness reduces the early strength of concrete, but they have long term advantages, such as improved long-term strength and durability, increased workability, reduced permeability and porosity, and reduced alkali-silica reaction expansion [34–39].

Preliminary studies have been conducted on the mechanical and durability properties of recycled aggregate concrete made with mineral admixtures. Berndt [40] reported that the recycled aggregate concrete mixtures containing 50% slag gave the best overall performance. Slag was particularly beneficial for concrete with recycled aggregate and could reduce strength losses. Durability

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tests indicated slight increases in coefficient of permeability and chloride diffusion coefficient when using recycled aggregate in concrete. However, values remained acceptable for durable concrete and the chloride diffusion coefficient was improved by incorporation of slag in the mixture. Corinaldesi and Moriconi [41] conducted experiments on concrete specimens that were manufactured by completely replacing fine and coarse aggregates with recycled aggregates using FA and SF as partial cement replacements. They found that satisfactory concrete properties can be developed with proper selection and proportioning of the mineral materials in the concrete. Ann et al. [42] found that the corrosion rate of recycled aggregate concretes made with 30% PFA and 65% GGBS was kept at a lower level after corrosion initiation, compared to the control specimens, presumably due to the restriction of oxygen and water access. However, it was less effective in increasing the chloride threshold level for steel corrosion.

The authors have published a number of papers on the use of FA in concrete prepared with recycled aggregates [43–45]. The advantages of using FA as an additional cementitious material in recycled aggregate concretes prepared by suitably combining coarse recycled aggregate particles were quantified.

This paper reports the results of a systematic study on the effect of different mineral admixtures in the strength, drying shrinkage, chloride ion penetration and UPV of recycled aggregate concrete. In the concrete mixtures, the replacement levels of cement were chosen at 10% SF, 15% MK, 35% FA and 55% GGBS, which are the common levels used in practice.

2. Materials and experiments

2.1. Materials

The cementitious materials used in this study were Portland cement (PC) equivalent to ASTM Type I, metakaolin (MK) named MetaStar 450 obtained from Imerys Minerals; and condensed silica fume (SF) named Force 10,000D microsilica obtained from W. Grace. ASTM Class-F fly ash obtained from CPL in Hong Kong and Ground granulated blast slag (GGBS) obtained from China mainland. The chemical compositions and physical properties of the cement, SF, MK, FA and GGBS are listed in Table 1.

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 recycled aggregate sourced from a recycling facility in Hong Kong was used (the RA contained more than 90% crushed recycled rubbles). 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 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. All aggregates were used at air dried condition. Regular tap water was used as mixing water.

2.2. Specimen preparation and curing

Three series of concrete mixtures were prepared in the laboratory using a Pan mixer. The absolute volume method was used in calculating the mixture proportions. SF, MK, FA and GGBS were used as cement replacements on a weight basis. In all concrete mixtures, a constant water/binder ratio at 0.50 was used. Series I concrete mixtures used natural aggregate as the coarse aggregate and the mixes were designated with the following codes: C (control, natural aggregate with 100% OPC), C-SF10 (natural aggregate with 10% SF), C-MK15 (natural aggregate with 15% MK), C-FA35 (natural aggregate with 35% FA) and C-GGBS55 (natural aggregate with 55% GGBS). In Series II and Series III, recycled aggregates were used to replace 50% and 100%, respectively of natural coarse aggregate. The mixtures were designated with the following codes: R50-SF10, R100-SF10 (50% or 100% recycled aggregate with 10% SF), R50-MK15, R100-MK15 (50% or 100% recycled aggregate with 15% MK), R50-FA35, R100-FA35 (50% or 100% recycled aggregate with 35% FA) and R50-GGBS55, R100-GGBS55 (50% or 100% recycled aggregate with 55% GGBS). The mixture proportions of the concrete are presented in Table 3.

The workability of the concrete mixtures were measured using the slump cone test according to ASTM C143-89a [46]. Each slump value reported in this paper is the average of three readings obtained from three different specimens in the same conditions.

