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Effect of micro-silica on mechanical and durability properties of high volume fly ash recycled aggregate concretes (HVFA-RAC)

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Abstract. This paper presents the effect of different micro-silica (MS) contents of 5, 10 and 15 wt.% as partial replacement of cement on mechanical and durability properties of high volume fly ash - recycled aggregate concretes (HVFA-RAC) containing 50% class F fly ash (FA) and 35% recycled coarse aggregate (RCA) as partial replacement of cement and natural coarse aggregate (NCA), respectively. The measured mechanical and durability properties are compressive strength, indirect tensile strength, elastic modulus, drying shrinkage, water sorptivity and chloride permeability. The effects of different curing ages of 7, 28, 56 and 91 days on above properties are also considered in this study. The results show that the addition of MS up to 10% improved the early age (7 days) strength properties of HVFA-RAC, however, at later ages (e.g. 28-91 days) the above mechanical properties are improved for all MS contents. The 5% MS exhibited the best performance among all MS contents for all mechanical properties of HVFA-RAC. In the case of measured durability properties, mix results are obtained, where 10% and 5% MS exhibited the lowest sorptivity and drying shrinkage, respectively at all ages. However, in the case of chloride ion permeability a decreasing trend is observed with increase in MS contents and curing ages. Strong correlations of indirect tensile strength and modulus of elasticity with square root of compressive strength are also observed in HVFA-RAC. Nevertheless, it is established in this study that MS contributes to the sustainability of HVFA-RAC significantly by improving the mechanical and durability properties of concrete containing 50% less cement and 35% less natural coarse aggregates.

Keywords: recycled coarse aggregates; fly ash; micro silica; mechanical properties; durability properties

1. Introduction

Concrete is one of the most widely used construction materials in the world and its increasing use is predicted every year due to growing demand for residential and commercial buildings, roads, bridges and other infrastructures. However, concrete itself is not environmentally friendly due to the use of ordinary Portland cement (OPC), which is responsible for about 5-7% carbon-di-oxide emission worldwide (Malhotra 2002). Another important factor is the use of natural aggregates as filler in concrete (which occupy almost 70-80% of volume of concrete), which affects the natural

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ecosystem. Currently lot of research is conducting to make the concrete more sustainable by partially replacing OPC as well as natural aggregates using industrial wastes and recycled materials. Among many industrial wastes, class F fly ash (FA) and micro silica (MS) which are by-products of coal fired power stations and silicon and ferrosilicon alloy production, respectively are most widely used in concrete. Many studies have been conducted to evaluate their effects on mechanical and durability properties of concrete. While both improved the mechanical and durability properties of concrete, the MS is more effective than FA due to its amorphous structure and smaller particle size, which significantly improve the properties at both early age as well as at later ages. FA, on the other hand, contributes to the long term properties of the concrete. With regard to the use of recycled materials in concrete, the use of old demolished concrete aggregates as partial or full replacement of natural aggregates in concrete is another widely studied area. It is also found that the use of recycled aggregates adversely affects the concrete's properties due to several reasons: firstly, due to adherence of old mortars on the recycled aggregates, which are more porous and weaker than the natural aggregates and secondly, the pre-existing micro cracks in the recycled aggregates due to the crushing process.

A number of studies have evaluated the effect of FA on the properties of concrete containing recycled aggregates. Somna *et al*. (2012) evaluated the effect of three different FA contents of 20%, 35% and 50% as partial replacement of cement on the compressive strength and water permeability of recycled aggregate concretes. Improvement in compressive strength is reported due to the use of 20% FA as partial replacement of OPC in their concretes, however, at higher replacement levels e.g. at 35% and 50% no improvements are observed. The water permeability was decreased at all FA contents in their study. Similar results are also observed in other studies (Ahmed 2013, 2014) on the recycled aggregate concrete containing 30-40% FA, where 7 and 28 days strengths were lower than those without FA. Corinaldesh and Moriconi (2009) studied the effect of addition of 20% fly ash on mechanical and durability properties of recycled aggregate concrete and reported improvement in both mechanical and durability properties due to addition of fly ash. Kou *et al.* (2007) also reported a study where the use of 25% and 35% FA reduced the compressive strength of recycled aggregate concrete measured at early ages as well as up to 28 days. Kou *et al.* (2013) recently published a 10 years long term study on the effect of three different fly ash contents of 25%, 35% and 55% on mechanical and durability properties of recycled aggregate concretes and reported that the recycled aggregate concrete incorporating fly ash significantly improved the resistance to chloride ion penetration, however, the carbonation coefficient increased with increase in recycled aggregate and fly ash contents. In order to overcome the reduction in the compressive strength up to 28 days observed in above studies, one promising approach is to use ultrafine pozzolanic materials e.g. micro silica (MS), nano silica, etc. However, no research so far is reported to evaluate the effectiveness of MS on the mechanical and durability properties of high volume fly ash recycled aggregate concretes (HVFA-RAC). This study is, therefore, designed to contribute to the existing knowledge on the effect of MS on improvement of both early and long-term mechanical properties of HVFA-RAC as well as on their durability properties. As such three MS contents of 5, 10 and 15% as partial replacement of OPC on the HVFA-RAC containing 50% FA and 35% recycled coarse aggregates (RCA) are considered in this study.

