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Mechanical properties of recycled aggregate concrete containing ternary blended cementitious materials

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Abstract

This paper presents the effect of silica fume (SF) on early-age and long-term mechanical properties of recycled aggregate concrete containing slag. In this study six series of mixes are considered. The first series is control concrete containing 100% ordinary Portland cement (OPC) and 100% natural aggregates. The second series is similar to the first series in every aspect except the natural coarse aggregate (NCA) which was partially replaced by 50% (by wt.) recycled coarse aggregate (RCA). The third series is also similar to the second series except the OPC which is partially replaced by 50% slag. The effects of 5, 10 and 15% (by wt.) SF on mechanical properties of concrete is evaluated in fourth, fifth and sixth series, respectively. Compressive strength, indirect tensile strength and modulus of elasticity of above concretes are measured at 3, 7, 28, 56 and 91 days. Results show that the addition of 50% slag significantly reduced the above mechanical properties of concrete containing 50% RCA at early age. Among three SF contents, the 10% SF improved the above mechanical properties of recycled aggregate concrete containing slag at early ages (3 and 7 days) as well as at 28 days. The addition of 10% SF also improved the 56 and 91 days compressive and tensile strengths of recycled aggregate concrete containing slag. It is also found that the long-term (56 and 91 days) compressive and tensile strengths of recycled aggregate concrete containing slag and 10% SF are even higher than the OPC concrete containing 50% RCA and control concrete, respectively. It is also observed that the slow pozzolanic reaction of slag contributed to the long-term compressive and tensile strengths of recycled aggregate concrete containing slag and 10% SF. Strong correlations of measured compressive strength with indirect tensile strength and elastic modulus of above environmentally friendly concretes are also established.
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Keywords: Slag; Silica fume; Recycled aggregate; Mechanical properties

1. Introduction

The addition of supplementary cementing materials (SCM), which are industrial by-products, as partial replacement of ordinary Portland cement (OPC) in concrete is widely practiced to reduce the carbon footprint of OPC concrete as the OPC manufacturing releases approximately 5–7% CO_2 in the air (Limbachiya et al., 2014; Malhotra and Mehta, 2002). In addition, the use of natural aggregates, which occupy approximately 75–80% of total volume of concrete (Neville, 2011), also affects the environment as the extraction of natural rocks significantly affect the natural eco-system. The release of CO_2 and the extraction of natural rocks will continue in future as the use of

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concrete in construction is unavoidable due to rapid urbanisation and housing demand in the world. However, efforts have been made to address these issues on environmental impact and the use of SCM e.g. 20–30% fly ash and slag and 5–10% silica fume as partial replacement of OPC and 20–30% replacement of natural aggregates by recycled concrete aggregates in concrete is accepted in many countries and significant amount of research has been done with good understanding on the properties of concrete containing these recycled aggregates and SCM materials.

In order to further improve the environmental friendliness of concrete and to maximise the use of these by-products and construction and demolition wastes in concrete the use of high volume fractions of these materials in concrete need to be incorporated. Significant amount of research is also conducted on the individual use of high volume fractions of SCM in concrete (Malhotra and Mehta, 2002; Shaikh et al., 2014a; Mo et al., 2015; Naik et al., 1994; Siddique, 2004; Kou et al., 2011, Supit and Shaikh, 2014; Shaikh and Supit, 2015) and the high amount of recycled concrete aggregates (Chen et al., 2003; Yong and Teo, 2009; Zhang and Ingham, 2010; Ahmed, 2014; Xiao et al., 2005; Yang et al., 2008; Shaikh et al., 2014b; Shaikh, 2015). It has been reported that the use of high volume fly ash and slag adversely affect the early age strength properties of concrete although in the longer term these concretes show improvement of the same strength properties due to pozzolanic reaction of fly ash and slag with calcium hydroxide of the hydration of cement. It has been also reported that the workability of these concretes is improved (Naik et al., 1994; Siddique, 2004; Kou et al., 2011). While in many research the effect of ultrafine SCMs (e.g. silica fume, nano particles, ultrafine fly ash, etc.) on the strength properties of concrete containing fly ash is studied, however, very little is reported on the effect of silica fume on the strength properties of slag concrete (Bashah, 2006; Kumar and Bhargari, 2015) and the results show that the inclusion of silica fume improves the early age as well as long-term compressive strength of high volume slag concrete.