The test specimens prepared were concrete cubes with sizes of 100 and 150 mm for compressive strength and UPV tests. In addition, concrete cylinders with 100 mm (diameter) and 200 mm (height), and 75 × 75 × 285 mm prism were cast for tensile splitting strength, chloride ion penetration and drying shrinkage test, respectively. The specimens were cast in accordance with ASTM C192-88 [47] Plastic sheets were used to cover the specimens to prevent the water from evaporating. All concrete specimens were first cured for 24 h in laboratory conditions. After which the specimens were demoulded and placed in a water curing tank at 27 ± 2 °C until the test ages.

2.3. Compressive and tensile splitting strength test

The 100 mm cubes and concrete cylinders with 100 mm (diameter) by 200 mm (height) were used for the determination of the compressive and tensile splitting strength, respectively at 1, 4, 7, 28, and 90 days according to BS 1881 Part 116 and Part 117 [48,49]. The compression load was applied using a compression

Table 1
Physical and chemical properties of cement, fly ash, silica fume, GGBS and metakaolin.

Contents	Cement	Fly ash	Silica fume	Metakaolin	GGBS
SiO_2	21.0	56.79	85–96	53.2	44.6
Al_2O_3	5.9	28.21	–	43.9	13.3
Fe_2O_3	3.4	5.31	–	0.38	0.9
CaO	64.7	<3	–	0.02	33.8
MgO	0.9	5.21	–	0.05	4.8
Na_2O	–	–	–	0.17	1.0
K_2O	–	–	–	0.10	–
TiO_2	–	–	–	1.68	–
SO_3	2.6	0.68	0.3–0.7	–	1.3
Loss on ignition (%)	1.2	3.90	3.5	0.50	0.2
Specific gravity (g/cm^3)	3.15	2.31	2.22	2.62	2.98
Fineness (>45 μm)	–	–	3–5	–	–
Specific surface (cm^2/g)	3520	3960	18,650	12,680	5350

Table 2
Properties of natural and recycled aggregates.

Type	Nominal size	Density (Mg/m^3)	Water absorption (%)	Initial moisture content (%)	Strength -10% fines value (kN)	MIP porosity (%)
Crushed granite	10 mm	2.62	1.12	0.86	159	1.62
	20 mm	2.62	1.11	0.92		
Recycled aggregate	10 mm	2.49	4.26	1.35	126	8.69
	20 mm	2.57	3.52	1.28		

Table 3
Concrete mix proportion.

	Constitution (kg/m^3)							
	Composite of binder			Sand	Series I	Series II (RA50)		Series III (RA100)
	Water	Cement	Mineral admixture		Coarse natural agg.	Coarse natural agg.	Coarse recycled agg.	Coarse recycled agg.
Control	195	390	0	678	1107	527	539	1078
SF10	195	351	39	664	1107	527	539	1078
MK15	195	331.5	58.5	669	1107	527	539	1078
FA35	195	253.5	136.5	640	1107	527	539	1078
GGBS55	195	175.5	214.5	658	1107	527	539	1078

machine with 3000 kN capacity, at the rate of 200 kN/min and 57 kN/min for compressive and tensile splitting strength test.

2.4. Drying shrinkage tests

The70 × 70 × 285 mm prism specimens were prepared for measuring the drying shrinkage. The prisms after de-moulding were placed in an environmental cambinet at 23 ± 2 °C and 50 ± 5% humidity, as per ASTM C157 (1997) for about 112 days [50].

2.5. Chloride ion penetration tests

Rapid chloride ion permeability tests were used to evaluate the permeability of concrete containing recycled aggregate. This test was based on the standard test method of ASTM C1202-91 (1991).

2.6. UPV tests

The ultrasonic equipment used in this study consisted of pulser/recever PUNDIT device manufactured by CNS Electronic Ltd. 54 kHz frequency was used throughout this study. UPV measurements were conducted according to procedure described in BS 1881. All prepared concrete specimens were evaluated for UPV at different curing ages of 1, 4, 7, 28 and 90 days. The distance between the transducers which is equal to the concrete specimen width (150 mm), was divided by the measured time to calculate the wave velocity. Two readings were performed for each specimen and averaged.