2. Experimental program

In this study five series of mixes were considered. The first series was a control concrete

Table 1 Chemical composition and physical properties of cementitious materials

Chemical Analysis	OPC (wt. %)	Class F Fly Ash (FA) (wt. %)	Micro silica (MS) (wt.%)
SiO_2	21.1	63.13	89.6
Al_2O_3	5.24	24.88	-
Fe_2O_3	3.1	3.07	-
CaO	64.39	2.58	-
MgO	1.1	0.61	-
K_2O	0.57	2.01	0.225
Na_2O	0.23	0.71	0.11
SO_3	2.52	0.18	-
LOI	1.22	1.45	3.8
Particle size	-	73% pass through 45 µm sieve	95% particles < 1µm
Specific gravity	3.17	2.68	0.625
BET Surface area (m^2/g)	-	1.53	15-30

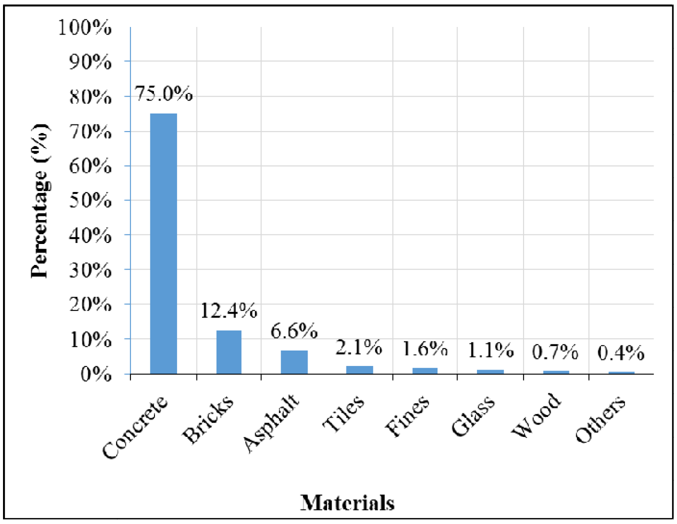


Fig. 1 Contents analysis of recycled coarse aggregates

consisting of OPC and natural aggregates. The second series was sustainable concrete where 50% (by wt.) OPC was replaced by FA and 35% natural coarse aggregate (NCA) was replaced by recycled coarse aggregate (RCA). It should be noted that the NCA were consisted of 10 and 20 mm sizes and 50% (by wt.) of the 20 mm size of NCA was replaced by the same size RCA (i.e. 20mm), resulting in about 35% replacement of total NCA by the RCA. The partial replacement of OPC by 50% or more FA in concrete is generally considered as high volume fly ash concrete (Siddique 2004) and the selected 35% RCA is based on many studies on recycled aggregate concretes where researchers reported significantly lower mechanical properties of concrete containing higher amount of recycled coarse aggregates (Ahmed 2013, 2014). In next three series, the effects of three different MS contents on the properties of concrete in the second series are evaluated. Thus, the third, fourth

Table 2 Properties of Aggregates

Aggregate properties	**RCA**	**NCA**
Uncompacted Density (kg/m^3)	1181	1420
Compacted Density (kg/m^3)	1247	1522
Water absorption (%)	5.9	1.3

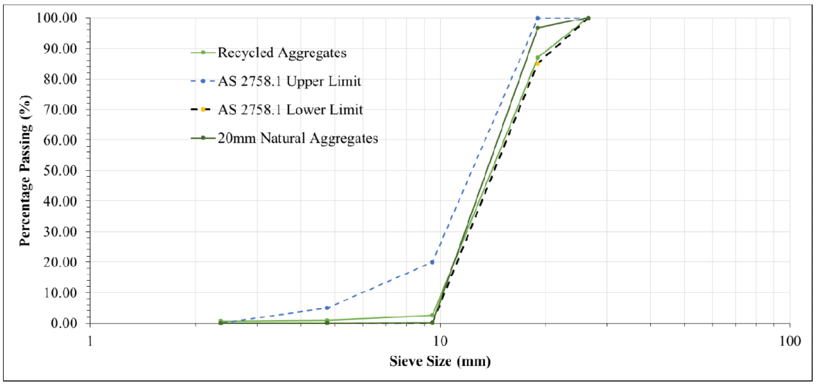


Fig. 2 Sieve analysis of recycled coarse aggregates and natural coarse aggregates.

and fifth series were similar to the second series in every aspect except the MS contents of 5, 10 and 15% (by wt.), which were used as partial replacement of OPC.

2.1 Materials

Ordinary Portland cement (OPC) was used in all concrete mixes. The fly ash used in this study was class F fly ash and was obtained from Eraring power station in New South Wales of Australia. Commercial micro silica (MS) supplied by Ecotec was used in this study. The MS is densified and amorphous with specific surface area of about 15-30 m^2/kg. The properties and chemical compositions of OPC, fly ash and MS are shown in Table 1. The recycled coarse aggregate was obtained from a local construction and demolition (C&D) waste recycling plant in Perth, Western Australia. Fig. 1 shows the analysis of contents of a 5 kg sample of the C&D waste used as RCA in this study. The percentages are based on mass. It can be seen that approximately 75% are from concrete and the rest consisted of masonry, tile, bitumen and others. Table 2 shows the properties of recycled and natural aggregates. Sieve analysis of RCA is also conducted and is shown in Fig. 2. It is observed that the RCA used in this study met the requirements specified in Australian standard (AS2758.1 1998). The natural coarse aggregates (NCA) used in this study were a mixture of 10mm and 20mm sizes. The sieve analysis of NCA is also shown in Fig. 2. The NCA and RCA used in this study were in saturated and surface dry condition before used in the mixing. A naphthalene sulphonate based high range water reducing admixture was used as superplasticizer in all concrete mixes in this study.