The environmental impact of concretes can significantly be improved by adding high amount of recycled aggregates as partial replacement of natural aggregates in the concretes containing slag. However, the mechanical properties of concretes containing slag and high amount of recycled aggregates are not widely reported. In addition, it is also expected that the early age mechanical properties of recycled aggregate concrete containing slag will be lower than the RAC due to slow pozzolanic reaction of slag. The addition of small amount silica fume or other ultrafine SCMs can compensate this deficiency. However, no study so far reported the effects of different amount of silica fumes on the early age and long-term mechanical properties of recycled aggregate concrete containing slag. Therefore, this research fills this gap and presents measured mechanical properties from 3 days to 3 months of recycled aggregate concrete containing 50% slag and 50% RCA as partial replacement of OPC and natural coarse aggregate, respectively. The effects of different silica fume contents of 5, 10 and 15% on the mechanical properties of above recycled aggregate concrete containing slag are also evaluated in this study.

2. Experimental program

In this study six series of mixes were considered. The first series was control concrete consisting of 100% OPC and 100% natural aggregates. The second series was very similar to the first series with only exception of replacement of 50% natural coarse aggregate with recycled coarse aggregate (RCA). The effect of 50% slag as partial replacement of OPC on second series concrete is evaluated in the third series. In fourth to sixth series the effect of 5%, 10% and 15% SF on the properties of recycled aggregate concrete containing 50% RCA and 50% slag is evaluated. In these series total replacement of OPC by slag and SF was kept at 50% in order to compare with the third series.

3. Materials

Ordinary Portland cement (OPC) was used in all concrete mixes. The blast furnace slag used in this study was

Table 1
Chemical and physical properties of ordinary portland cement (OPC), slag and silica fume (SF).

Chemical analysis	OPC (wt.%)	Slag (wt.%)	Silica fume (wt.%)
SiO_2	21.1	32.45	89.6
Al_2O_3	5.24	13.56	–
Fe_2O_3	3.1	0.82	–
CaO	64.39	41.22	–
MgO	1.1	5.1	–
K_2O	0.57	0.35	0.225
Na_2O	0.23	0.27	0.11
SO_3	2.52	3.2	–
LOI	1.22	1.11	3.8
Particle size	–	–	95% particles < 1 μm
Specific gravity	3.17	–	0.625
BET Surface area (m^2/g)	–	–	15–30

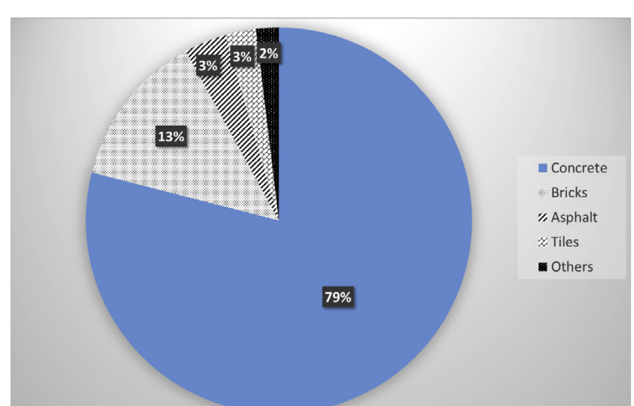

Fig. 1. Analysis of construction and demolition wastes used as recycled coarse aggregates in this study.

obtained from a local supplier. Commercial silica fume (SF) supplied by Ecotec was used in this study. The SF is densified and amorphous with specific surface area of about 15–30 m^2/kg. The properties and chemical compositions of OPC, slag and SF 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 79% are from concrete and the rest consisted of masonry, asphalt, tiles 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 (2010a). The natural coarse aggregates (NCA) used in this study were mixture of 10 mm and 20 mm 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 concretes containing SF only. Table 3 shows the mix proportions used to produce the test samples. The percentage replacements of NCA by RCA, OPC by slag and SF were on the basis of weight. The water/cement ratio is kept constant at 0.4 in all mixes. In concretes containing SF superplasticizer was added in order to maintain a target slump range of 80–100 mm.