3. Result and discussion

3.1. Slump

Fig. 1 shows that the slump values of the concrete mixtures increased with an increase in recycled aggregate content which is consistent with the results of our previous study [51]. This is due mainly to the increased amount of free water that was required to be added during mixing to compensate for the higher water absorption values of the RA because the aggregates were used at the air dried condition during the preparation of the concrete mixtures (although the size distributions of the aggregates may also had some effects). Moreover, the slump value of both the natural and recycled aggregate concrete made with 10% of SF and 15% of MK decreased. This might be attributed to the extremely high sur-

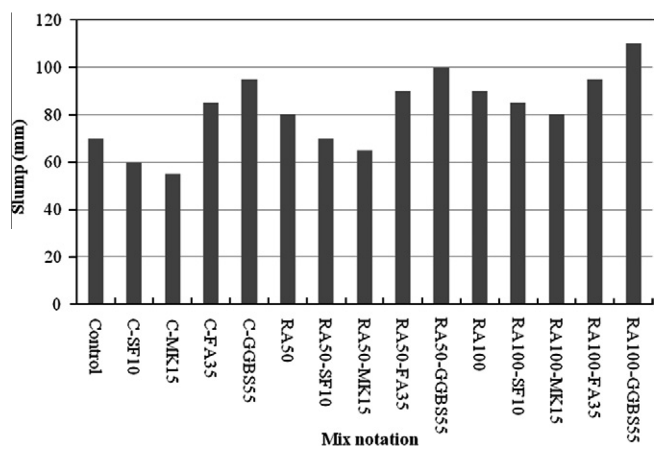

Fig. 1. Slump of concrete mixtures.

face areas of SF (18,650 cm^2/g) and MK (12,680 cm^2/g). Furthermore, the slump of concrete mixtures with 35% of FA and 55% of GGBS was higher than the control.

3.2. Compressive strength

The compressive strength of the natural and recycled aggregate concretes made with mineral admixtures was determined on day 1, 4, 7, 28, and 90. The results are presented in Figs. 2–4. It can be seen that at all test ages, the compressive strength of the natural and recycled aggregate concrete made with 10% SF and 15% MK were higher than the other corresponding concrete mixtures. At the early ages (4, 7 and 28 days), the contributions of SF and MK to compressive strength for both the natural and recycled aggregate concrete were higher than that at 90 days. At 28 day, the compressive strength of concrete mixtures C-SF10, R50-SF10 and R100-SF10 were higher by 9.8%, 7.2% and 10.8%, whereas at 90 day, the strength of the concrete mixtures was only slightly higher by 2.0%, 3.2% and 2.2% than that of the corresponding control concrete. The concrete mixtures containing MK showed similar strength development to that of the SF concretes. Since the average particle sizes of SF and MK were very small compared to the cement particles, the filler effect of mineral admixtures may be as important as their pozzolanic effect according to Goldman and Bentur [52].

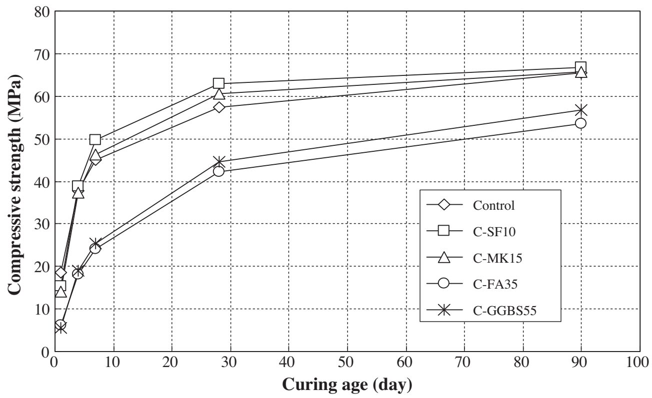

Fig. 2. Development of compressive strength of concrete mixtures in Series I.