2.2 Mix proportions

Table 3 shows the mix proportions used to produce the test samples. The percentage

Table 3 Mix proportions of concretes

Materials	Series 1	Series 2	Series 3	Series 4	Series 5
	Control	35%RCA+ 50%FA	35%RCA+ 50%FA+ 5%MS	35%RCA+ 50%FA+ 10%MS	35%RCA+ 50%FA+ 15%MS
	Kg/m3				
Natural coarse aggregates (NCA)	1216	792	792	792	792
Recycled coarse aggregates (RCA)	0	424	424	424	424
Sand	654	654	654	654	654
OPC	450	225	203	180	158
Fly Ash (FA)	0	225	225	225	225
Microsilica (MS)	0	0	23	45	68
Water	180	180	180	180	180
Water/binder ratio	0.4	0.4	0.4	0.4	0.4
Superplasticiser	1.79	2.25	3.54	4.10	4.43

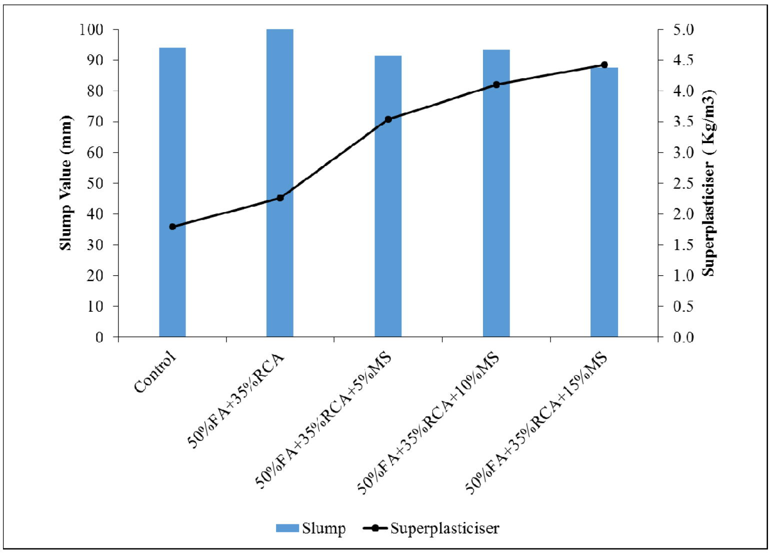


Fig. 3 Workability of concretes

replacements of NCA by RCA, OPC by FA and MS were on the basis of weight. The water/cement ratio is kept constant at 0.4 in all mixes.

2.3 Casting and tests methods

The compressive strength, indirect tensile strength, elastic modulus, drying shrinkage, water sorptivity and chloride ion permeability were measured at 28, 56 and 91 days for each mix except the compressive and indirect tensile strengths which were also measured at 7 days for all series. Slump test was done immediately after mixing the concrete to measure the workability of each mix.

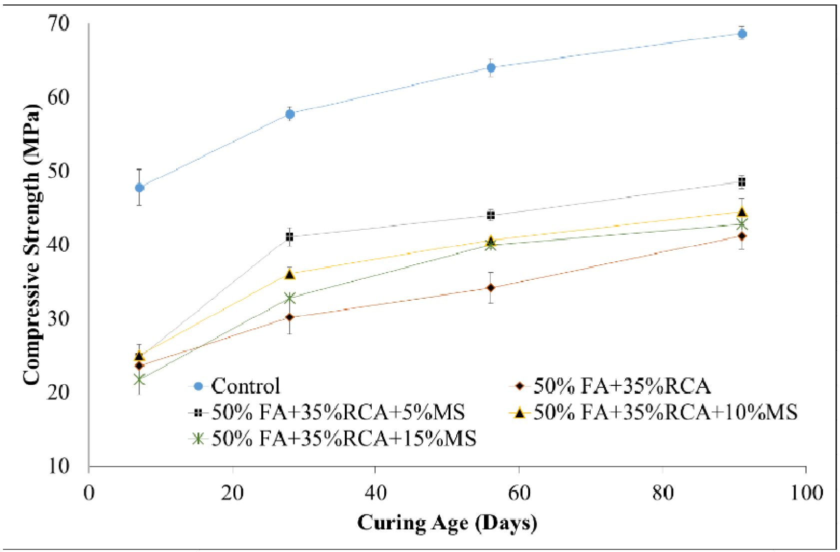


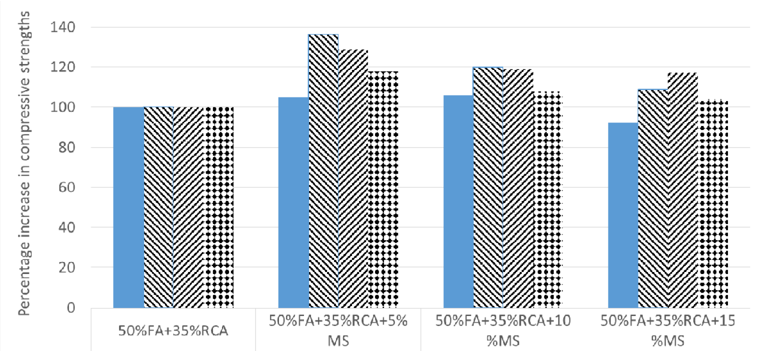
Fig. 4 Effects of MS on the compressive strength of high volume fly ash recycled aggregate concretes

At least three specimens were cast and tested in each series for each property measured in this study. All specimens were water cured until the day before the test date.