Table 2
Properties of natural coarse aggregate (NCA) and recycled coarse aggregate (RCA).

Properties	Natural coarse aggregate (NCA)	Recycled coarse aggregate (RCA)
Water absorption (%)	0.4	5.7
Un-compacted bulk density (kg/m3)	1460	1310
Compacted bulk density (kg/m3)	1600	1410

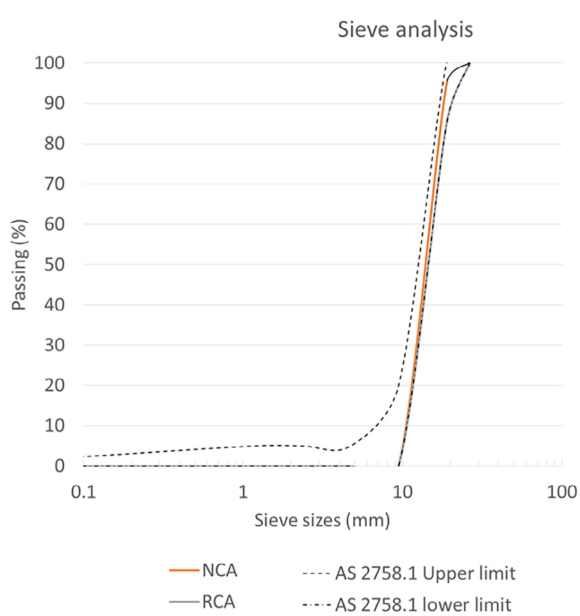

Fig. 2. Sieve analysis of natural coarse aggregates and recycled coarse aggregates.

4. Methods

The compressive strength and indirect tensile strength were measured at 3, 7, 28, 56 and 91 days for all mixes except the elastic modulus which was measured at 3, 7 and 28 days. 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. The compressive strength, indirect tensile strength and elastic modulus were measured according to Australian standards AS1012.9 (2010b), AS1012.10 (2010c) and AS1012.17 (2010d), respectively. The 100 × 2 00mm cylinders required for the compressive strength and modulus of elasticity were sulphur capped to ensure a smooth surface and improve test results. A Controls MCC8 3000 kN 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 2500 kN Universal Testing Machine was

Table 3
Mix proportions and workability of concretes.

Series	Mix proportions (kg/m^3)									Slump (mm)
	OPC	Slag	SF	FA	NCA-10 mm	NCA-20 mm	RCA	Water	SP	
Control	455	–	–	770	770	330	–	182	–	95
50% RCA	455	–	–	770	385	165	550	182	–	–
50%RCA + 50%Slag	228	228	–	770	385	165	550	182	–	105
50%RCA + 45%Slag + 5%SF	228	203	23	770	385	165	550	182	1.82	90
50%RCA + 40%Slag + 10%SF	228	182	46	770	385	165	550	182	2.58	90
50%RCA + 35%Slag + 15%SF	228	159	68	770	385	165	550	182	2.80	100

Note: OPC = Ordinary Portland Cement; SF = Silica fume; FA = Fine aggregate (sand); NCA = Natural coarse aggregate; RCA = Recycled coarse aggregate; SP = Superplasticizer.

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.

Fig. 3. Test setup to measure the elastic modulus of concrete cylinder.

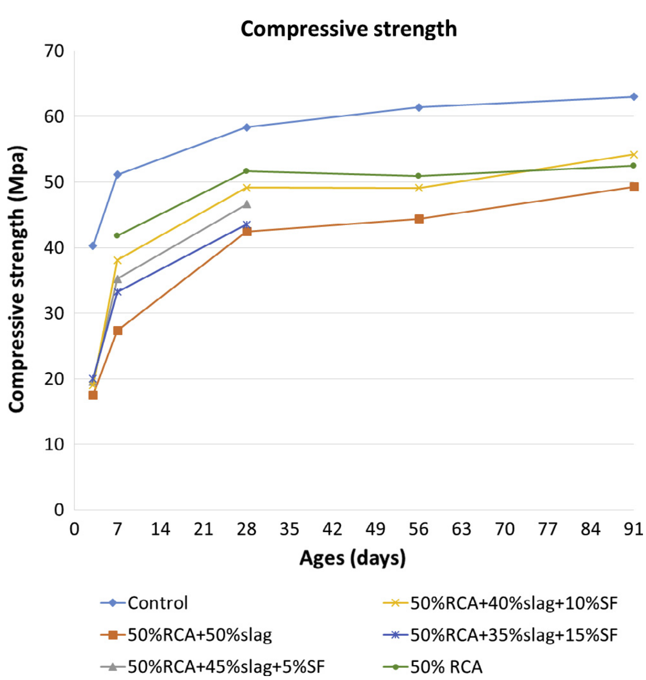

Fig. 4. Compressive strength development of concretes over time.