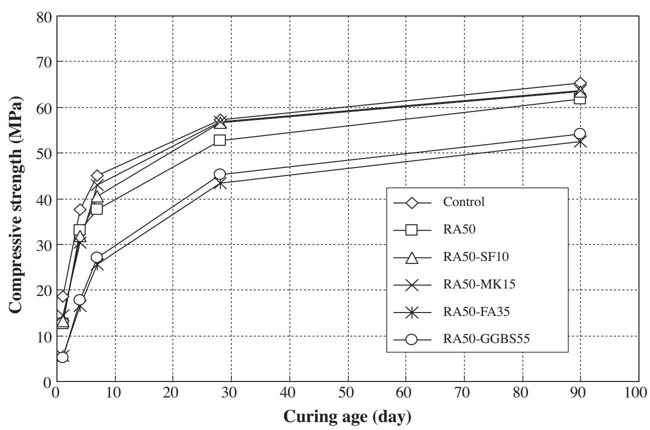

Fig. 3. Development of compressive strength of concrete mixtures in Series II.

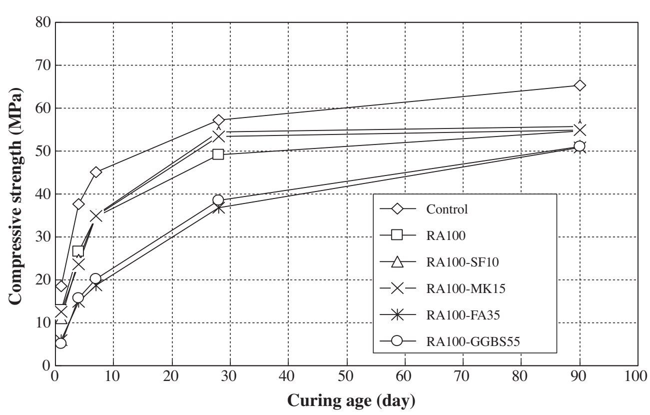

Fig. 4. Development of compressive strength of concrete mixture in Series III.

Although the compressive strength of concretes made with 35% FA and 55% GGBS were lower than that of corresponding control concrete mixtures, the contributions of FA and GGBS to the long term compressive strength were higher than that of the corresponding concrete mixtures with SF and MK. The compressive strength gains of the concrete mixtures C-FA35, C-GGBS55, R50-FA35, R50-GGBS55, R100-FA35 and R100-GGBS55 were 66.2%, 66.5%, 68.6%, 67.2%, 70.9% and 69.1%, respectively between 4 days and 90 days. Whereas during the same period, the strength gains of the concrete mixtures C-SF10, C-MK15, R50-SF10, R50-MK15, R100-SF10 and R100-MK15 were 41.7%, 43.3%, 49.8%, 52.2%, 55.7% and 56.8%, respectively. These results clearly indicated that the compressive strength gains of recycled aggregate concrete prepared with mineral admixtures were higher than that of the natural aggregate concrete.

The 100% recycled aggregate concrete mixture prepared with the use of mineral admixtures had the highest compressive strength gain, and this might be attributed to the nature of RA. Generally RA are more porous than natural aggregates. When concrete containing RA are prepared with the use of mineral admixtures, two possible mechanisms may enhance the properties of the concrete produced: (1) part of the mineral admixtures would penetrate into the pores of RA, which would subsequently improve the interfacial transition zone (ITZ) bonding between the paste and the aggregates; (2) cracks originally present in the aggregates would be filled by hydration products.

3.3. Tensile splitting strength

The tensile splitting strength of the concrete mixtures was determined at days 7, 28, and 90. The results are presented in Fig. 5. It can be seen that at all test ages, the tensile splitting strength of the natural and recycled aggregate concrete made with SF and MK were higher than that of the corresponding control concrete mixtures. Similarly, FA and GGBS decreased the tensile splitting strength of the concretes as they decreased the compressive strength of the concrete mixtures, especially at the early ages.