The compressive strength and elastic modulus tests were carried out on 100ø×200 mm cylinders and the indirect tensile strength was determined on 150ø×300 mm cylinders. Indirect tensile strength is also known as split-cylinder strength of concrete. The compressive strength, indirect tensile strength and elastic modulus were measured according to Australian standards AS1012.9, AS1012.10 and AS1012.17, respectively. The 100ø×200mm cylinders required for the compressive strength and modulus of elasticity were sulphur capped to ensure a smooth surface and improved test results. A Controls MCC8 3000kN machine was used to test the compressive strength and indirect tensile strength of all concrete samples. For the determination of modulus of elasticity a DMG/Rubicon 2500kN Universal Testing Machine was used to apply a constant load rate up to 40% of the ultimate load of respective concrete mix, while two linear variable differential transducers (LVDT) were used as shown in Fig. 3 to measure the axial deformation of the cylinder. The slope of the recorded stress vs strain curve yielded the elastic modulus of the concrete.

The rate of water absorption (sorptivity) of concrete samples with 50 mm thick disk was determined at 28, 56 and 91 days according to ASTM C1585-13 (ASTM 2013). The principle of the method is that a specimen has one surface in free contact with water (no more than 5 mm above the base of the specimen) while the other sides are sealed. This test determined the rate of absorption of water by hydraulic cement concrete by measuring the increase in the mass of a specimen resulting from absorption of water as a function of time. In this study, the mass of the concrete specimen was regularly measured to determine the initial absorption from 1 min to the first 6 hours. The absorption (I) was the change in mass divided by the product of the cross-sectional area of the test specimen and the density of water. The initial rate of water absorption value ($mm/min^{1/2}$) was calculated as the slope of the line that is the best fit to I plotted against the square root of time ($min^{1/2}$).

The chloride ion penetration resistance of concrete popularly called the rapid chloride permeability test (RCPT) was conducted according to ASTM C1202 (2012) standard. The



	50%FA+35%RCA	50%FA+35%RCA+5% MS	50%FA+35%RCA+10 %MS	50%FA+35%RCA+15 %MS
7 days	100	105	106	92
28 days	100	136	120	109
56 days	100	129	119	117
91 days	100	118	108	104

Fig. 5 Percentage changes in the compressive strength of HVFA-RAC relative to concrete in series 2 due to addition of MS

specimens from each series were tested after 28, 56 and 91 days of water curing. Details procedure from preparation of specimens to test can be found in ASTM C1202 (2012). Drying shrinkage test was performed on 75×75×280 mm prism as per AS 1012.13 (2012).

3. Results and discussion

The effect of MS on the workability of HVFA-RAC is shown in Fig. 4. The workability of concretes in all five series in this study were designed to keep between 80 and 100mm slump in order to have good compaction. However, to achieve this target workability especially in series 2 to 5 the dosages of superplasticizer were increased. It can be seen in the figure that the slump value of series 2 concrete is increased slightly by increasing the superplasticizer despite the presence of 50% FA. This is due to the presence of RCA as replacement of NCA. Reduction of concrete slump due to addition of RCA is reported in many studies and is due to higher angularity of RCA than that of NCA (Ahmed 2013). The use of 5, 10 and 15% MS as partial replacement of OPC in concrete in series 2 resulted in the reduction in workability despite the increase in superplasticizer dosages. This can be attributed to the well-known effect of high water demand of MS due to their small particles sizes and very high specific surface area.

3.1 Effect of micro silica on mechanical properties

The effects of different MS contents on the compressive strength of HVFA-RAC at various curing ages are shown in Fig. 5. It can be seen that at 7 days the compressive strength of HVFA-RAC containing 5% and 10% MS is about 5% and 6%, respectively higher than that without MS (series 2 concrete). The MS content of 15% on the other hand did not show any improvement at 7 days. The higher 7 days compressive strength of HVFA-RAC containing 5% and 10% MS than the 15% MS can be attributed to the better dispersion of MS due to smaller amount than the 15% MS. It is also interesting to see that the improvement of compressive strength at 7 days is relatively low compared to other researchers' results (Barbhuiya *et al*. 2009, Nochaiya *et al*. 2010). However, at

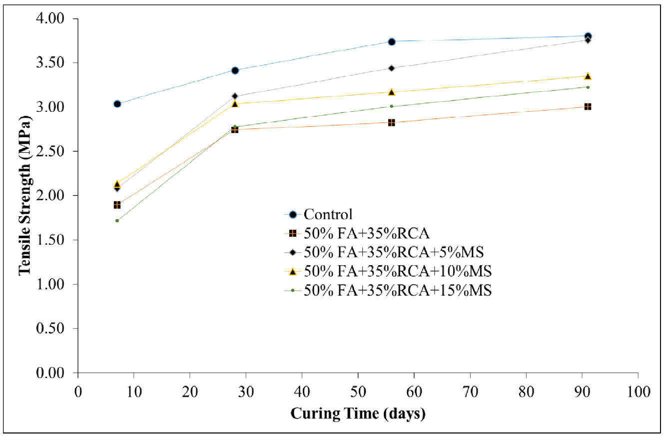


Fig. 6 Effects of MS on the indirect tensile strengths of high volume fly ash recycled aggregate concretes