5. Results and discussion

5.1. Effects of RCA and slag

The effects of SF on the compressive strength, tensile strength and elastic modulus of recycled aggregate concrete containing slag at early ages (3 and 7 days) as well as at long-term (28, 56 and 91 days) are shown in Figs. 4–6, respectively. In the same figures the above mechanical

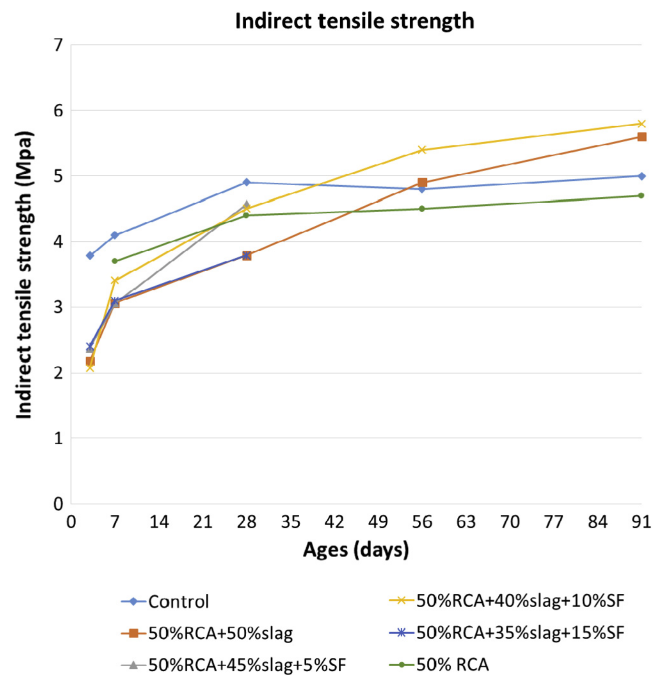

Fig. 5. Indirect tensile strength development of concretes over time.

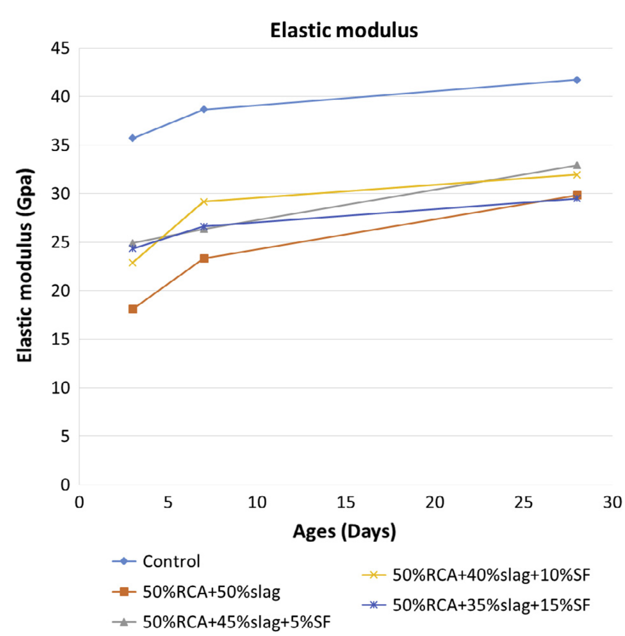

Fig. 6. Elastic modulus development of concretes over time.