Fig. 6 shows the ratio of the tensile splitting strength of the concrete mixtures to the 28th day strength value of the control concrete. It can be seen that the strength gain of the control concrete from 7 to 90 days was lower than that of the recycled aggregate concrete. The results show that the splitting tensile strength of the Control, C-SF10, C-MK15, C-FA35 and C-GGBS increased 17.2%, 23.1%, 26.4%, 35.3% and 33.0%, respectively between 7 and 90 days. But R50, R50-SF10, R50-MK50, R50-FA35 and R50-GGBS55 showed increases of 23.9%, 34.9%, 36.9%, 40.5% and 38.8%, respectively. Moreover, the concrete mixtures R100, R100-SF10, R100-MK15, R100-FA35 and R100-GGBS55 showed increases of 24.6%, 46.2%, 40.8% 48.0% and 44.9%, respectively. It is clear that the mineral admixtures contributed more to the tensile splitting strength of the recycled aggregate concrete than to the natural aggregate concrete. Furthermore, the strength gains of the concrete mixtures with FA and GGBS were higher than that of the corresponding concrete mixtures with SF and MK.

The concrete mixtures prepared with 100% recycled aggregate and SF and MK had the highest splitting tensile strength (higher than the control concrete) and the highest strength gains. This may be due to the presence of the mineral admixtures in the concrete improved the microstructure of the interfacial transition zone (ITZ) and increased the bond strength between the new cement paste and the RA.

3.4. UPV

Fig. 7 shows the effect of percentages of recycled aggregates and mineral admixtures on UPV and the UPV gains of the concrete mixtures are given in Table 4. It can be seen that the UPV of the natural aggregate concrete was higher than that of the recycled aggregate concrete. SF and MK improved the UPV of both the natural and the recycled aggregate concretes. Whereas the UPV values of the concrete mixtures with FA and GGBS were lower than that of the corresponding control concrete. Table 4 indicates that from 1 to 7 days the percentage of UPV gains of the natural and recycled aggregate with SF and MK were lower than that of the corresponding control concrete. Moreover, from 7 to 90 days the% gains of UPV of all concrete mixtures were similar. Furthermore, the percentage gain of UPV of the recycled aggregate concrete with mineral admixtures

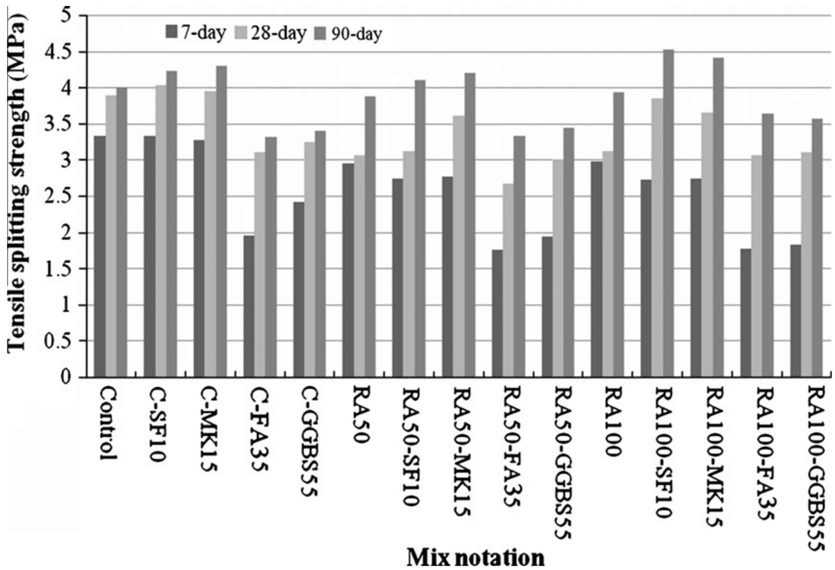

Fig. 5. Tensile splitting strength of concrete mixtures.