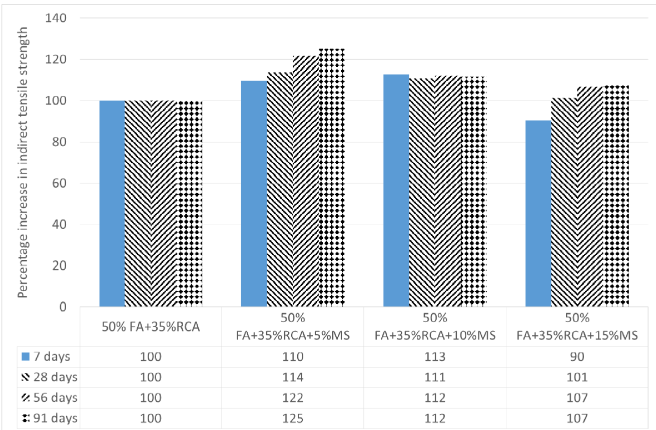


Fig. 7 Percentage changes in the indirect tensile strength of HVFA-RAC relative to concrete in series 2 due to addition of MS

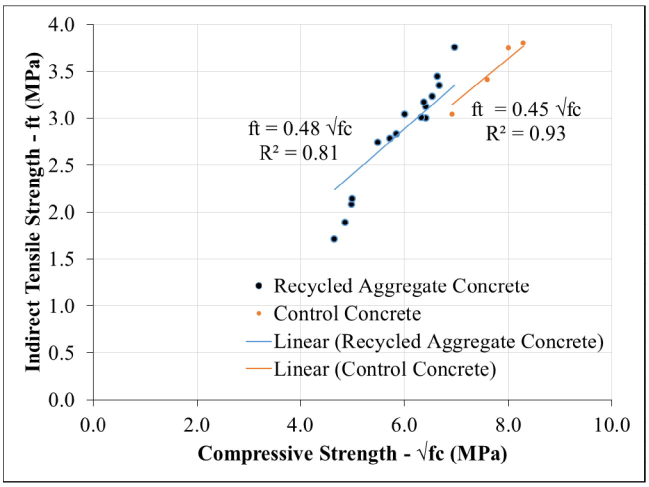


Fig. 8 Correlation of indirect tensile strengths with compressive strengths

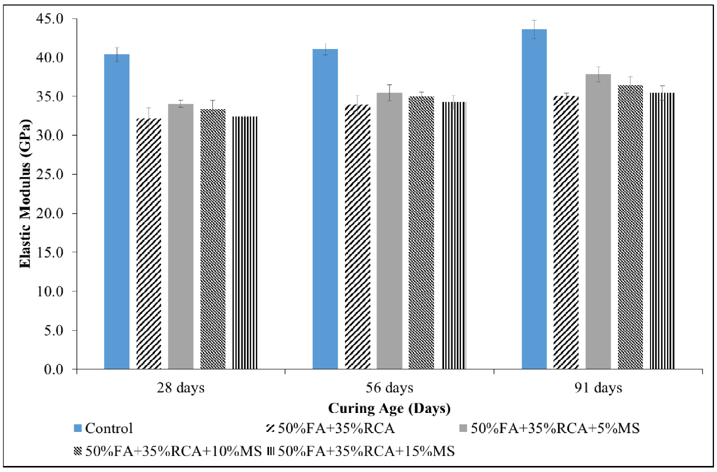


Fig. 9 Effects of MS on elastic modulus of high volume fly ash recycled aggregate concretes

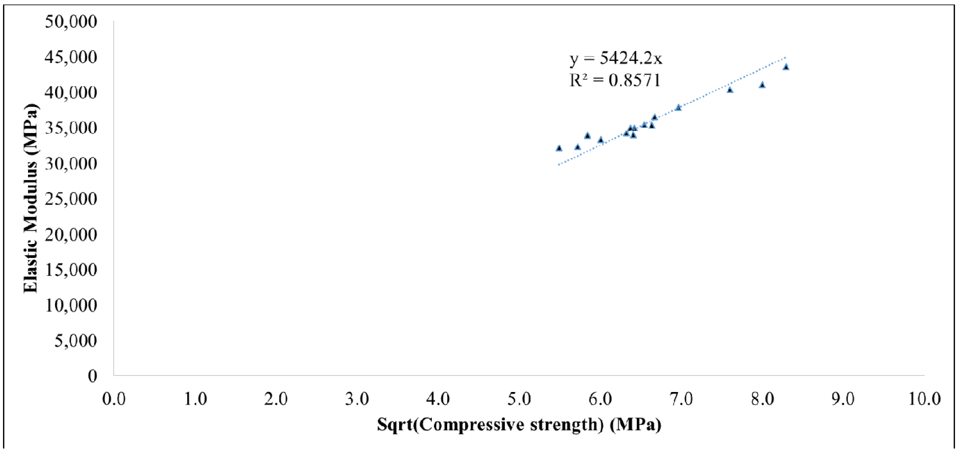
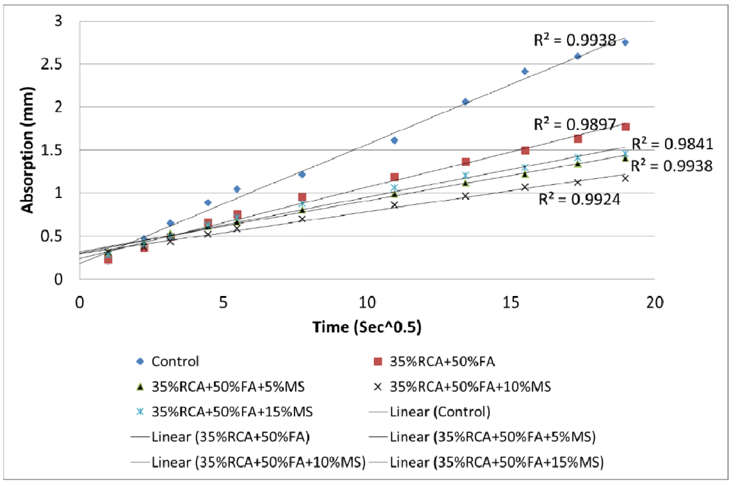