properties of concrete containing 50% RCA as partial replacement of natural coarse aggregates and recycled aggregate concrete containing 50% slag and 50% RCA are also shown. The results show that the addition of 50% RCA reduced the 7-days compressive and tensile strengths of control concrete by about 19 and 10%, respectively (see Figs. 7 and 8), which was anticipated and reported by many researchers (Shaikh et al., 2014b; Shayan and Xu, 2003). The adherence of porous mortar on the RCA, the porous interfacial transition zone (ITZ) in RCA and the presence of pre-existing micro-cracks due to crushing of RCA influenced the reduction of above mechanical properties. No significant improvement on the compressive strength of 50% RCA concrete is observed due to longer curing, however, in the case of tensile strength slight improvement is observed. The effect of addition of 50% slag as partial replacement of OPC in the concrete containing 50% RCA on compressive and tensile strength can also be seen in Figs. 7 and 8, which show that at 7 days the reduction of compressive and tensile strength is highest among all curing ages and with increase in curing days the strength loss in both cases decreases and at 91 days the difference in compressive strength between the control concrete and that containing 50% slag and 50% RCA is only 6%. This can be attributed to the contribution by the pozzolanic reaction of SiO_2 and Al_2O_3 in the slag with the $Ca(OH)_2$ in the matrix, which produced additional calcium-silica-hydrate (C-S-H) gels and reduced the pores and

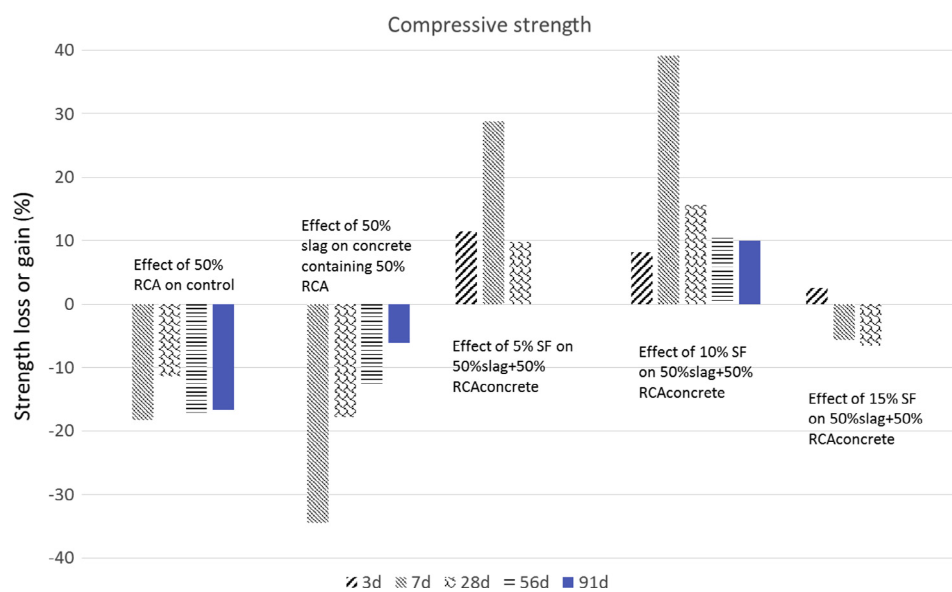

Fig. 7. Effects of RCA, slag and SF on compressive strength of concretes.