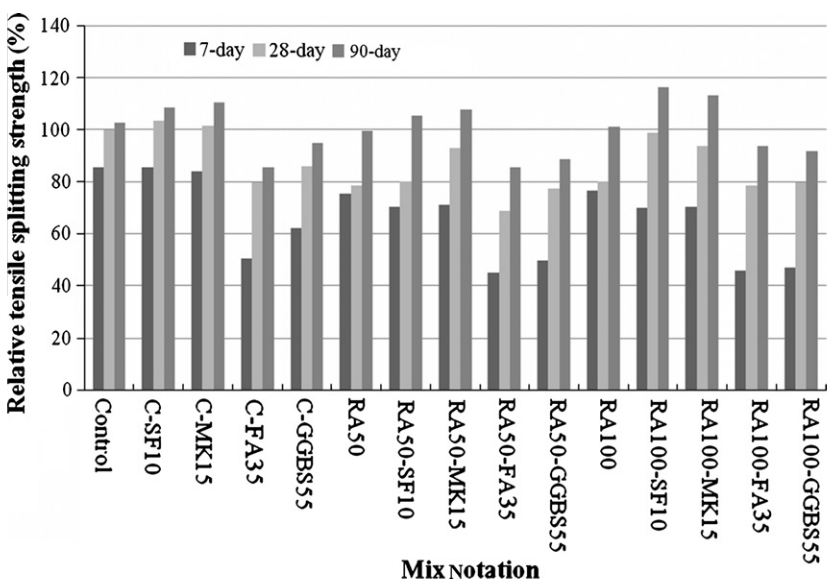

Fig. 6. Relative tensile splitting strength of concrete mixtures.

was higher than that of the natural aggregate concrete. This can also be attributed to the mineral admixtures improved the microstructure of the interfacial transition zone (ITZ) and increased the bond strength between the new cement paste and RA.

Figs. 8 and 9 show that there are very good correlations between UPV and compressive strength, with R^2 values near 0.9 in all cases. These results are consistent with other several studies conducted on natural aggregate concretes [53,54].

3.5. Drying shrinkage

The drying shrinkage of concrete mixtures measured at 112 day in Series I, II and III are presented in Fig. 10. In general, the use of RA increased the drying shrinkage of the produced concretes. This might be due to the presence of old cement mortar in and the lower stiffness RA. It can be seen that the drying shrinkage values of the natural and recycled aggregate concrete made with SF and MK were higher than that of the corresponding control concrete

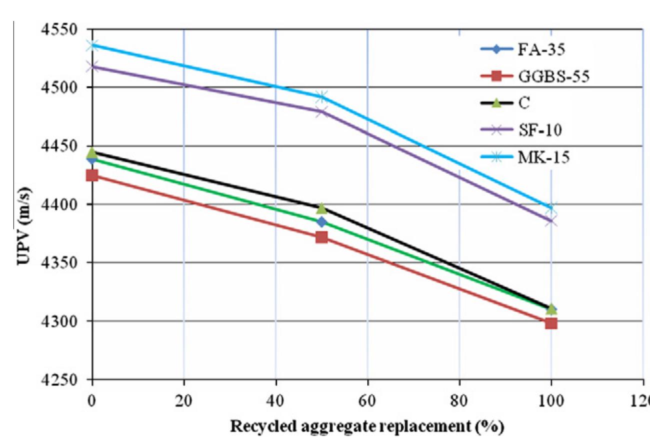

Fig. 7. Effect of recycled aggregates and mineral admixtures on UPV of concrete mixtures at 28 days.

Table 4
UPV gain of concrete mixtures.