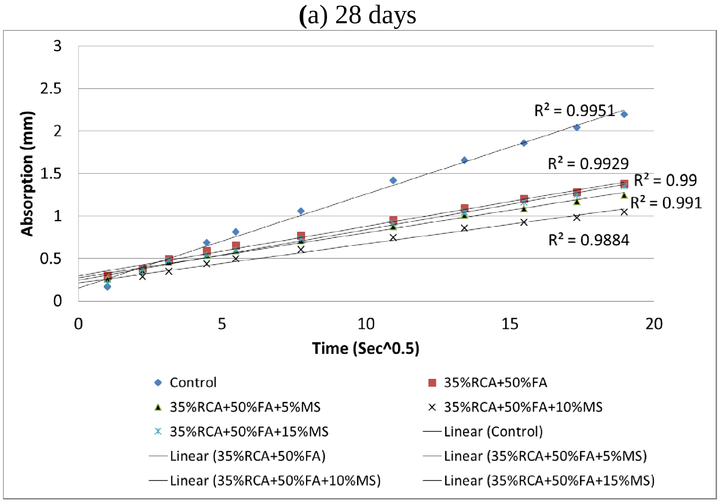
Fig. 10 Correlation of elastic modulus with compressive strengths

28 days and beyond, the improvement of compressive strength is significant in all MS contents and the 5% MS exhibited the highest compressive strength among all (Fig. 6). This significant improvement in compressive strength is due to the high amorphous nature of the MS and its extremely small particle size, which accelerated the pozzolanic reaction, generated additional calcium silica hydrate (C-S-H) gels in the matrix and densified the matrix through particle packing.

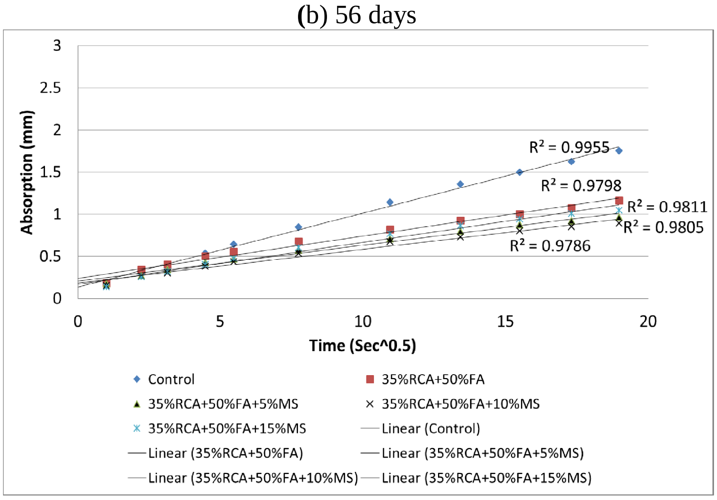
The effect of MS on indirect tensile strength of HVFA-RAC is shown in Fig. 7 and it can be seen that similar to compressive strength results, the addition of 5% and 10% MS also increased the indirect tensile strength of HVFA-RAC in Series 2 by about 10% and 13%, respectively at 7 days (Fig. 8). At 28 days and beyond the HVFA-RAC containing MS exhibited higher indirect tensile strength than that without MS and the 5% MS exhibited the highest indirect tensile strength at all ages (Fig. 8). Correlation between the indirect tensile strength (f_t) and the square root of compressive strength ($\sqrt{f'_c}$) of concretes containing NCA and HVFA-RAC containing fly ash and RCA are also established and is shown in Fig. 9. It can be seen that there is a very good correlation with R^2 values of 0.81 and 0.93 in concrete containing NCA (series 1) and concretes containing RCA, FA and MS



(a) 28 days



(b) 56 days



(c) 91 days

Fig. 11 Effects of MS on the rate of water absorption of HVFA-FAC at (a) 28 days, (b) 56 days and (c) 91 days