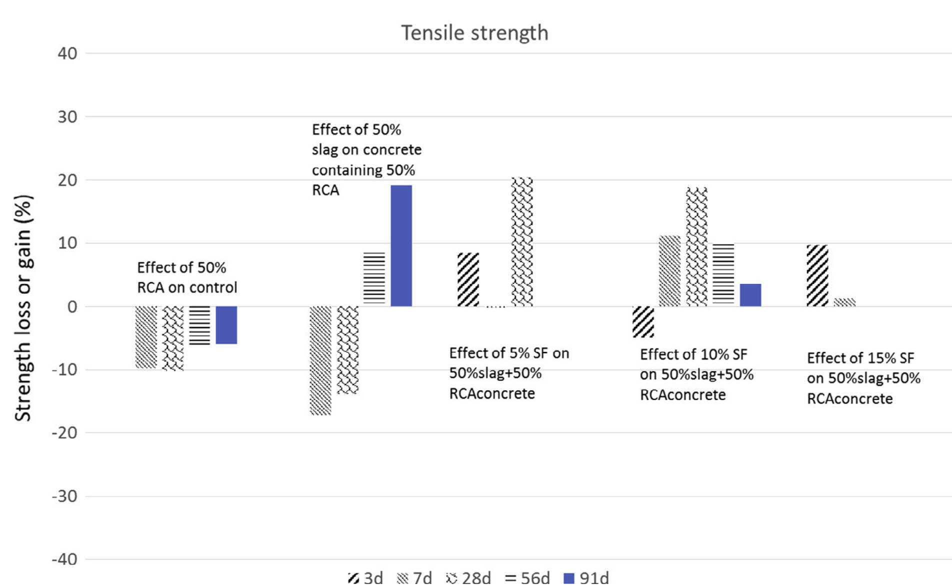

Fig. 8. Effects of RCA, slag and SF on indirect tensile strength of concretes.

densified the ITZ of RCA with the matrix (Malhotra and Mehta, 2002). However, most significant influence is observed in the case of tensile strength at 56 and 91 days which is increased by about 9–18%.

5.2. Effect of silica fume on early age mechanical properties

The effects of different SF contents of 5, 10 and 15% on the early age compressive strength, tensile strength and elastic modulus of recycled aggregate concrete containing slag are also shown in Figs. 4–6. It can be seen that the compressive strength is increased by about 11% and 28% at 3 and 7 days, respectively due to addition of 5% SF (see Fig. 7). Similar improvement is also observed in the case of tensile strength at 3 days with no significant improvement at 7 days (Fig. 8). However, the elastic modulus is increase by about 36% and 11% at 3 and 7 days, respectively (see Fig. 9). It can also be seen that when the SF content is increased to 10% the 3 and 7 days compressive strength is increased by about 12% and 38%, respectively. The tensile strength and elastic modulus are also increased due to addition of 10% SF. However, no significant improvement is observed in all three mechanical properties when 15% SF is added (see Figs. 7–9), most probably due to poor dispersion of SF particles in the mix due to their significantly higher specific surface area compared to slag and OPC. Inferior properties of concrete containing 15% SF due to poor dispersion of SF is also reported by other researchers (Ajileye, 2012; Hanumesh et al., 2015). By comparing the improvement in compressive strength, tensile strength and elastic modulus of recycled aggregate concrete containing slag and 5 and 10% SF, it can be seen that the 10% SF shows higher improvement than the 5% SF. Hence, the effect of 10% SF on long term mechanical properties of recycled aggregate concrete containing slag is studied and its effect is discussed in the next section. Nevertheless, it can be seen that both 5 and 10% SF showed improvement in early age compressive strength, tensile strength and elastic modulus of recycled aggregate concrete containing slag and contributed by the additional C-S-H gels formed due to pozzolanic reaction of amorphous SiO_2 of extremely small SF particles.

5.3. Effect of silica fume on long-term mechanical properties

The effect of 10% SF on the compressive and tensile strengths of recycled aggregate concrete containing slag at 28, 56 and 91 days is also shown in Figs. 4–6. It can be seen that the compressive strength of recycled aggregate concrete containing slag and10% SF is also increased at later ages, however, the percentage increment is not as high as observed at early ages e.g. at 7 days. It can also be seen that at 91 days the compressive strength of recycled aggregate concrete containing slag and10% SF exceeded the compressive strength of OPC concrete containing 50% RCA. On the other hand, it can also be seen that the compressive strength development of concrete containing 50% RCA and 50% slag from 28 days to 91 days is very similar to that of recycled aggregate concrete containing slag and10% SF. This clearly shows the slag has contributed to the long-term compressive strength development due to their slow pozzolanic reaction compared to SF, which has been reported by many researchers. In the case of tensile strength the effect of 10% SF is even prominent after 28 days where the recycled aggregate concrete containing slag and10% SF exceeded the control concrete. When comparing the tensile strength development between the recycled aggregate concrete containing slag and that containing 10% SF, one can see that from 28 to 56 days the strength development is very similar but from 56 to 91 days the rate of strength development is higher in recycled aggregate concrete containing slag. It can also be seen in Fig. 8 that