Series I			Series II			Series III		
Mix. notation	% Gain from 1 to 7 days	% Gain from 7 to 90 days	Mix. notation	% Gain from 1 to 7 days	% Gain from 7 to 90 days	Mix notation	% Gain from 1 to 7 days	% Gain from 7 to 90 days
Control	11.5	7.7	RA50	18.2	12.3	RA100	21.2	8.9
C-SF10	13.8	9.6	RA50-SF10	18.9	11.4	RA100-SF10	18.6	8.6
C-MK15	15.5	8.3	RA50-MK15	20.6	8.5	RA100-MK15	20.1	7.7
C-FA35	24.8	9.1	RA50-FA35	24.5	6.6	RA100-FA35	26.0	7.6
C-GGBS55	26.9	9.6	RA50-GGBS55	26.2	9.5	RA100-GGBS55	29.5	9.4

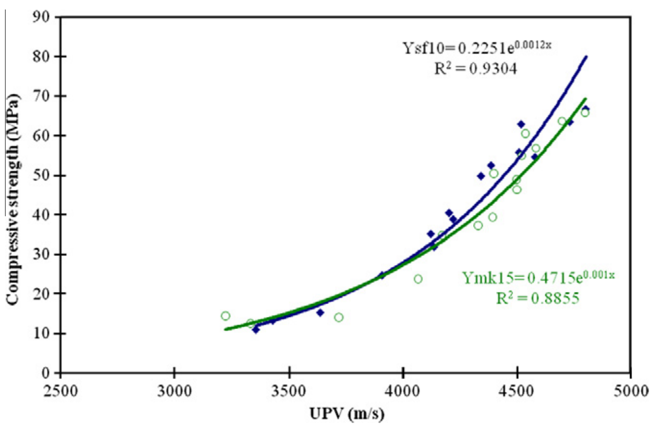

Fig. 8. Correlation between compressive strength and UPV of concrete mixtures with SF and MK.

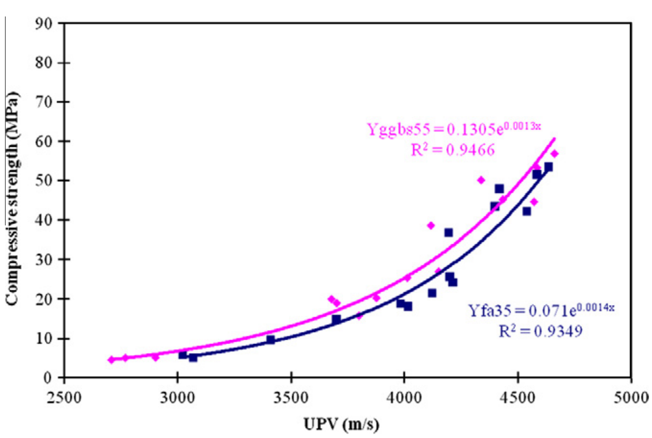

Fig. 9. Correlation between compressive strength and UPV of concrete mixtures with FA and GGBS.

due to the pozzolanic reaction between SF/MK and $Ca(OH)_2$ which led to a higher content of C–S–H gel in the pastes. However, the drying shrinkage of the concrete mixtures containing FA and GGBS were lower. This can be attributed to the lower hydration rates of FA and GGBS and the possible restraining effects of the unhydrated powder particles in the pastes. These findings are consistent those reported previously [43,44].

3.6. Chloride ion penetration

As shown in Fig. 11, the total charge passed increased with the use of RA. However, the resistance to chloride ion penetration of

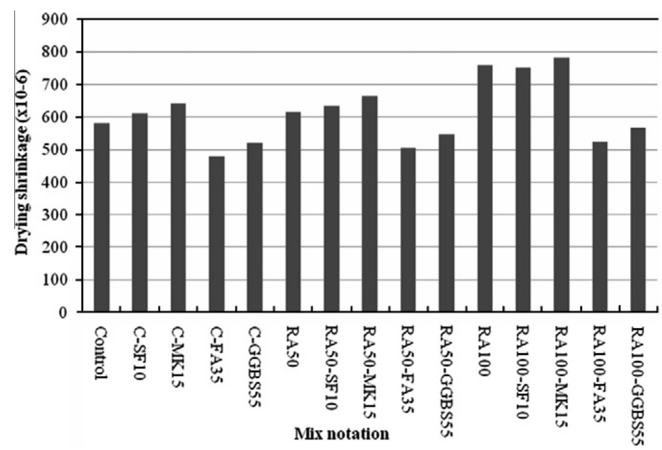

Fig. 10. Drying shrinkage of concrete mixtures at 112 days.