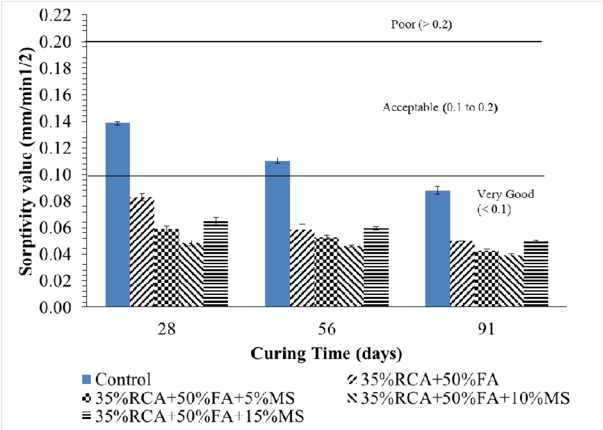


Fig. 12 Effect of MS on water sorptivity of HVFA-RAC

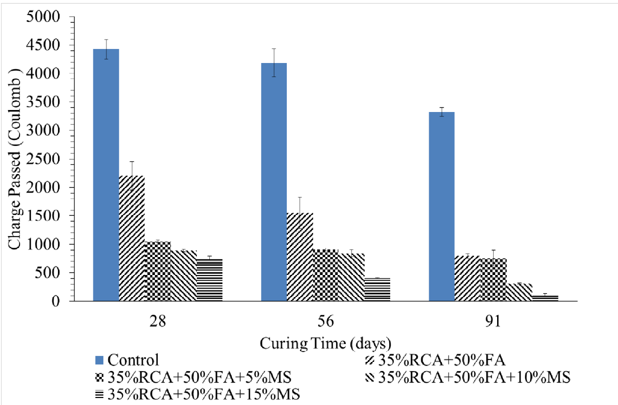


Fig. 13 Effect of MS on chloride ion permeability of HVFA-RAC

(series 2-5). In the case of concrete containing NCA the ratio of $f_t/\sqrt{(f'_c)}$ is 0.45 and in the case of HVFA-RAC the ratio is 0.48. Nevertheless, both values are very close to 0.4 for ordinary concrete according to AS 3600. The effect of MS on the elastic modulus of HVFA-RAC is also evaluated in this study (Fig. 10) and similar to the strengths results the addition of MS improved the elastic modulus of HVFA-RAC at all ages. The 5% MS exhibited the highest improvement in elastic modulus values at all ages among all MS contents. A good correlation between the elastic modulus (Ec) and the square root of compressive strengths ($\sqrt{(f'_c)}$) of HVFA-RAC is also established (Fig. 11) with $E_c/\sqrt{(f'_c)}$ ratio of 5424, which is very close to 5050 for ordinary concrete (Warner et al., 1999). The above correlations show that the existing empirical relations to predict the indirect tensile strength and elastic modulus in the literature can be used however, with slight underestimated values.

3.2 Effect of micro silica on durability properties

Water sorptivity describes water ingress into pores of unsaturated concrete due to capillary suction. It is a function of porosity including pore volumes and continuity of pores within concrete

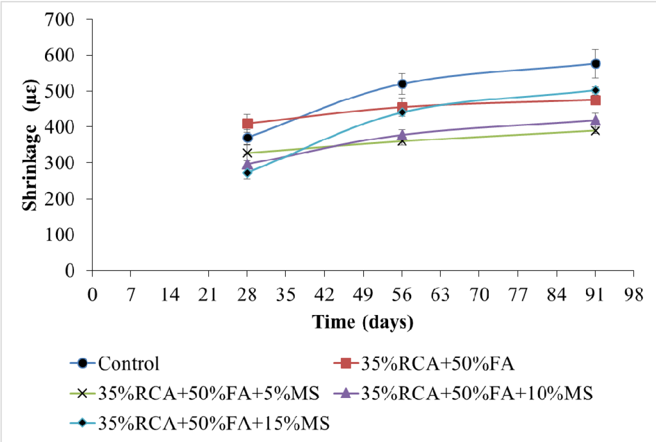


Fig. 14 Effect of MS on drying shrinkage of HVFA-RAC

matrix and can be related to permeability. The water absorption of the specimen up to 6 hours was fitted using linear regression and the slope of the line obtained was used to describe the sorptivity in the first 6 hours. The rates of water absorption (mm) of all concrete mixtures at 28, 56 and 90 days are presented in Figs. 12(a)-(c). The best-fit lines in these Fig.s are based on R^2 values greater than 0.98 according to ASTM C1585 (2013) for all mixes. It can be seen that the rate of water absorption of the concrete specimens increased with increase in time. The slope of the obtained line defines the sorptivity of different concretes during the initial 6 hours of testing. It can be clearly seen that the rate of water absorption of all concretes is reduced at 56 and 90 days due to continuous moist curing, which densified the pores due to formation of additional C-S-H gels.

It is also evident from this study that the inclusion of MS decreased the sorptivity of HVFA-RAC (see Fig. 13). With regards to the HVFA-RAC containing MS, the water sorptivity dropped by 30% and 40% at 28 days when 5% and 10% MS was added, respectively. However at 56 and 91 days there was no significant difference between the HVFA-RAC concretes containing 5% and 10% MS as relative to 28 days. The sorptivity decreased approximately by 9% and 4% at 56 and 91 days, respectively of above two concretes which indicate that, most of the pores sizes and pore volumes have been reduced to maximum level by the hydration products. It is interesting to see that the HVFA-RAC containing 15% MS had a higher water sorptivity than those containing 5% and 10% MS at all curing ages. However, the rate of water absorption drop was consistent with all the mixes and the sorptivity is lower than the HVFA-RAC containing no MS and control concrete. Overall, these results indicate that the incorporation of fly ash and MS has resulted in low water sorptivity of HVFA-RAC compared to control. The values of sorptivity coefficients are less than 0.1mm/min$^{1/2}$ which lies in the performance limit of very good as proposed by Papworth and Grace (1985).

The effects of different MS contents and curing times on the chloride ion permeability of HVFA-RAC are shown in Fig. 14. Rapid chloride permeability testing (RCPT) according to ASTM C1202 (2012) was used to measure the chloride ion penetration resistance of concretes in this study. It can be seen that the chloride ion permeability resistance of concrete increases with increasing moist curing ages. This has been apparent in most researches whereby a longer moist curing reduces the interconnectivity of the pore system and the ingression of chloride ions. According to Kou *et al.* (2007), this improvement is due to increase in volume of hydration products which creates impermeable regions that narrows down the capillary pores. It is also interesting to notice that, the recycled aggregate concrete containing high volume fly ash achieved better resistance than the control concrete. It is observed that the reduction of cement content by 50% in series 2 concrete resulted in a moderate chloride ion penetration at 28 days as compared to a high level for the control concrete. The concrete in series 2 exhibited about 52% less charge passed than the control at 28 days. At 56 and 91 days, the resistance to chloride ion penetration improved significantly in that concrete. The charge passed in series 2 concrete is reduced by 30% and 65% at 56 and 91 days, respectively of the corresponding 28 days values, resulting in a low and very low permeability of chloride ions in to the concrete. Similar trend is also reported by Naik *et al*. (1994). The significantly lower chloride ion penetration in high volume fly ash concrete can also be attributed to the formation of Friedel's salt which is formed through the reaction of chloride ions with additional calcium aluminate hydrates (Kayali *et al*. 2013).