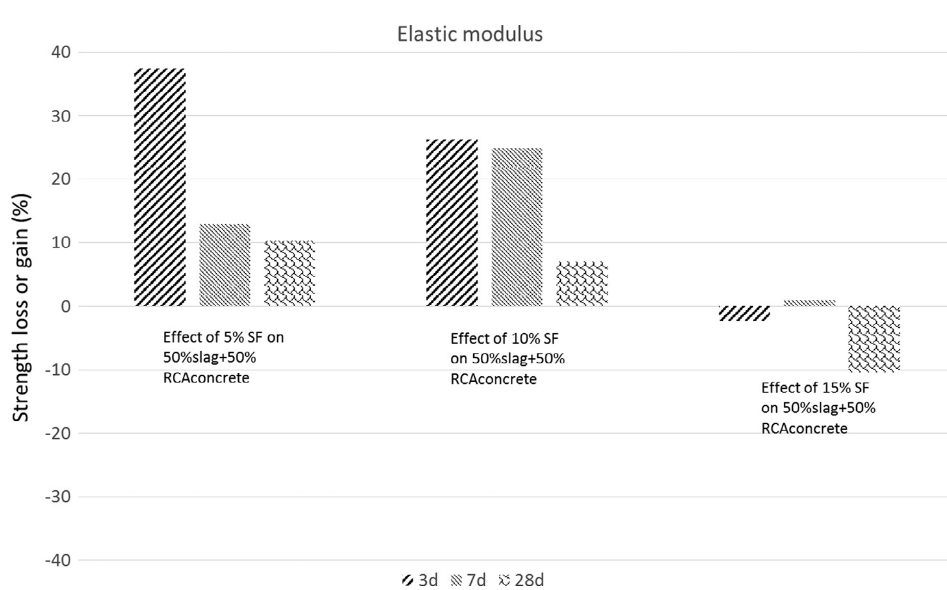

Fig. 9. Effects of RCA, slag and SF on elastic modulus of concretes.

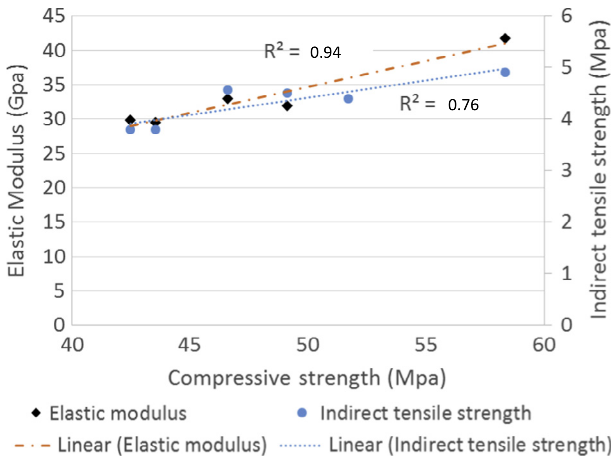

Fig. 10. Correlations of compressive strength with elastic modulus and indirect tensile strength of concretes.

the tensile strength of recycled aggregate concrete containing slag increase with increase in curing ages after 56 days and that containing 10% SF decreases with increase in curing ages. This clearly shows the contribution of slag in the long term strength development of recycled aggregate concrete containing slag.

The mechanical properties results obtained in this study are also correlated and are shown in Fig. 10. It can be seen strong correlations of compressive strength with elastic modulus and indirect tensile strength in the figure with increasing trend of elastic modulus and indirect tensile strength with increase in compressive strength.

6. Conclusions

This paper presents mechanical properties of an environmental friendly concrete containing 50% less OPC and 50% less natural coarse aggregates, which were measured at as early as 3 day to later ages at 3 months. The effects of three different SF contents on the above mechanical properties of above environmental friendly concrete are also evaluated. Based on preliminary results the following conclusions can be made:

1. Addition of 10% silica fume significantly improved the early age (3 and 7 days) compressive strength, indirect tensile strength and elastic modulus of concrete containing 50% RCA and 40% slag compared to 5% and 15% SF.
2. The 10% SF is found to be an optimum content to improve the mechanical properties of the concrete containing 50% RCA and 40% slag.
3. The long term mechanical properties of the concrete containing 50% RCA and 40% slag containing 10% SF is also improved, however not as high as observed at early ages.
4. Environmentally friendly concrete containing less than half of total amount of OPC cement and natural coarse aggregates is developed whose 28 days compressive strength is close to 50 MPa, indicating its applicability as structural concrete.

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