the natural and recycled aggregate concrete improved with the use of the mineral admixtures. The improvement order (from the lowest to highest) is SF10 concrete, MK15 concrete, FA35 concrete, and GGBS55 concrete. This behavior can be explained by the improvement in impermeability of the concrete and the improvement in chloride binding capacity of SF, MK and/or FA. Detwiler et al. [55] suggested that it was effective to use supplementary cementing materials to increase the chloride resistance of accelerated cured concrete. Bilodeau and Malhotra [56] reported that the resistance of concrete to chloride penetration was enhanced significantly with the presence of fly ash. Furthermore, Yiğiter et al. [57] concluded that blended cement with GGBS was very effective to prevent the chloride ingress of seawater in concrete. Yeau and Kim [58] concluded that chloride-ion penetration of GGBS concrete mixtures was reduced as the period of curing was increased.

4. Conclusion

The following conclusions are drawn from the results of this investigation

(1) The compressive strength of concrete containing recycled aggregate at 1, 4, 7, 28 and 90 days was lower than that of the control specimen, but could be compensated by the use of 10% SF or 15% MK. However, the use of 30% FA or 55% GGBS lowered the strength.
(2) The tensile splitting strength of natural and recycled aggregate concrete made with SF and MK was higher than that of the corresponding control concrete at all test ages, whereas FA and GGBS decreased the tensile splitting strength of the concretes.

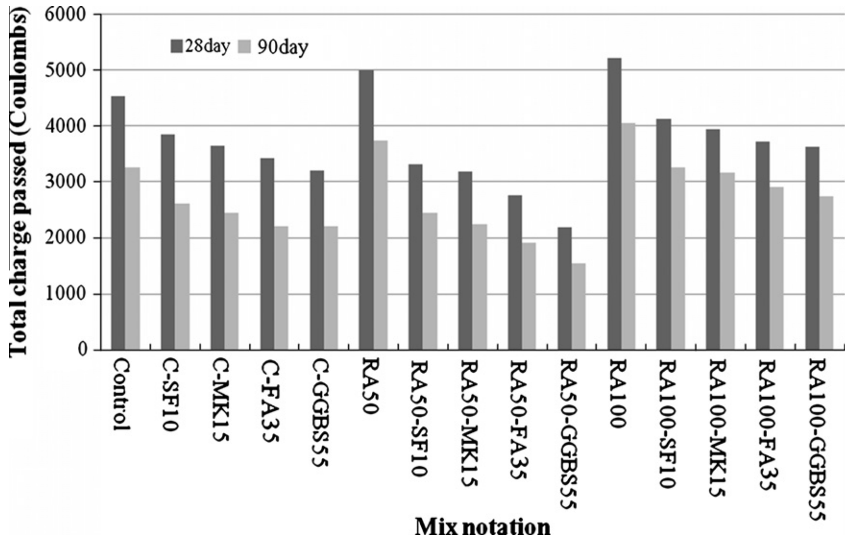

Fig. 11. Total charge passed in coulombs of concrete mixtures.

(3) SF and MK increased UPV of both the natural and recycled aggregate concrete.
(4) The drying shrinkage values of the natural and recycled aggregate concrete made with SF and MK were higher than that of the control. However, the drying shrinkage of the concrete mixtures containing FA and GGBS was lower than the control concrete.
(5) The rapid chloride ion penetration test indicated that the concrete containing recycled aggregate had a more open pore structure, compared to the control concrete. The use of mineral admixture resulted in a decrease in the charge passed through the concrete specimens.
(6) The test results show that SF and MK can improve both mechanical and durability properties of recycled aggregate concrete. But the use of FA and GGBS significantly improved the durability performance of the recycled aggregate concrete.
(7) The results show that the contributions of the mineral admixtures to performance improvement of the recycled aggregate concrete are higher than that to the natural aggregate concrete.

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