Interestingly, the addition of MS to the HVFA-RAC resulted in a higher resistivity to chloride ions. At 28 days, the charge passed was 52%, 60% and 65% less for 5%, 10% and 15% MS, respectively than that for the high volume fly ash recycled aggregate concrete. At later ages (e.g. 56 and 91 days), the resistivity increased at a higher rate in HVFA-RAC containing MS than that without MS. In addition, there was a significant decrease in chloride ion penetration for series 4 and 5 concretes at 91 days by 65% and 85%, respectively. The MS used for this study had a high content of $Si0_2$ which combines with the free lime ($Ca(OH)_2$) to form additional C-S-H gels that reduces the porosity of concrete, thereby prevents the penetration of chloride ions (Ioannides *et al*. 2006).

Drying shrinkage of concrete is an important durability property as it cause cracking of reinforced concrete structures during their service life. The drying shrinkage was determined in accordance to AS 1012.13 (1992). Three specimens of each series were tested. After measuring the initial length of the specimens after 7 days of wet curing all specimens were left in laboratory under controlled temperature at 20 ±3°C and at reasonably dry environment until 28, 56 and 91 days. Three measurements of each specimen were recorded and averaged. Fig. 15 shows the drying shrinkage of control concrete and HVFA-RAC containing 0, 5, 10 and 15% MS relative to drying time. It can be clearly seen that the shrinkage strains of all concretes increase with increase in drying time. It can also be seen that at 28 days the drying shrinkage of concrete containing RCA and high volume fly ash is slightly higher than the control concrete without the RCA. The higher porosity of RCA, which is evident from the water absorption test of the aggregates in this study, is believed to be responsible of higher drying shrinkage values of recycled aggregate concretes. The effect of MS on the drying shrinkage of HVFA-RAC can also be seen in Fig. 15. It can be seen that addition of MS reduced the shrinkage of HVFA-RAC at all drying ages except the MS content of 15% which slightly exceeded the shrinkage of HVFA-RAC concrete at 91 days. Among all three MS contents, the 5 and 10% MS exhibited the lower shrinkage (5% MS performed slightly better than the 10%) than the 15% MS.

One anticipated finding was that, there was an increase in drying shrinkage of HVFA-RAC containing 15% MS (Series 5) at 91 days even though there was a reduction in cement content by 5% as compared to Series 4 concrete containing 10% MS. The drying shrinkage strain obtained was almost similar to Series 2 concrete which had 15% more cement content than the Series 5 concrete. This phenomenon can be related to the addition of superplasticizers. Regardless of the cement content, high amount of superplasticiser reduces the surface tension of water which causes higher strains in concrete as claimed by (Brooks 1989; Atis 2003 and Holt and Leivo 2004). It is apparent from Fig. 14 that the addition of high quantities of superplasticizer resulted in an increase in shrinkage strain of concrete in series 5. Furthermore, Malathy and Subramanian (2007) also recorded a higher shrinkage strain for 15% MS as compared to 5% and 10% MS.

4. Conclusions

This paper presents an experimental study on the effects of micro silica on the mechanical and durability properties of high volume fly ash concrete containing recycled coarse aggregate as partial replacement of natural coarse aggregate. Based on limited micro silica contents the following conclusions can be drawn

1. The addition of 5% and 10% micro silica improved the 7 days compressive strength of HVFA-RAC by about 5% and 6%, respectively. In the case of indirect tensile strength this improvement was about 10% and 13%, respectively.

2. At 28, 56 and 91 days all micro silica contents exhibited improvement in compressive strength, indirect tensile strength and elastic modulus of HVFA-RAC with most significant improvement at 5% micro silica.

3. It is also observed that the above improvement in compressive strength, indirect tensile strength and elastic modulus of HVFA-RAC is affected with increasing micro silica contents especially at 15% due to poor dispersion of micro silica particles.

4. Good correlation of indirect tensile strength and elastic modulus of HVFA-RAC with compressive strength are established.

5. The rate of water absorption of HVFA-RAC decreased with increase in micro silica contents and curing ages. 10% micro silica exhibited the lowest sorptivity of HVFA-RAC among all three micro silica contents. It is also observed that the difference in sorptivity values between 5% and 10% micro silica contents is very negligible and this difference decreased with increase in moist curing up to 91 days.

6. In the case of drying shrinkage, similar results to the sorptivity are also observed where the 5% and 10% micro silica showed lower drying shrinkage of HVFA-RAC than the 15% micro silica and the difference in shrinkage strains at 5% and 10% micro silica is also negligible.

7. The HVFA-RAC exhibited a significant reduction in chloride ion penetration compared to control concrete due to the presence of high fly ash content which also helped to bind the chloride ions in the form of Friedel’s salt. The addition of micro silica also significantly reduced the chloride ion penetration of HVFA-RAC, which is represented in terms of coulombs values and this reduction increases with increasing micro silica contents and extended moist curing.

8. The use of micro silica decreased the water sorptivity, chloride ion penetration and drying shrinkage of HVFA-RAC which is lower than the control concrete. This research also shows that durable concrete can be developed using 55% to 60% less OPC (50% fly ash and 5-10% micro silica as partial replacement of cement) and 35% less natural coarse aggregates, whose durability properties are better than the ordinary Portland cement concrete.

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